Article

Fl. Medit. 35: 85-108
https://doi.org/10.7320/FlMedit35.085
Version of Record published online on 5 August 2025

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Impact of climate change on Holm Oak mortality and dieback in the High Atlas, Morocco's Mediterranean climate

Abstract

Gharnit, Y., Mokrane, S., Outourakhte, A., Moujane, A., Hasib, A. & Boulli, A.: Impact of climate change on Holm Oak mortality and dieback in the High Atlas, Morocco's Mediterranean climate. — Fl. Medit. 35: 85-108. 2025. — ISSN: 1120-4052 printed, 2240-4538 online.

Forests are facing unprecedented mortality and dieback globally. While Holm oak decline is well-studied in the northern Mediterranean, its drivers in North Africa remain poorly understood, challenging conservation efforts. In Morocco's High Atlas, Holm oak forests span altitudes of 1200–2200 meters on limestone substrates in subhumid and semi-arid bioclimates. The Standardized Precipitation Evapotranspiration Index (SPEI) reveals severe droughts, and PCA analyses show strong links between reduced precipitation, rising temperatures, and Holm oak decline. Areas with low rainfall and high temperatures suffer the most, especially during hot seasons. Mixed Holm oak shrubs exhibit the highest decline rate (40.31%), followed by pure Holm oak shrubs (25.88%) and forests (19.92%). Mixed forests are more vulnerable. Larger trees with greater height and diameter at breast height (DBH) show higher resistance, while factors like elevation, soil type, and canopy cover have minimal impact. Southern slopes are particularly affected due to increased solar radiation. Holm oak decline begins with dieback, leading to mortality. This decline underlines significant ecological and socio-economic consequences, including habitat loss and severe impacts on local community. These findings emphasize the need for targeted conservation strategies to mitigate the effects of climate change on these forests.

Key words: *Quercus ilex*, Forest, Decline, Tree resilience, Drought, SPEI.

Article history: Received 3 January 2025; received in revised form 14 July 2025; accepted 20 July 2025; published 5 August 2025.

Introduction

Forest ecosystems serve as important long-term sinks for carbon and essential nutrients source (García-Angulo & al. 2020). In addition, forests serve as highly diverse habitats and ecological systems that cover nearly a third of the world's land surface area (Fischbein & Corley 2022). Furthermore, forest ecosystems are crucial to the survival and development of human societies (Zhang & al. 2022). Generally, forests are a cornerstone of our planet's health, offering immense economic, ecological, and cultural values (Kassie & al. 2024).

However, these ecosystems are under unprecedented pressure, for instance, climatic change, invasive species, natural disasters, land use change, and pest/diseases that can severally impact the ability of forest to sustain ecosystem services (Randhir & Erol 2013). Indeed, forests are experiencing growing risks of drought-induced mortality in a warming world (Batllori & al. 2020). Trees mortality is an emergent worldwide environment phenomenon (Allen Breshears 2007). In addition, biotic agents and abiotic stress factors interact in time and space to produce tree decline (Jung & al. 2000; Oliva & al. 2013; Sena & al. 2018; Gea-Izquierdo & al. 2021) The decline of forests in developed countries, including Morocco, has become a global concern (Mueller-Dombois 1988). Moroccan forests are also subject to degradative pressures, which vary in intensity depending on the region (Dallahi & al. 2023), for instance, Atlas cedar dieback and decline (Linares & al. 2011; Camarero & al. 2021) as well as cork oak decline (Dorado & al. 2022), palm tree (Rafiqi & al. 2022; Khayi & al. 2023), Aleppo pine (Vieira & al. 2022) and the holm oak. Indeed, *Quercus* forests are suffering serious decline worldwide, closely linked to the consequences of climate change (Rodríguez-Romero & al. 2022).

In general, woodland mortality in the Mediterranean Basin, is strongly influenced by severe water deficit(Peñuelas & al. 2001; Linares & Tíscar 2010; Linares & al. 2013). The study of natural forest dynamics in Mediterranean ecosystems is challenging due to the frequency and severity of disturbances (fires, firewood cutting, coal mining, grazing, etc.) (Panaïotis & al. 1997). In addition, Holm oak forests are a dominant type of vegetation in transition zone between temperate forests, and tropical forests, where large human populations, massive tourism, and intense industrial activity are significant (Terradas 1999). Indeed, the regions of occurrence of holm oak areas are highly affected by human activities, such as fire, grazing pressure, shifting agriculture, and overcutting for fuel and other purposes (Caliskan 2014). This tree is also subjected to water stress, reduced foliar nutrient concentrations, and damage to foliage by insects (Landsberg & Wylie 1983). It is distributed mainly in the thermo-, meso- and supra-Mediterranean altitudinal vegetation level and in semiarid to humid Mediterranean climates (Rivas Martínez & Gandullo 1987). In Morocco, holm oak grows between 600 and 2700 m, covering 1.4 million ha, over 30% of the natural forest area (Braun-Blanquet & Maire 1921; Khatouri 1992; Terradas 1999). The forest domain of Holm oak woodlands in Morocco covers approximately 1,430,000 hectares, extending from the Rif region in the north to the Anti-Atlas in the south (Benaibid 1985). *Quercus ilex* L. is native to the central-western Mediterranean basin, where it represents the dominating species, in North Africa from Tunisia to Morocco, on several large islands, e.g., Crete, Sicily, and Corsica, and southern (continental) Europe, along a continuum from Turkey to Portugal (Michaud & al. 1995). It is very important due to its significant ecological and economical values (Liñán & al. 2011). Holm oak reproduces through mast seeding and shoot production (Le Roncé & al. 2023). Increase in holm oak decline has been observed in the last decade (Alderotti & Verdiani 2023).

Holm oak growth was strongly controlled by climatic changes in recent decades (Natalini & al. 2016). Climatic stress has been proposed as the primary cause of diebacks and declines around the world (Jurskis 2005). In the Mediterranean region, it is predicted that temperatures will rise (Molina & al. 2020), climate change may affect Holm oak fecundity by changing weather patterns, physiological processes, and resource allocation (Le Roncé & al. 2021), indeed extreme climatic events, such as heatwaves, frost, drought and flooding, usually reduces plant production and induces mortality (Niu & al. 2014). The mechanisms underlying such mortality, however, are debated, owing to complex interactions between the drivers and the processes. Understanding drought-related mortality is fundamental for ecosystem management and climate-feedback predictions (Anderegg & al. 2013).

The use of vegetation indices is a common approach for analyzing seasonal vegetation variations in satellite imagery (Meneses-Tovar 2011). The Normalized Difference Vegetation Index (NDVI) is the most frequently used indicator to monitor tree mortality, representing 28% of the studies (Eliades & al. 2024). These techniques enable accurate assessments, thereby reducing costs and saving time (Gharnit & al. 2025). The main hotspots of mortality studies are North America (39%) and Europe (26%) (Eliades & al. 2024).

In a recent study by Gharnit & al. (2024), the vegetation cover in the Central High Atlas was evaluated. The findings indicate severe degradation of *Juniperus thurifera* L., *Pinus halepensis* Mill. forests, *Quercus ilex* and *Juniperus phoenicea* L. forests (Gharnit & al. 2025). In addition, Youssef & al. (2024) have demonstrated that the percentage of vegetation density, oak groves, Matorrals, red juniper, and thuja, displays a declining trend, as medium cover vegetation decreased by 29.5%, while dense vegetation decreased considerably by 70.9% (Youssef & al. 2024; Outourakhte & al. 2025).

The mortality and decline of Holm oak has been extensively studied in the northern Mediterranean (Europe), providing valuable insights into the factors driving this decline. However, our understanding of this phenomenon in the southern part (North Africa) remains limited, leaving a significant knowledge gap in our understanding of the region's ecological dynamics and key factors that drive this degradation. This highlights the critical need for research to address the factors driving Holm oak decline in this region. Consequently, the study aims to determine the primary factors contributing to the recent decline in Morocco's Holm oak forests and to assess how Holm oak forest decline is evolving in relation to the important ecological factors.

Fig. 1. The aspect of the lower limit of *Quercus ilex* mixed with *Juniperus phoenicea*, *J. oxycedrus*, and *Pistacia lentiscus* is particularly vulnerable to decline and mortality. While Holm oak shrubs are significantly impacted, other species in this community, such as *Juniperus* and *Pistacia*, show greater resistance.

Materials and Methods

Study area

Central High Atlas is located in central Morocco, the altitudes range from 500 to 3700 meters, with an average elevation of 1588 meters. The climate is Mediterranean with four distinct seasons: winter, spring, summer, and autumn (Ouchbani & Romane 1995), generally, the climate is characterized by hot and dry summers in contrast to cold and rainy winters. Precipitation varies between 400 and 730 millimeters, the bioclimate is semi-arid and subhumid (Gharnit & al. 2023) , the temperatures mean is about 18 °C and significant snow contribution occurs during the winter, temperatures fall below 0 °C in winter and may reach more 46°C in summer (Bell & al. 2022). The substrate types are generally carbonates (limestones, dolomite, or limestones associated with dolomite) and clays associated with sandstone (Gharnit al. 2025). The figure 1 represent the geographic location of the study area.

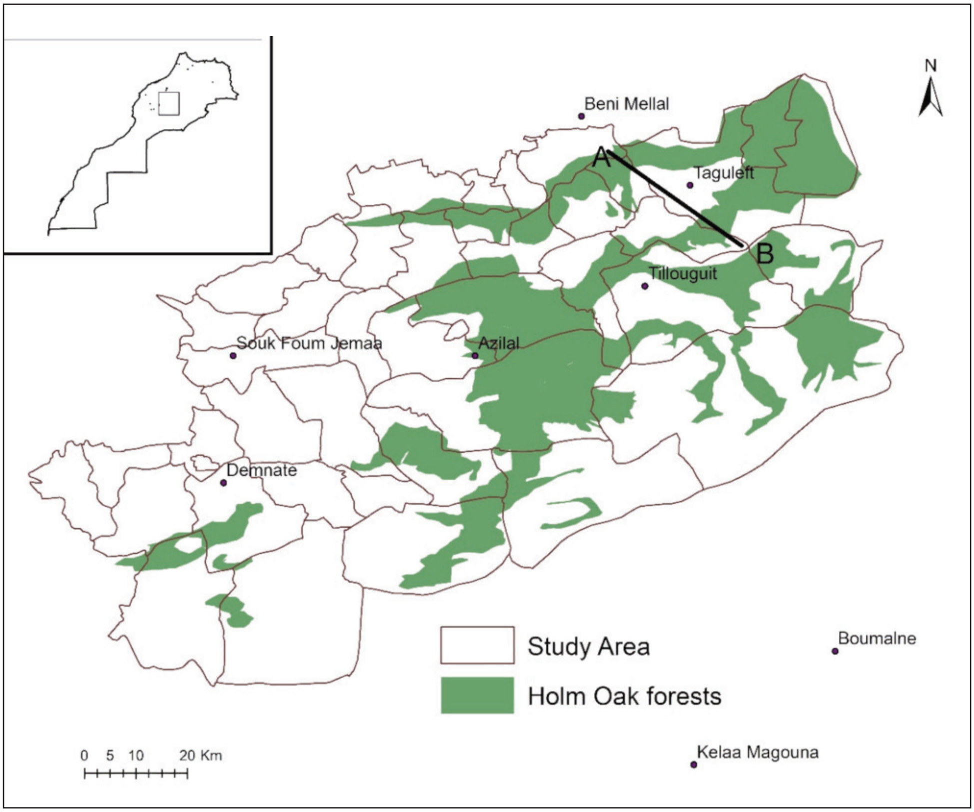

Fig. 2. Study area location

Vegetation patterns and decline sampling

The vegetation sampling was conducted using 80 rectangular plots measuring 10 × 20 meters, separated by 100 meters. Within each plot, data collected included the number of individuals, dieback trees, mortality, DBH (Diameter at Breast Height), plant height, and cover. To measure DBH, we used a measure tape. Tree height was measured using a clinometer and the following formula:

$$H = (\tan(a) \times D) + h$$

H is the height of the tree, tan(a) is the tangent of the angle (a) between the observer's eye and the top of the tree, D is the distance between the observer and the tree, and h is the height of the observer's eye level.

In this study, dieback refers to a plant where at least one branch is dead, while mortality is considered when the entire plant is dead. Decline is considered as the combination of mortality and dieback rates. Additionally, both mortality and dieback rates are calculated as the proportion of affected plants within each plot.

To identify the specific periods of the year when decline occurs, four sites were selected. Collectively, these sites contained 855 Holm oak trees. Dieback and mortality were assessed throughout the year, including winter, spring, summer, and autumn.

In addition, elevation, slope and aspect values were determined for each plot.

Climate data

The climate data is downloaded from Nasa Data Access Viewer (https://power.larc.nasa.gov/data-access-viewer/). This data included precipitation (P), minimum temperature (Tmin), maximum temperature (Tmax). These climatic factors were then used to calculate the Standardized Precipitation Evapotranspiration Index (SPEI) and Potential Evapotranspiration (PET). The bioclimate are determined based on Emberger method created to classify Mediterranean climate:

$$Q2 = 2000P/M^2\text{-}m^2$$

Where P represents the average of annual precipitation, M represents the temperature of the hottest month of the year, and m represents the temperature of the coldest month.

To determine the temperature at each plot, punctual data was downloaded from Nasa Data Access Viewer. 31 stations are used, subsequently, Kriging interpolation was employed to generate maps of climate parameters.

PET and SPEI

The evapotranspiration is the loss of water by evaporation of the soil surface and transpiration from plants in a given area during particular period (Novák 2011). The PET is also called reference evapotranspiration (Allen & al. 1998). PET is crucial for computing crop and vegetation evapotranspiration, and for characterizing the local climate (Paredes & Pereira 2019) :

$$PET\ (mm/day) = 0.0135\ (Tmean + 17.78)\ Rs$$

where: Tmean = average temperature (°C), Rs = incident solar radiation (mm/day), Rs = R0KT (tmax − tmin)0.5, R0 = extraterrestrial solar radiation (MJules/m2/day), KT = empirical coefficient (0.162 for interior and 0.19 for coastal areas), tmax = maximum temperature (°C), and tmin = minimum temperature (°C).

SPEI presents the overall climatic water balance as the difference between precipitation and potential evapotranspiration at different time scales (Zhang & al. 2018). Positive values of SPEI indicate conditions that are wetter than average, whilst negative values indicate conditions that are drier than average. The calculation of this index uses the accumulated differences between precipitation and potential evapotranspiration (Montes-Vega & al. 2023):

$$SPEI = (P-PET)/\sigma;$$

P is precipitation, PET is potential Evapotranspiration and σ = standard deviation of P-PET. R software is used to compute SPEI and PET.

Remote sensing

Several remotely sensed vegetation indices are used in vegetation monitoring and assessment. Indeed, NDVI (Normalized Difference Vegetation Index) is now the most popular index used for vegetation assessment (Huang al. 2021). It is related with the vegetation cover decline, and employed as an indicator to reflect the response of the vegetation dynamics (Zheng & al. 2018). NDVI is an indicator of vegetation health, as the decrease in greenness is reflected by NDVI decrease (Meneses-Tovar 2011). Hence NDVI is implemented to detect the amount of change in vegetation and the most affected zones by mortality and dieback in the study area. Google Earth Engine is implemented to compute NDVI maps.

Statistical analysis

The statistical analysis to investigate the impact of different environmental factors on Holm oak decline was conducted in R software (https://posit.co/download/rstudio-desktop/). Principal Component Analysis (PCA) was used to study the influence of quantitative variables such as precipitations, temperatures (Tmin and Tmax), elevations, cover, slopes, density (number of trees per plot or number of individuals per m2), and NDVI. Multiple correspondence analysis (MCA) was employed to test the relationship between qualitative variables (soil types, aspect) and the levels of dieback and mortality. Dieback and mortality were categorized into three levels: Low (values below the first quartile, Q1), Moderate (values between the first and third quartiles, Q2 and Q3), and High (values above the third quartile, Q3).

Results

The Central High Atlas of Morocco presents a biodiverse, generally Mediterranean vegetation cover. This region is formed by depressions with low altitudes, where the substrates are clay and sandstone, and the climate is semi-arid with fresh or locally temperate variants. The main vegetation cover at this level includes *Tetraclinis articulata* (Vahl) Mast., associated with *Juniperus phoenicea* L., *Ceratonia siliqua* L., *Pistacia lentiscus* L., and *Olea europea* var. *sylvestris* (L.) (Mill.) Lehr. As the elevation rises, *Juniperus phoenicea* dominates, along with *Pistacia lentiscus*. Holm oak in the High Atlas forms distinct tree communities at different altitudes. Its lower limit (linked to upper limit of *Juniperus phoenicea*) is characterized by mixed Holm oak forests with a diverse Mediterranean tree community, including *Juniperus phoenicea, Pistacia lentiscus*, and *Phyllirea angustifolia*.

The second level consists of pure Holm oak shrubs, while higher and medium altitudes feature well-developed pure Holm oak forests, the bioclimate is subhumid at this level, with *Juniperus thurifera* often found at the upper limit as the climate shifted to semi-arid with its cold variant. As revealed by Figure 3 (according to axis AB in figure 2), the Holm oak occurrence coincides with limestone (and locally dolomite or dolomite associated with limestone) substrates. Generally, Holm oak occupies particularly mesomediterranean (Meso), supramediterranean (Supra), and locally mountain Mediterranean (M Med) zones. Additionally, some dispersed thermophilic individuals can be found in the thermomediterranean (Thermo) zone, while the oromediterranean (Oro) lacks generally the woody plants and hosts the xerophytes. Two bioclimates are located in the study area: semi-arid and subhumid. The semi-arid bioclimate has two variants: semi-arid hot at low altitudes and cold semi-arid at high altitudes.

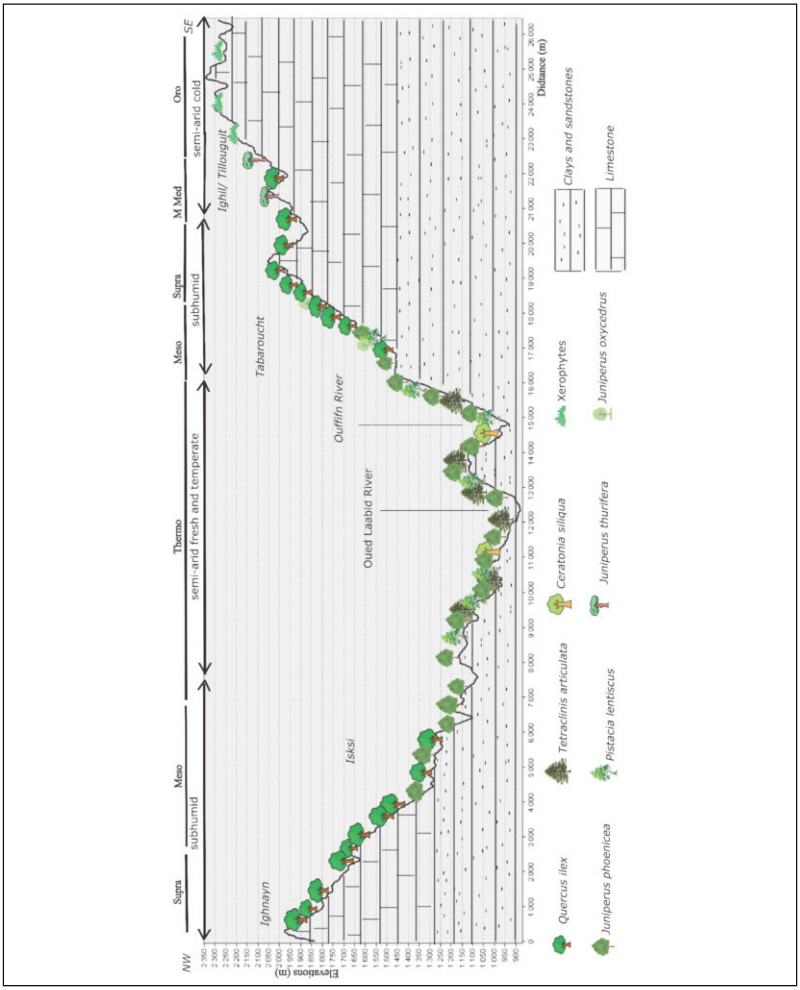

Fig. 3. Ecological overview of the study area. The decline rate varies significantly among different holm oak forest structures. Mixed shrubs, where Holm oak is the most vulnerable, experience the highest decline, with significant dieback and mortality. The decline rate within these structures reaches 40.31%. In contrast, pure Holm oak shrubs have a decline rate of 25.88%, and large trees in Holm oak forests exhibit a decline rate of 19.92% (Fig. 4).

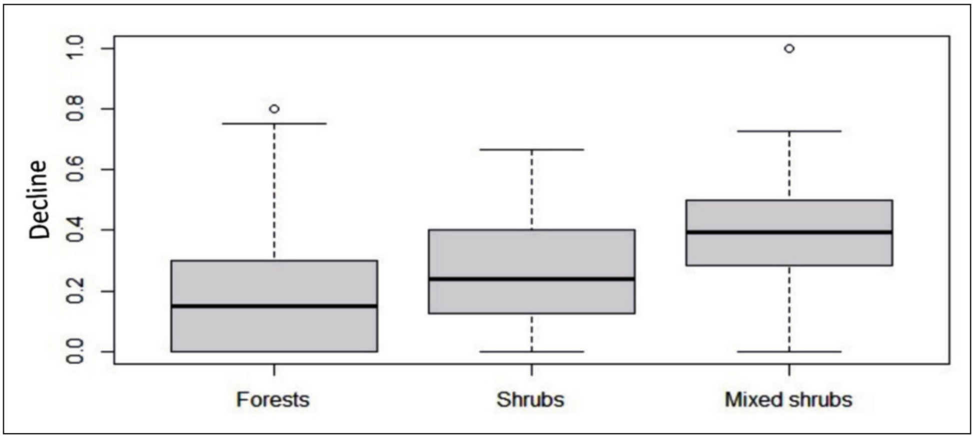

Fig. 4. The decline of Holm oak varies according to forest type.

Based on tree size, healthy plants are taller and larger than declining trees. Healthy oak trees have a larger diameter at breast height (mean = 30 cm) than declining oak trees (mean = 28 cm). Additionally, healthy plants have a mean height of 8.2 meters, while declining plants have a mean height of (Fig. 5).

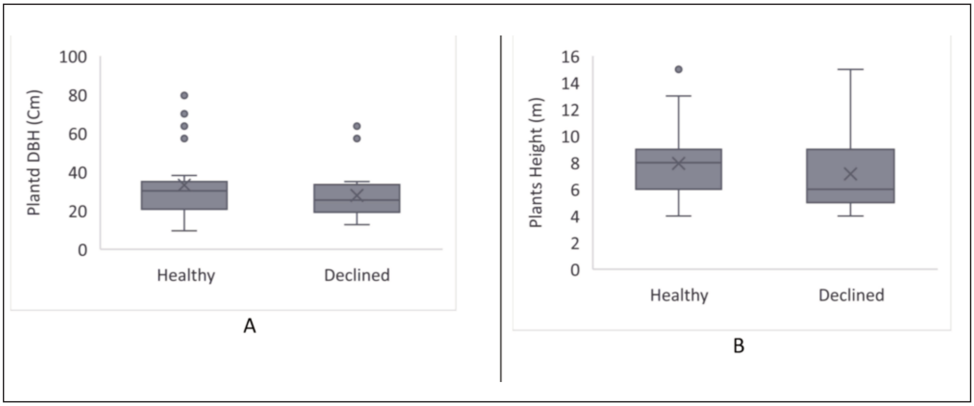

Fig. 5. Plant decline according to plant size: A) DBH and B) Height.

Figures 6a, 6b, and 6c depict the spatial variations of climate variables (Precipitation, Tmax, and Tmin) within the study area. Figure 6 d illustrates the bioclimatic classification of the regions, categorizing them as semi-arid and subhumid.

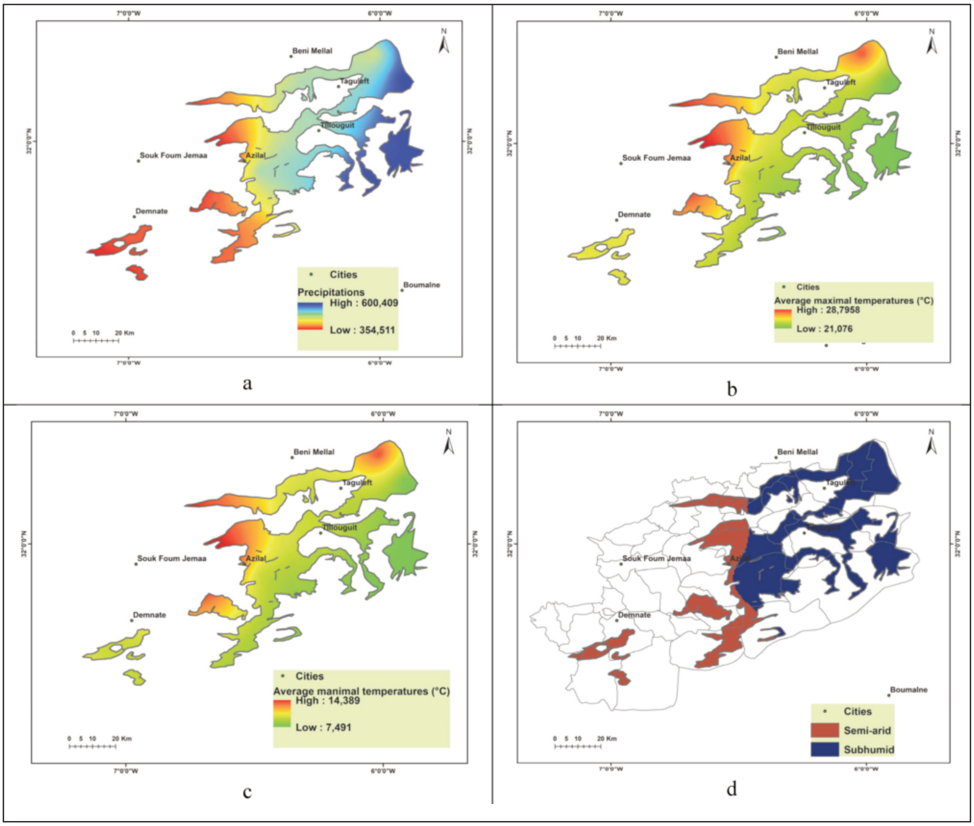

Fig. 6. Climatic parameters for 2024: a) precipitations, b) average of maximum temperatures, c) average of minimum temperatures and d) the Holm oak forests bioclimates.

The figure 7 represents the climate factors evolution between 1982 and 2024, and demonstrates a continuous increase in temperatures and decrease in precipitation accompanied with irregularities.

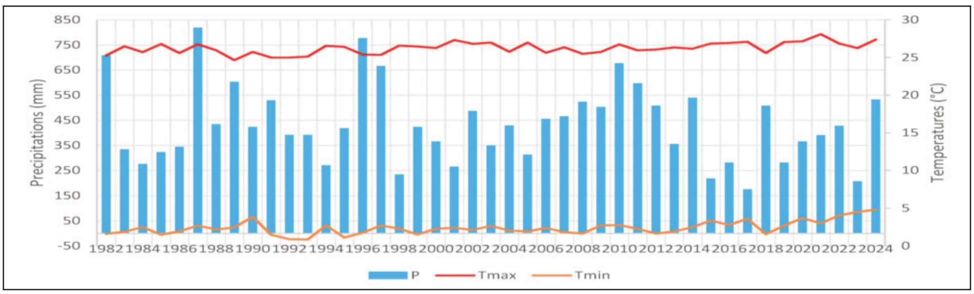

Fig. 7. The temperatures and precipitations variation between 1982 and 2024.

The PET trend over the last 42 years shows a significant increase in recent years (p-value = 0.004) (Fig. 8).
According to the SPEI, the region experienced five drought periods (Table 1)

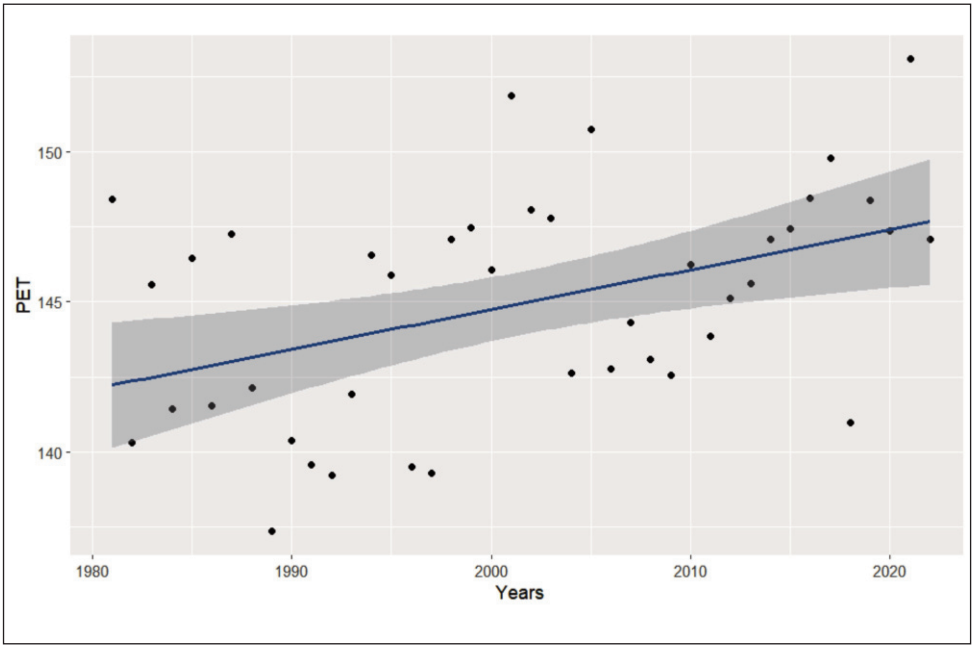

Fig. 8. The PET trend in the study area from 1980 to 2023.

Table 1.The drought episodes in the study area according to SPEI.

Drought Period	SPEI max value	Interpretation (drought severity)
1984-1988	< -1.4	Moderately dry
1994-1996	< -1.3	Moderately dry
2000-2004	< -1.4	Moderately dry
2006-2007	< -1.2	Moderately dry
2014-2022	>-2	Extremely dry

Over the past 42 years, the region has experienced recurrent drought periods. However, the severity of the drought in recent years is unprecedented, indicating extremely dry conditions (Fig. 9).

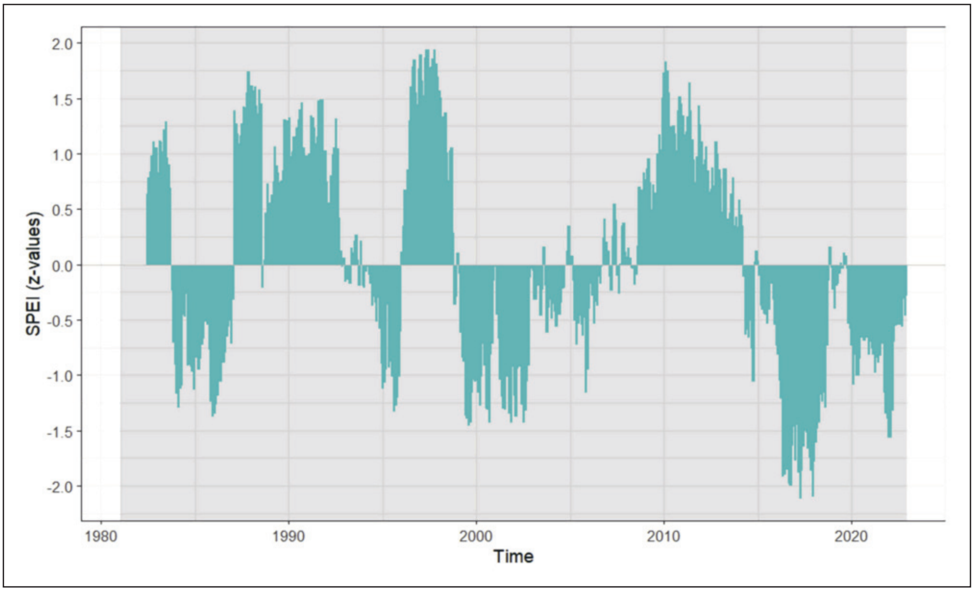

Fig. 9. The SPEI (Drought Index) variation in the study area between 1982 and 2023.

Dim 1 and Dim 2 explain 41.32% and 15.4% of the variance, respectively. Mortality and decline are closely clustered in the same quadrants, indicating that mortality is prevalent in areas with significant dieback. Strong drivers of forest dieback and mortality include minimal and maximal temperatures (Tmax and Tmin), which are positively correlated with forest decline. Furthermore, precipitation exhibits a negative correlation with dieback and mortality, with both increasing as precipitation decreases. Slope, cover, density, and elevation have a lesser influence on mortality and decline. NDVI and plant decline (mortality and dieback) are located on opposite sides, confirming that higher vegetation health (indicated by high NDVI values) corresponds to lower levels of decline (Fig. 10).

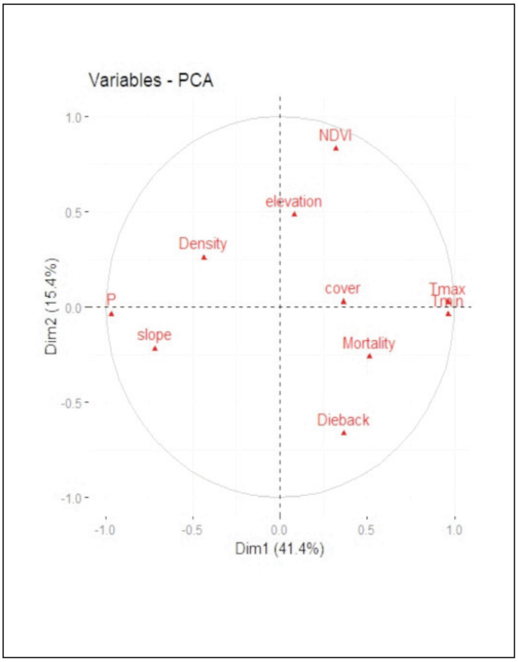

Fig. 10. Principal Component Analysis plot of variables affecting Holm oak decline.

The mortality and dieback of Holm oak occur primarily during the summer and autumn months, when temperatures reach extreme levels and heatwaves are frequent (Figs. 11 a & b).

The mortality of plants is rarely sudden. Most dead plants show signs of dieback and decline over time. In fact, 81.08 % of the newly reported dead trees had a history of dieback during previous years, while the remaining dead trees declined completely at once (Fig. 11 c).

Fig. 11. The holm oak decline in the study area, a) The mortality fluctuation during 2024. b) The dieback fluctuation during 2024, c) Plant mortality and its relation to dieback in 2024.

Regarding the MCA test (Fig. 12), mortality is relatively related to aspect. Indeed, terrain observations revealed that mortality is high in sunny aspects (south). However, soil types have less effect on decline. The main soil types in the area are limestones: earthy limestone, rocky limestone, organic limestone soils, and basaltic areas.

The northern parts of the holm oak forests are highly degraded (Fig. 13). The NDVI change confirms the 3769 Ha of holm oak forests are degraded during three years (2022, 2023 and 2024). Table 2 depicts the vegetation cover changes in different climate variants. In addition, the holm oak decline affects all the climate variants as reflected in Table 2.

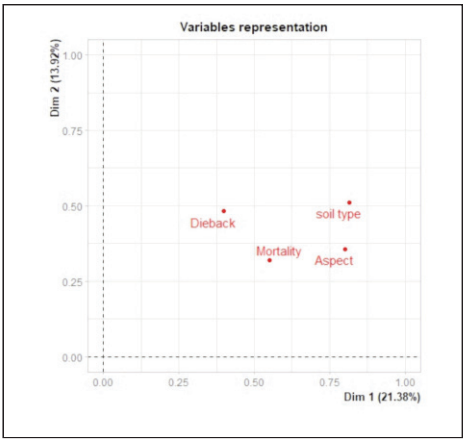

Fig. 12. MCA (Multiple Correspondence Analysis) plot.

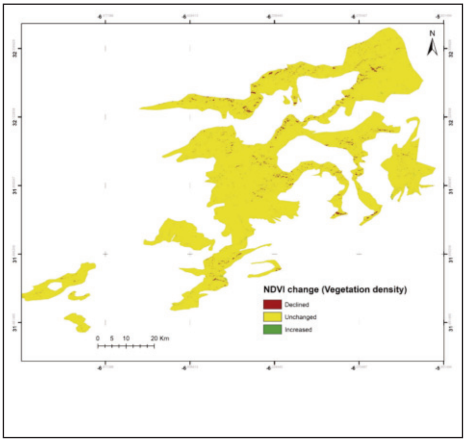

Fig. 13. Map of the vegetation cover change between 2022 and 2024.

Table 2. Change in vegetation cover in Semi-arid and Subhimid bioclimatic zone during 2022-2024.

Period	Bioclimate	Rate	Decline (ha)	Unchanged (ha)	Uncreased (ha)
2022-2024	Semi-arid	30,79 %	745	89931	96
	Subhumid	69.21 %	2885	201358	140
	Total	100	3630	300399	236

Discussion

The Holm oak occupies subhumid and semi-arid bioclimates in the Central High Atlas. Generally, these forests occupy limestone substrates between 1200 and 2200 m. The Central High Atlas exhibits a diverse range of vegetation levels with distinct plant communities, the mesomediterranean zone is the main level of finest Holm oak groves, while supramediterranean, also featuring significant Holm oak stands, and mountain Mediterranean presents Holm oak mixed with *Juniperus thurifera*. Some dispersed thermophile Holm oaks are also located at the upper limits of the thermomediterranean. Similar findings are reported by Benabid (1982) and Gharnit & al. (2024), indicating that Holm oak forms large groves at the mesomediterranean level in the High Atlas between 1100 and 1500 m, and at the supramediterranean level between 1500 and 2000 m (Benabid 1982; Gharnit & al. 2024).

The study revealed that *Quercus ilex* mortality and dieback is a major forest decline driver in High Atlas of Morocco. This fact has been corroborated by numerous studies conducted in Mediterranean countries and climate (Alderotti & Verdiani 2023). Furthermore, the decline due to dieback and mortality is unprecedented and threaten the future of this fortune, as this phenomenon is appeared in High Atlas during last few years. the decline rate inside these structures achieves 40.31% in mixed shrubs. As for the pure holm oak shrubs, the decline rate is 25.88 %, while the large trees holm oak forests have a decline rate of 19.92%. Generally, the forests are widely degraded in the High Atlas due to human activities combined with climate change (Youssef & al. 2024).

There is a fundamental relationship among biodiversity, production, resilience and stability in forests (Thompson & al. 2009). In our study area, the decline within the shrubs is highly important comparing to forests. While, diversity at different levels (genetic, specific and ecosystemic) facilitates forest ecosystems adaptation to dramatic climate changes (DeHayes & al. 2000). However, the biodiverse shrubs present considerable decline and mortality compared with pure holm oak shrubs. This effect is explained by a potential strong competition between species where the cover is biodiverse, as the accumulated competition-caused stem volume loss, combined with age effect and site condition (Pretzsch & al. 2023). In addition, mortality may increase because trees under competition stress are more vulnerable to climate change as their growth is already compromised (Magalhães & al. 2021). The holm oak shrubs in High Atlas are mixed with a biodiverse cover at low altitudes, consisting of *Juniperus phoenicia, Pistacia atlantica, Phillyrea* sp. These regions, characterized by low elevations and mixed shrubland, are semi-arid. In contrast, Holm oak, whose moisture requirement is higher than other Mediterranean evergreen oaks (Yilmaz & al. 2024), is generally well-adapted to subhumid and humid Mediterranean climates (Gharnit & al. 2024). This difference in a response to climate may favor and support the other mentioned species (Figure 1) over Holm oak in these areas, yet this constatation needs further investigation.

Potential Evapotranspiration (PET), a measure of plant water loss, has increased significantly in recent years. Furthermore, the High Atlas region, and Morocco territory, has experienced a series of drought episodes (notably: 1984-1988, 1994-1996, 2000-2004, 2006-2007, and 2014-2022). While the earlier drought periods were moderate in severity and often followed by significant precipitation events that could potentially regulate the water balance and allow plant recovery, the recent drought episodes, as indicated by SPEI values, has been the longest and most severe. This unprecedented drought has resulted in widespread decline and mortality, highlighting the crucial role of accumulated scarce precipitation, as revealed by negative strong correlation between precipitations and decline (Figure 13). Additionally, a strong correlation has been established between Holm oak decline and temperature. The decline primarily occurs during the summer and autumn (hot seasons) when temperatures and heatwaves are prevalent. Several studies have shown similar findings in the Mediterranean region, particularly the western and central Mediterranean basin, which is facing increasing decline and dieback episodes due to the severity and frequency of heatwaves and drought events (Liyaqat & al. 2024). In the south-western Iberian Peninsula, Mediterranean holm oak open woodlands currently undergo large-scale population-level tree die-off due to temperature and aridity increase during recent decades (Natalini & al. 2016). Indeed, warmer climate with longer droughts had a key-role determining the mortality process (Natalini & al. 2016), and strong evidence indicate that drought events (regardless of the accumulation period) increased the risk of all-cause mortality and for specific causes (Salvador al. 2024). Holm oak dieback episodes are generally associated with extreme events such as wildfires, heat waves and droughts (Alderotti & Verdiani 2023). The Mediterranean species are adapted to summer droughts but may not be able to cope with future increases in drought intensity, duration, and/or frequency (Barbeta & Peñuelas 2016). In addition, an increase in winter drought spells might have contributed significantly to the decline of this species (Alderotti & Verdiani 2023). By definition, a Mediterranean climate is characterized by rainy and cold winters, while the summers are dry and hot (Daget 1977; Gharnit & al. 2023; Youssef & al. 2024). However, winters have also become drier.

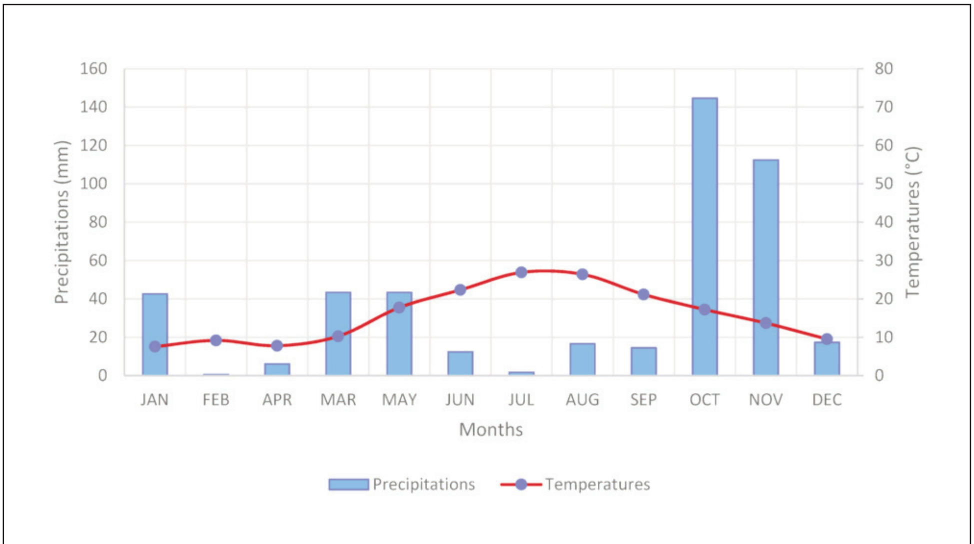

Fig. 14. Climatic diagram of the area during 2024.

Why some individuals in the same location and under similar conditions exhibit varying levels of sensitivity to climate change? Climate extremes can cause differential survivorship among species due to their different sensitivity (Niu & al. 2014), this is due; intuitively, to individual variations. Furthermore, the plant mortality is not sudden; indeed, the plants death generally is a progressive process, as the majority of new reported dead plant has a dieback history (Figure 11 c). This funding are in consistent with Gea-Izquierdo et al., indicating that the plants dieback and decline is not sudden and marks a drought legacies (Gea-Izquierdo & al. 2021). A relative difference in DBH and height were observed between healthy and declined plants. Notably, larger trees (with higher DBH and height) exhibited greater resistance to mortality. Larger plants, as products of efficient water management, biomass production, and other vital biological and physiological processes, are better equipped to mitigate stress effects. A review study assessed more than 125 studies, proved that taller trees present a range of structural and functional adjustments, including more efficient water use and transport and greater water uptake and storage capacity, that mitigate the path-length-associated drop in water potential (Fernández-de-Uña & al. 2023). Other factors that may favor large plants are, strong root systems, as the roots are capable of reach important depth. In addition mortality is often skewed towards young trees but recent evidence suggests that large, old trees are also vulnerable (Da Costa & al. 2010; Lindenmayer & Laurance 2017; Choat & al. 2018). In fact, large trees may exhibit large mortality rate, especially when community-wide mortality was high or when bark beetles (parasites) were present (Bennett & al. 2015). In addition, the root distribution and rooting depth are the main belowground plant functional traits used to indicate drought resistance in arid and semiarid regions (Lihui & al. 2021). Obviously the rises in temperatures and precipitation reductions lead to reduced soil moisture as well as VPD, knowing that VPD is a combined function of air temperature and relative humidity (Medina & al. 2019), and the transpiration rate of the plant is driven by changes in VPD (Kholová & al. 2012; Belko & al. 2013). Stomatal conductance declines under high VPD and transpiration increases in most species , leading to photosynthesis and growth reduction, and higher risks of carbon starvation and hydraulic failure (Grossiord & al. 2020). In addition, the stomatal closure strongly reduces holm oak carbon uptake (Peguero-Pina & al. 2008), hence, the depletion of plant water and carbon pools are accelerated (McDowell & al. 2022).

The main soil types in the area are limestones: earthy limestone, rocky limestone, organic limestone soils, and basaltic areas. Generally, the holm oak forests show decline under all the soil variants. However, holm oak decline and mortality under climate change can be resulted in soil stoichiometric imbalances triggered by net losses of essential oligonutrients (García-Angulo & al. 2020). In addition, the impact of climate on forest decline may be influenced by topographic features. Previous studies provide substantial evidence that local modifications of the climate by topography and canopy cover can create microclimates at the forest floor, which can partially mitigate regional macroclimate variability (Rita & al. 2021). Besides climate change and disturbance that influence tree growth, topography is a factor determining the vulnerability of forest declines (Allen & Breshears 1998; Wang & al. 2021). However, our study reveals a slight effect of elevation on dieback and mortality. Additionally, plant responses to climate effects vary based on aspect. Southern slopes exhibit higher levels of forest decline, likely due to increased solar radiation exposure, as showed by the relatedness of mortality and aspect in Fig. 12. Indeed, south-facing slopes are characterized by drier and hotter microclimates and, thus, harsher environments for trees (Wang & al. 2021), and the highest rates of evapotranspiration occur on south-facing slopes, followed by ridges, valleys, and north-facing slopes (Dyer 2009).

The carbon and water pools and fluxes are interdependent and underlay plant defenses against biotic agents (McDowell & al. 2022), hence, attacks by insects or pathogens are frequent with drought associated mortality (Anderegg & al. 2015; Kichas & al. 2020). Dead holm oak infected by *Phytophthora cinnamomi* Rands expressed drought legacies (Gea-Izquierdo & al. 2021). *P. cinnamomi* (root rot) is one of the main causes of oak mortality in Mediterranean open woodlands (Ruiz-Gómez & Miguel-Rojas 2021; Tkaczyk & Sikora 2024). However, other factors, such as age, prior parasite infestations, and individual tree health, may significantly influence the variability in mortality rates observed in response to climate change. These factors were beyond the scope of the present study but warrant further investigation. A deeper understanding of these additional variables is crucial for a more comprehensive understanding of Atlas Holm oak decline.

The High Atlas Holm oaks forests are subject to various stressors, including overgrazing; Gharnit & al. (2025) assessed the Geoparc M'goun rangelands (located in the Central High Atlas) and reported that 27.73% of the assessed species are threatened according to IUCN (International Union for Conservation of Nature) criteria, while a significant portion (74.45%) lack adequate evaluation. Endemism is high, with 21% of species endemic to Morocco, and nearly half of these (49.5%) restricted solely to the country. Additionally, 17.43% of species are considered rare(Gharnit & al. 2025). In recent years, the exploitation of these plants for wood and charcoal production has intensified, further exacerbating the pressure on these ecosystems (Moujane & al. 2023).

Mortality and decline rates can reach 40% in some areas. To mitigate economic losses and prevent further degradation, it is recommended to harvest dead trees for wood production. Additionally, removing dead trees can protect healthy trees and limit potential pest outbreaks, as the vulnerable trees are predisposed to parasites attacks. Mortality and dieback rates are particularly pronounced in shrublands. These findings underscore the importance of targeted forest restoration initiatives in the High Atlas, prioritizing areas where Holm oak is favored. Implementing such strategies can help preserve these valuable ecosystems and mitigate the impacts of climate change and other mentioned stressors.

Climate change is profoundly affecting the dynamics of vegetation cover, not only in terms of density and quality, as confirmed by de decline in NDVI change during last three years, but also in terms of the nature and floristic composition of these forests. For instance, as mixed forests become increasingly degraded, they are transitioning from Holm oak-dominated forests towards *Juniperus phoenicea* forests or other species that coexist with Holm oak. This shift is further influenced by the differential responses of various species to climate fluctuations, as illustrated in Figure 1.

The province of Azilal, where the study area is located, is home to extensive rangelands. The province is a home to approximately 2,770,000 sheep flocks, 378,000 cattle herds, and 967,000 goat herds roam (Gharnit & al. 2025). In addition, the local population relies on the forests for firewood and as a source of forage for their livestock (Moujane & al. 2023; Youssef & al. 2024). As a result, the dieback and mortality of High Atlas forests have significant socio-economic consequences, including potential increases in poverty and out-migration from rural areas.

These High Atlas forests are home to a diverse array of fauna, including 24 wild mammal species and over 100 bird species. Many of these species are listed as critically endangered, endangered, or vulnerable on the IUCN Red List, such as the Barbary sheep, Barbary macaque, Cuvier's gazelle, Eurasian otter, red fox, African wolf, Barbary ground squirrel, wild cat, and common genet (Alami 2022). Therefore, the degradation of these forests will significantly alter their habitat and breeding sites. The combined effects of climate change on forests and shrubs can lead to significant changes in ecosystem structure and function (Kodero & al. 2024).

Conclusion

The High Atlas is a biodiversity hotspot in Morocco, dominated by Mediterranean Holm oak forests. These forests provide invaluable ecosystem services to the local population, including timber, habitat for aromatic and medicinal plants, and grazing land for large herds of livestock. However, in recent years, these forests have come under significant pressure from human activities and climate change, leading to unprecedented levels of dieback and mortality. This degradation has detrimental impacts on the ecological and economic services provided by these forests. As a result, urgent mitigation and conservation measures are imperative. Our findings emphasize the need for more accurate assessments of the processes underlying Holm oak dieback and mortality, particularly understanding the physiological responses that contribute to decline.

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