Bulletin of Geography. Physical Geography Series, No. 29 (2025): 65–84
http://doi.org/10.12775/bgeo-2025-0010

Spatiotemporal dynamics of vegetation dieback in the Talassemtane fir forest (western Rif, Morocco)

Hajar Lamrhari[1*], Mariem Ben-Said[2a], Taoufik Aadel[3], Hassan Bouziane[1]

[1]Abdelmalek Essaadi University, Department of biology, Faculty of Science Laboratory of Applied Botany, Tetouan, Morocco

[2]University Abdelmalek Essaadi, Department of biology, Faculty of Sciences, Laboratory of Biology, Ecology and Health, Tetouan, Morocco

[3]National Agency for Water and Forests, Rabat, Morocco

E-mail: hajar.lamrhari24@gmail.com

[a]https://orcid.org/0000-0002-5171-0542

Abstract. Forest dieback is becoming an increasingly serious concern worldwide. Its causes are multiple, complex and often difficult to disentangle. The primary reports of dieback in the Moroccan fir forest go back to the beginning of the 21st century, but there are no studies dedicated to dieback in this forest documenting those earlier observations. In this study, we quantify the spatiotemporal evolution of dieback in the Talassemtane fir forest through remote-sensing- and field-based assessments between 2009 and 2019. We analysed the inter-annual and seasonal variations in the Normalised Difference Vegetation Index (NDVI) and the effect of precipitation and temperature on forest cover. We found evidence of earlier and recent dieback symptoms, though their extent has declined over time from 369.27 ha in 2009 to 100.08 ha in 2019. During this period, NDVI values increased significantly, mean precipitation increased slightly but not significantly, and mean temperature decreased significantly. NDVI was positively influenced by precipitation and negatively affected by temperature. Overall, spring temperature and precipitation had a strong impact on vegetation cover during the subsequent summer. The highest NDVI values were concentrated on north- and west-facing slopes, within an altitudinal range of 1229 to 1800 m. These findings provide valuable initial insights to aid forest managers in identifying locations of dieback for the planning of a monitoring strategy and highlight the need for further research to better understand the drivers of Moroccan fir forest dieback.

Key words:
Abies marocana,
Talassemtane National Park,
forest health,
forest dieback,
NDVI

Introduction

In the context of global warming, hot and dry conditions decrease tree growth and increase mortality rates in numerous forest ecosystems worldwide, including Mediterranean forests (Tikvić et al. 2008; Camarero et al. 2015; Ogaya et al. 2015; Colangelo et al. 2017; Ripullone et al. 2020; Gazol et al. 2020; Moreno-Fernández et al. 2021; 2022). Forest dieback is a complex phenomenon (Derak et al. 2008). Stress factors interact, which can lead to non-linear tree responses (Camarero et al. 2015). Several causes have been reported to be involved in tree dieback, such as warming and drought stress (Camarero et al. 2015, 2021a, 2021b; Ripullone et al. 2020; Moreno-Fernández et al. 2022; Miletić et al. 2024), fungal pathogens (Jankowiak et al. 2016; Gomez-Gallego et al. 2022), and bark beetle outbreaks (Spruce et al. 2019; Miletić et al. 2024).

As with many other forests showing dieback symptoms worldwide, particularly in the Mediterranean context where vegetation is facing deep climate change impacts, so too Moroccan forests have been reported to suffer from the dieback phenomenon. In Morocco, several dieback issues have been reported and studied, mainly for Atlas cedar *Cedrus atlantica* (Endl.) Carrière (Derak et al. 2008; Ghailoule et al. 2012; Zine El Abidine et al. 2013; Aoubouazza, 2017; Aadel et al. 2021; Camarero et al. 2021b), Barbary thuja *Tetraclinis articulata* (Vahl) Master (Ghaioule and Lumaret, 2020), and cork oak *Quercus suber L.* (Dallahi et al. 2023). The available findings emphasise the decisive role of several inducing factors, including stand structure and competition, inappropriate sylvicultural management, socio-economic demands, pathogen attacks, soil properties, drought and grazing (Derak et al. 2008; Ghailoule et al. 2012; Zine El Abidine et al. 2013; Aoubouazza 2017; Aadel et al. 2021; Camarero et al. 2021b; Dallahi et al. 2023). Moroccan fir forest is considered very sensitive to drought and potentially threatened by global warming if drought intensity and frequency increase (Sánchez-Salguero et al. 2017), with high levels of dieback already having been observed since 2003 (Oughilass 2012).

Moroccan fir forest grows in the Talassemtane National Park, a remarkable mountainous ecosystem of the Rif Mountain chain belonging to the Mediterranean Basin hotspot of biodiversity (Médail and Diadema 2009). The park was created in 2004 and included in the Mediterranean Intercontinental Biosphere Reserve of Morocco and Spain, which has been recognised by the Man and the Biosphere Programme of UNESCO since 2006. The park hosts a large number of endemic species, of which at least 100 species are strictly endemic to the park and surrounding areas, which have still been only poorly studied (Alaoui et al. 2025). However, this ecosystem is facing several threats that affect its perennity (Boubekraoui et al. 2024; Ghallab et al. 2024; Chemchaoui et al. 2025). Accordingly, focusing on the endemic Moroccan fir forest is important due to its specific climate and soil conditions, along with its high socio-economic and cultural values (Aafi 1995; Benabid 1982, 2000; Ben-Said and Sakar 2023).

Geospatial analysis is considered an effective tool for mapping and monitoring forest cover in the world. The use of remotely sensed, efficient and low-cost methods (e.g., satellite images) for assessing and monitoring forest diseases and pests across large scales is significantly facilitating forest conservation (Ghavidel et al. 2021; Dallahi et al. 2023; Miletić et al. 2024). Satellite data have been widely used to monitor forest dieback in several regions worldwide, such as in Mediterranean holm oak *Q. ilex* L. (Ogaya et al. 2015) and cork oak forests (Dallahi et al. 2023), the northern Iranian Buxus hyrcana Pojark forests (Ghavidel et al. 2021), Spanish *A. pinsapo* forests (Cortés-Molino et al. 2022), wood- and shrublands of Spain and Italy (Castellaneta et al. 2022) and Norway spruce in Serbia (Miletić et al. 2024). Indeed, using remote-sensing data, the variation in plant thermal and visual characteristics could be assessed to monitor plant health (Ghavidel et al. 2021). Among pixel-based methods, vegetation indices such as the Normalised Difference Vegetation Index (NDVI) are the most widely used spectral indices in environmental monitoring and they are widely used to evaluate plant biophysical features that are otherwise difficult to sample in the field (Ghavidel et al. 2021; Moreno-Fernández et al. 2021). Based on reflectance from vegetation-sensitive red and near-infrared bands, NDVI can discriminate vegetated from non-vegetated cover and evaluate vegetation growth and density (Ni et al. 2025). Multispectral indices have been reported to have the capability to detect forest dieback before the symptoms are visible, which has been described as an early-warning signal of the dieback phenomenon (Camarero et al. 2015; Moreno-Fernández et al. 2021).

In contrast to other Mediterranean fir forests that have received remarkable attention to assess the dieback phenomenon, particularly using remote-sensing tools, the Talassemtane fir forest (western Rif, Morocco) has not been the subject of such investigations. We therefore aim to fill this gap by quantifying the spatiotemporal evolution of forest dieback using remote sensing. Specifically, we used NDVI derived from Landsat imagery time-series along with field-based assessment to detect dieback, measured in terms of distribution, severity and incidence.

Materials and methods

Study area

In northern Morocco, the Talassemtane fir forest is the core of the Talassemtane National Park located on the eastern portion of the calcaro-dolomitic Riffian Ridge (Benabid 2000). The forest is dominated by Moroccan fir *Abies marocana* Trab. Trees (see a comprehensive review in Ben-Said and Sakar 2023). This tree species forms mixed stands dominated by holm oak *Quercus rotundifolia* Lam. or zeen oak *Q. faginea* Lam. at the lower altitudes of the forest and *C. atlantica* towards higher altitudes (Benabid 1985). In the lower level of the forest, the presence of the endemic black pine *Pinus nigra* Arnold subsp. mauretanica (Maire & Peyerimh.) Heywood (Fennane et al. 1999) (synonym: *Pinus nigra* subsp. salzmannii (Dunal) Franco) is remarkable. More details on the study area can be found in Ben-Said et al. (2024).

Satellite image processing

Landsat satellite images (TM, ETM+ and OLI/TIRS) were obtained from the United States Geological Survey (USGS) archives from 2009 to 2019 (https://glovis.usgs.gov) (Accessed 11 March 2020). We selected images acquired during the spring, summer and autumn seasons. This dataset was used for assessing the spatiotemporal evolution of the NDVI (see below). For the dieback assessment, we selected Landsat images for only four dates (i.e., 2009, 2013, 2016 and 2019), which were acquired during the summer season, because this season coincides with the vegetative period (from mid-June to mid-July) and were used to calculate the NDVI.

Firstly, the satellite images were subjected to a series of treatments. We applied a geometric correction for these images in accordance with the Universal Transverse Mercator (UTM) zone 30 projection system. Then, the satellite images were subjected to radiometric correction and spectral enhancement techniques to eliminate the impact of atmospheric aerosols and optimise their visual quality.

NDVI computation

To detect and identify the spatiotemporal evolution of forest dieback in the Talassemtane fir forest during the study period 2009–2019, we calculated the NDVI from the visible red channel (R) and the near-infrared channel (NIR) according to the following formula (Tucker 1979):

$$\mathrm{NDVI} = \mathrm{NIR}\ - \mathrm{RED}\ /\ \mathrm{NIR} + \mathrm{RED}$$

Like other vegetation indices, the NDVI is founded on the assessment of absorbed photosynthetically active radiation (Moreno-Fernández et al. 2021). It is based on the fact that green leaves absorb radiation at red wavelengths (640–670 nm) due to the presence of chlorophyll pigments, while radiation at near-infrared wavelengths (700–1100 nm) is diffused due to the internal structure of the leaf (Sellers 1987). In contrast, a bare soil surface has a higher reflectance at red wavelengths and a lower reflectance at near-infrared wavelengths (Tucker 1979).

In our study, the NDVI values were grouped into six classes: negative ($\mathrm{NDVI}<0.1$), very low ($0.1\leq\mathrm{NDVI}<0.2$), low ($0.21\leq\mathrm{NDVI}<0.3$), average ($0.31\leq\mathrm{NDVI}<0.4$), high ($0.41\leq\mathrm{NDVI}<0.5$), and very high ($\mathrm{NDVI}\geq0.5$); then, the corresponding areas were calculated for the study period 2009–19. Given that our objective is the assessment of the forest dieback status, the negative classes were excluded, since they correspond to water bodies and bare lands. Satellite image processing and NDVI computation were carried out using ArcGIS 10.2.2 software.

Climatic data

Climatic data from the nearest weather station (coordinates: 35.06°N, –5.3°W, altitude: 305 m a.s.l.) to the Talassemtane fir forest were obtained from the Provincial Directorate of Agriculture, but they contain many gaps. To overcome the lack of climatic data for certain years and/or months in our study area, we used the monthly mean temperatures and total precipitations available for the period 2009-2019 from the "historical climate data" datasets (https://power.larc.nasa.gov/data-access-viewer/, accessed 28 August 2019). The choice of these two climatic factors was justified by their significant influence on the Rif fir forest as demonstrated by previous studies (Ghallab 2018; Alaoui et al. 2021; Moukrim et al. 2022). Average seasonal and annual precipitations and temperatures were calculated for the same period (i.e., 2009–2019). The NDVI of spring (March–May), summer (June–August) and autumn (September–October) seasons, and the NDVI of the growing season (April–October) was generated from averages of the respective monthly NDVI values.

Data analysis

Simple linear regression analysis was used to examine interannual and seasonal variations in NDVI and climatic factors during the study period (2009–2019), considering time as the independent variable. Pearson correlation test was performed to analyse the relationship between NDVI and climatic factors. Next, multiple regression was performed to evaluate the effect of climatic factors on NDVI. To determine the seasonal effect of climatic factors on NDVI during the growing season, we performed correlation analyses between seasonal mean NDVI, precipitation and temperature of spring, summer and autumn. In addition, principal component analysis (PCA) was performed on the database composed of nine variables including NDVI, precipitation and temperature of the three seasons (spring, summer and autumn). To compare NDVI of the three altitude ranges, i.e., 1229–1400 m, 1400–1800 m and 1800–2159 m, analysis of variance (ANOVA) was performed followed by Tukey’s post-hoc test, which was used to determine whether altitude ranges had different NDVI values. In addition, a Kruskal–Wallis test followed by pairwise multiple comparisons was used to determine whether there are differences in the NDVI according to aspect (E, W, N and S). All statistical analyses were performed using R 4.2.2 software (R Development Core Team 2022).

Field-based assessment of dieback symptoms

In addition to remote-sensing-based assessment, we characterised stand dieback in six main mountains (*Jbel*) of the Talassemtane fir forest (Table 1). The visual estimate of dieback was based on a predefined scoring sheet according to Ramzi et al. (2009) and Assali (2009). It includes information on location, stand description and dieback symptoms. The dieback symptoms were visually estimated at the level of each of the six mountains, through three criteria: severity, incidence and affected area. The severity was assessed by the proportion of damage affecting the tree (Oughilass 2012). The main tree damages included those observed on the leaves (abnormal colouring (red/brown), consumption and microphyllia), branches (break, deformation and peeling bark), and/or trunk (wound, resin flow and barking). However, the stand may be affected by damage whose severity varies from one tree to another. Thus, we estimated the percentage of trees showing dieback symptoms according to six severity classes ranging from 0 to 5 and corresponding to null, weak, moderate, serious, severe and very severe (Ramzi et al. 2009). Biotic agents (pests and pathogens) mainly included insect nest, witch's brooms, mistletoe and lichen invasion. The incidence represents the estimated severity per surface covered. In addition to these criteria and in order to gain an idea of the mechanisms of damage propagation (contamination), we estimated how dieback is present at the stand level as follow: patches, sparse and isolated trees (Ramzi et al. 2009).

Table 1. Main characteristics of the six sampled stands in the Talassemtane fir forest

Mountain	**Main species**	**Aspect**	**Altitude (m a.s.l.)**	**Coordinates**	
				Latitude	**Longitude**
Jbel Bouslimane	Am, Qr, Qf, Ag	NW	1604	35°07’4,67”	5°07’59,47”
J. Lakraa	Ca, Am, Qr	E	1749	35°07’40,75”	5°08’10,64”
J. Talassemtane	Am, Qr, Ca	N	1731	35°08’21,59”	5°07’55,89”
J. Taloussisse	Am, Pn, Pm, Jo, Ag	NW	1642	35°07’ 30,6”	5°06’39,15”
J. Sfiha Telj	Am, Ca	SW	1755	35°11’10,75”	5°13’16,14”
J. Abdoune	Am, Qr	W	1588	35°11’25,14”	5°12’52,69”

Explanations: Am: *Abies marocana*; Qr: *Quercus rotundifolia*; Qf: *Quercus faginea*; Ag: *Acer granatense*; Ca: *Cedrus atlantica*; Pn: *Pinus mauretanica*, Pm: *Pinus maghrebiana*; Jo: *Juniperus oxycedrus*

Results

Interannual and Seasonal Trends in NDVI and Climatic Variables

Regression analysis showed a significant increase in the mean NDVI ($R^2=0.83$, $p<0.001$), a non-significant increase in mean precipitation ($R^2=0.28$, $p=0.09$), and a significant decrease in mean growing season temperature ($R^2=0.45$, $p=0.02$) in the study area during the study period 2009–2019 (Fig. 1). The minimum values of mean temperature of the growing season were reached in 2013, 2014 and 2018 and coincided with the maximum NDVI values. In contrast, the minimum values of the mean NDVI of the growing season coincided with the maximum values of the mean temperature of the growing season (Fig. 1). This indicates that high temperatures during the growing season have a negative effect on vegetation, where plants are particularly sensitive to temperature increase. NDVI and temperature variations were inversely associated (Fig. 2).

Regarding seasonal variation, we detected a significant increase in the mean NDVI of spring, summer and autumn (i.e., $R^2=0.625$, $p=0.003$; $R^2=0.91$, $p<0.001$; $R^2=0.56$, $p=0.007$, respectively; Fig. 3), a non-significant increase in precipitation and a non-significant decrease in mean temperature for the three seasons. The mean summer NDVI shows peaks in 2011, 2013 and 2014 and a minimum

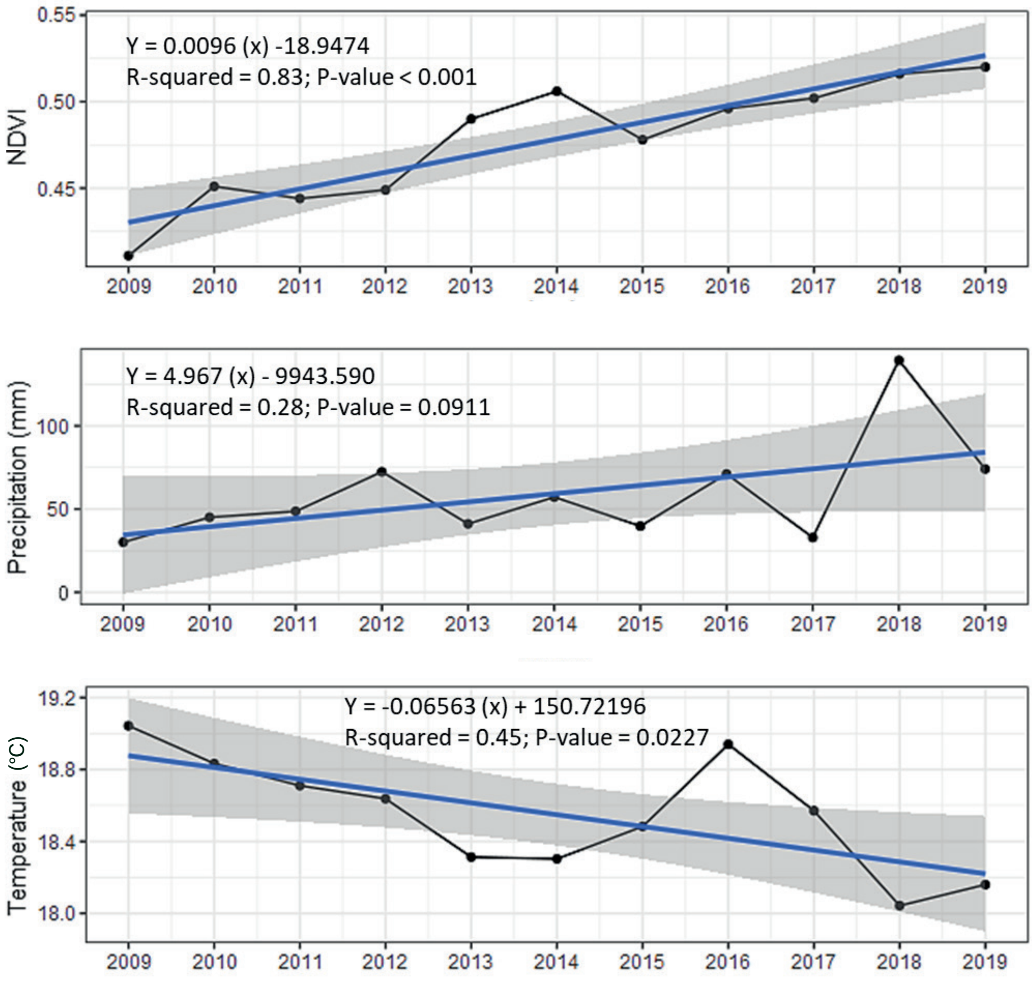

Fig. 1. Interannual variations in NDVI, total precipitation and mean temperature in the Talassemtane fir forest, 2009–2019

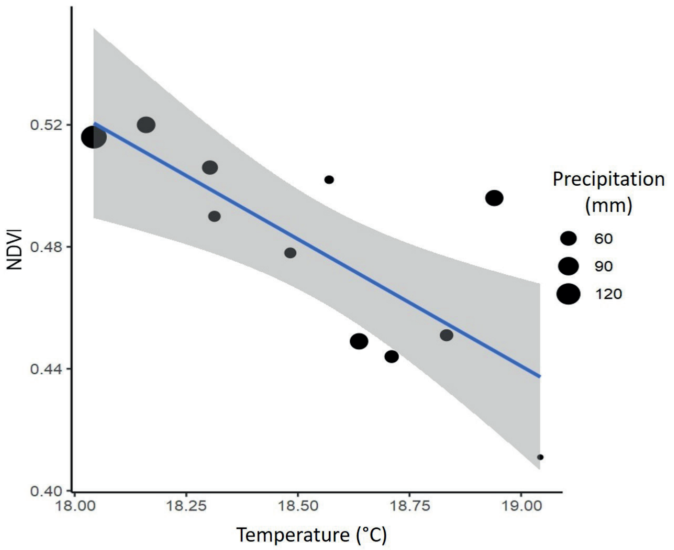

Fig. 2. Linear relationship between temperature and NDVI values, with confidence intervals in light grey

in 2009, indicating a strong positive correlation between mean summer precipitation and NDVI. For temperature, a clear reverse trend was observed, especially in spring. For the autumn, the high values of mean NDVI were recorded in 2013 and 2014 and the low values in 2011 and 2018. As in the spring season, variations in mean summer temperature follow inverse trends compared to precipitation and NDVI (Fig. 3). Overall, we observed a significant increase in seasonal NDVI during the study period.

The NDVI showed a significant negative correlation with mean temperature (R=–0.76, p=0.006) and a non-significant positive correlation with precipitation during the growing season (Table 2). These results likely indicate that mean temperature has a greater effect on vegetation health.

The first two PCA axes approximately collected 78.1% of the total variance (Fig. 4). The first axis separated the years into two groups: group A (2009, 2010, 2011, 2012 and 2015) characterised by high summer and spring temperatures and low NDVI values, and group B (grouping the years 2013, 2014, 2016, 2017, 2018 and 2019) characterised by summer and spring precipitation peaks, high temperature in autumn, and high NDVI values. Therefore, the increase in NDVI values suggests that the condition of the forest cover in the study area improved from 2016 to 2019. The PCA results suggest that temperature peaks during the summer and spring period have a negative effect on NDVI values (Fig. 4).

According to the results in Table 3, the summer mean NDVI was positively correlated with mean precipitation and negatively correlated with spring mean temperature. However, the autumn mean NDVI was positively correlated with mean precipitation and negatively and highly significantly correlated with summer mean temperature.

Distribution of mean annual NDVI according to altitude and aspect

We used ANOVA to compare NDVI across elevation because NDVI data met both normality of residuals (Shapiro–Wilk p>0.05) and homogeneity of variance of residuals (Levene’s test p>0.05) assumptions. We found that the forest vegetation at the lowest altitudinal range (1229–1800 m) had high NDVI values, while the highest range (1800–2159 m) had very low values (Fig. 5). The ANOVA results indicate that NDVI significantly differed between the three altitude classes (F=11.5; df=30; p=0.000196). Tukey's multiple comparisons test showed significant differences in NDVI valuesbetween the highest and the other two ranges on the one hand and between the highest and medium ranges. By contrast, there was no significant difference between the medium and lowest ranges (i.e., 1400–1800 and 1229–1400 m) (Table 4).

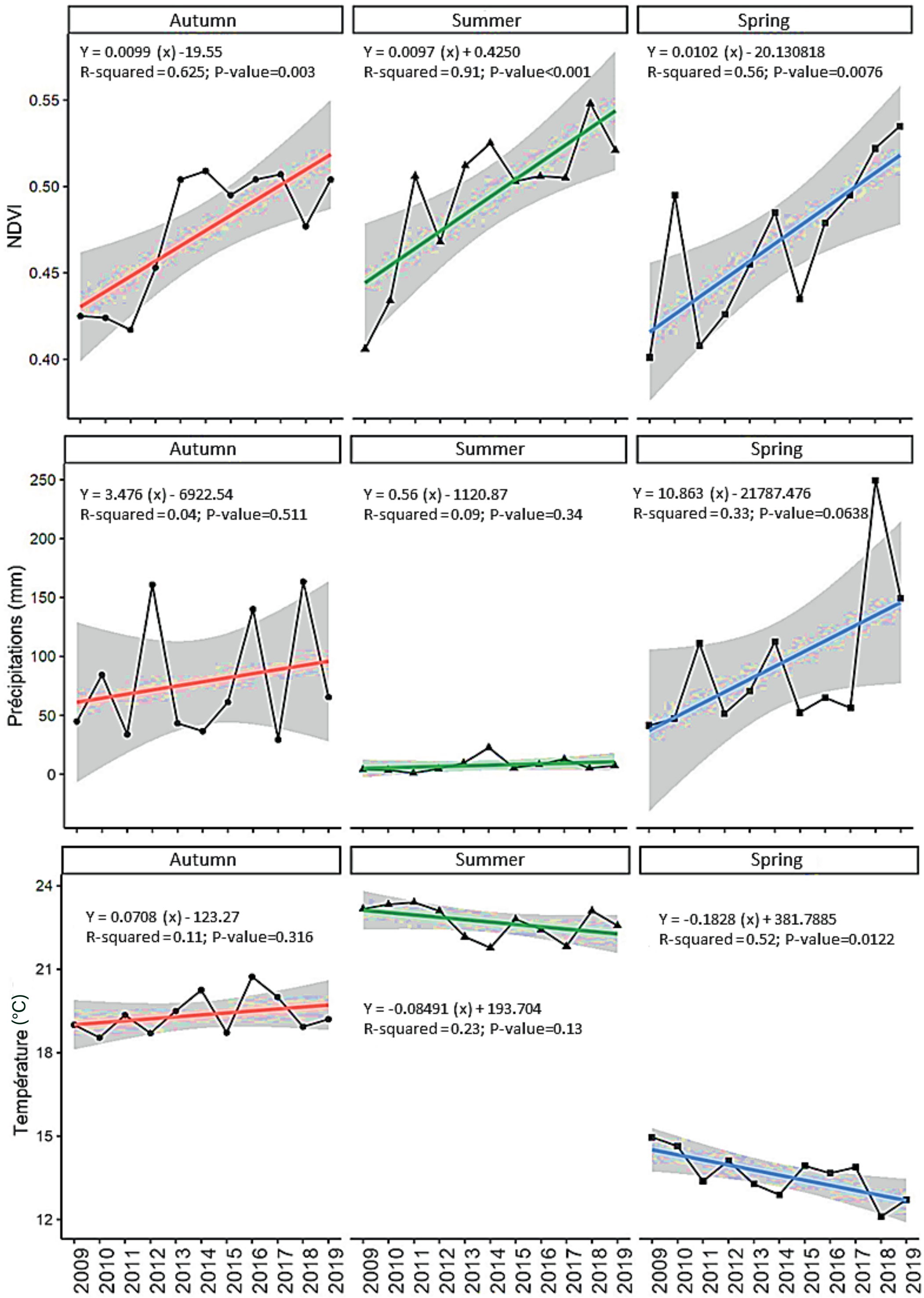

Fig. 3. Seasonal variations in NDVI, total precipitation and mean temperature in the Talassemtane fir forest, 2009–2019

Table 2. Pearson correlation coefficient (R) and p-value between growing season NDVI, precipitation and temperature, 2009–2019

NDVI and precipitation		NDVI and temperature	
Correlation coefficient	*p*-value	Correlation coefficient	*p*-value
0.49	0.13	**-0.76**	0.006**

Explanations: **significant at the 0.01 level

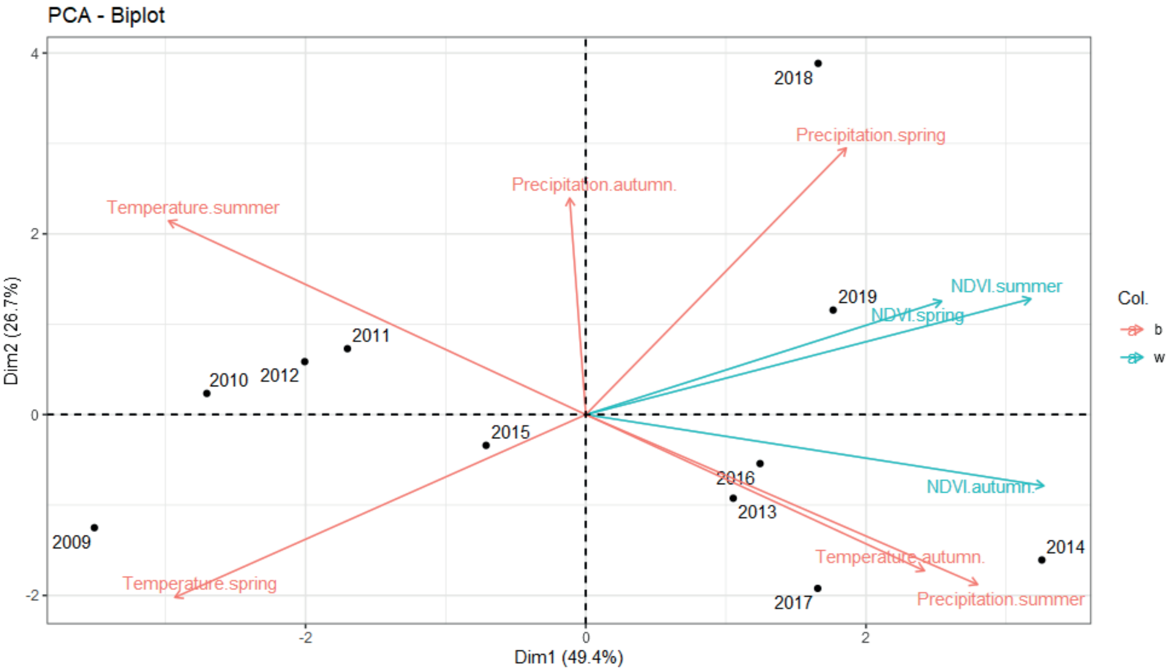

Fig. 4. Principal Component Analysis (PCA) showing the distribution of years according to NDVI (blue arrow) and seasonal temperature and precipitation (red arrow)

Table 3. Correlation coefficients between seasonal NDVI, precipitation and temperature in the Talassemtane fir forest, 2009–2019

NDVI	Precipitation			Temperature		
	Spring	Summer	Autumn	Spring	Summer	Autumn
Spring	0.56			-0.59		
Summer	**0.68***	0.39		**-0.92****	-0.463	
Autumn	0.17	**0.69***	-0.03	-0.52	**-0.86****	0.57

Explanations: *Significant at the 0.05 level; **significant at the 0.01 level

In terms of aspect, we used the Kruskal–Wallis test for aspect comparisons due to the assumptions of the normality of residuals and homogeneity of variance of residuals being violated, thus making the non-parametric approach more appropriate; both choices were validated through rigorous assumption testing prior to analysis. The spatial distribution of NDVI showed that the high values mainly occurred on the northern aspect (Fig. 5). The results of the Kruskal–Wallis test indicated that the NDVI values were significantly different. Specifically, there was a difference between northern and southern aspects on the one hand (Table 5) and between western and southern aspects on the other hand (p=0.035 and 0.033, respectively).

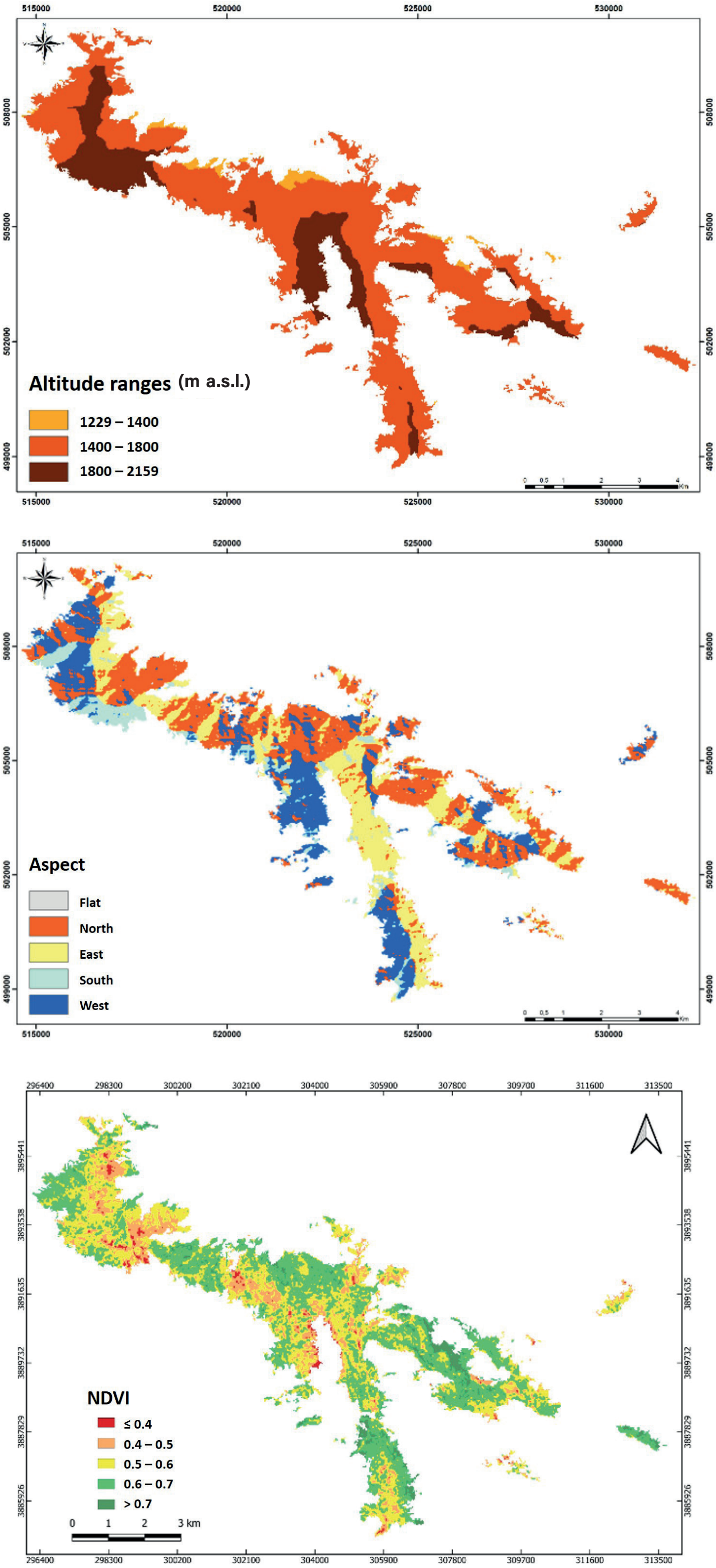

Fig. 5. Maps of altitude classes, average NDVI and aspect in the Talassemtane fir forest, 2009–2019

Table 4. Result of Tukey test illustrating the multiple comparisons between the NDVI values at three altitude classes

Altitude classes (m a.s.l.)	Confidence interval			
	Min	Max	Difference	p
(1400–1800) / (1229–1400)	-0.06	0.03	-0.011	0.810903
(1800–2159) / (1229–1400)	-0.12	-0.12	-0.079	0.0003 ***
(1800–2159) / (1400–1800)	-0.11	-0.02	-0.068	0.0018 **

Explanations: *Significant at the 0.05 level; **significant at the 0.01 level; ***significant at the 0.001 level

Table 5. P-value of Chi-square multiple comparisons between the NDVI values according to aspect

Group 1	Group 2	p
East	North	0.34
East	West	0.167
East	South	0.081
North	West	0.339
North	South	0.035*
West	South	0.033*

Dieback levels based on the NDVI

The NDVI values belonging to the “very high” class and corresponding to a vegetation with very good photosynthetic activity increased considerably from 2009 to 2013, stabilised until 2016, then increased again in 2019 (Table 6). This NDVI class occupied the largest area of the Talassemtane fir forest; with 57%, 57% and 62% of the study area in 2013, 2016 and 2019, respectively. In contrast, the other classes, i.e., “high”, “average”, “very low” and “low”, occupied lower areas and decreased from 44% to 22%, 32% to 11%, 10% to 3%, and 0.9% to 0.2%, respectively, over the study period (Table 6). The “very low” and “low” NDVI classes corresponding to a declined vegetation experienced a continuous regression between 2009 and 2016, while they showed a slight increase in 2019. These results indicate that the photosynthetic activity in the forest was low in 2009 and progressively increased in 2013, 2016 and 2019 (Fig. 6).

Characterisation of dieback symptoms

The results of the dieback symptom assessment in six mountains are summarised in Table 7. The severity classes ranged between 2 (J. Sfiha Telj) and 4 (J. Bouslimane, J. Lakraa and J. Taloussisse). The most-affected stands extended over more than 40% of the Mountain areas, and the declining trees mainly occurred as patches, although these patches extended over smaller areas, i.e., less than 2 ha (Table 4). By contrast, the lower severity classes (2 and 3) have smaller incidence ranging from 6% to 17% and occurred as isolated and sparse trees that extended, however, over vast areas (of more than 10 ha).

In almost all the sampled stands, branch mortality along with severe (or very severe) leaf deficit appear to be the most frequent symptoms of the declining trees that occur either as isolated, sparse or patches (Table 7). The abnormal colouring (or very marked abnormal colouring) sign seems to be less important and only affects isolated and sparse trees, mainly on J. Taloussisse (with total reddening) and J. Sfiha Telj (brownish-red or brown colour). On J. Taloussisse, we noted that some trees of Maghreb maritime pine *Pinus pinaster var. maghrebiana* Huguet del Villar trees were attacked by witches' brooms and mistletoe, and that a single tree of *A. marocana* was attacked by xylophagous insects of the genus *Phaenops sp*. Here, we also observed some signs of stem cutting and patch clearing to create new lands for Cannabis cultivation. Other dieback signs (i.e., drying with peeling of bark, wilting of leaves and

Table 6. Areas and percentages occupied by the five NDVI classes in the Talassemtane fir forest, 2009–2019

NDVI classeS	2009		2013		2016		2019		2009–2019	
	ha	%	ha	%	ha	%	ha	%	ha	%
Very low (0.11–0.2)	28.35	0.90	3.06	0.10	1.44	0.05	5.04	0.16	-23.31	-69.81 ▽
Low (0.21–0.3)	340.92	10.78	85.41	2.88	65.43	2.07	95.04	3.08	-245.88	-56.4 ▽
Average (0.31–0.4)	1017.45	32.19	370.26	12.47	366.57	11.6	356.76	11.58	-660.69	-48.08 ▽
High (0.41–0.5)	1393.65	44.09	794.79	26.76	921.15	29.14	693.09	22.49	-700.56	-33.57 ▽
Very high (≥ 0.51)	380.7	12.04	1716.12	57.79	1806.48	57.15	1931.67	62.68	1550.97	+67.07 △

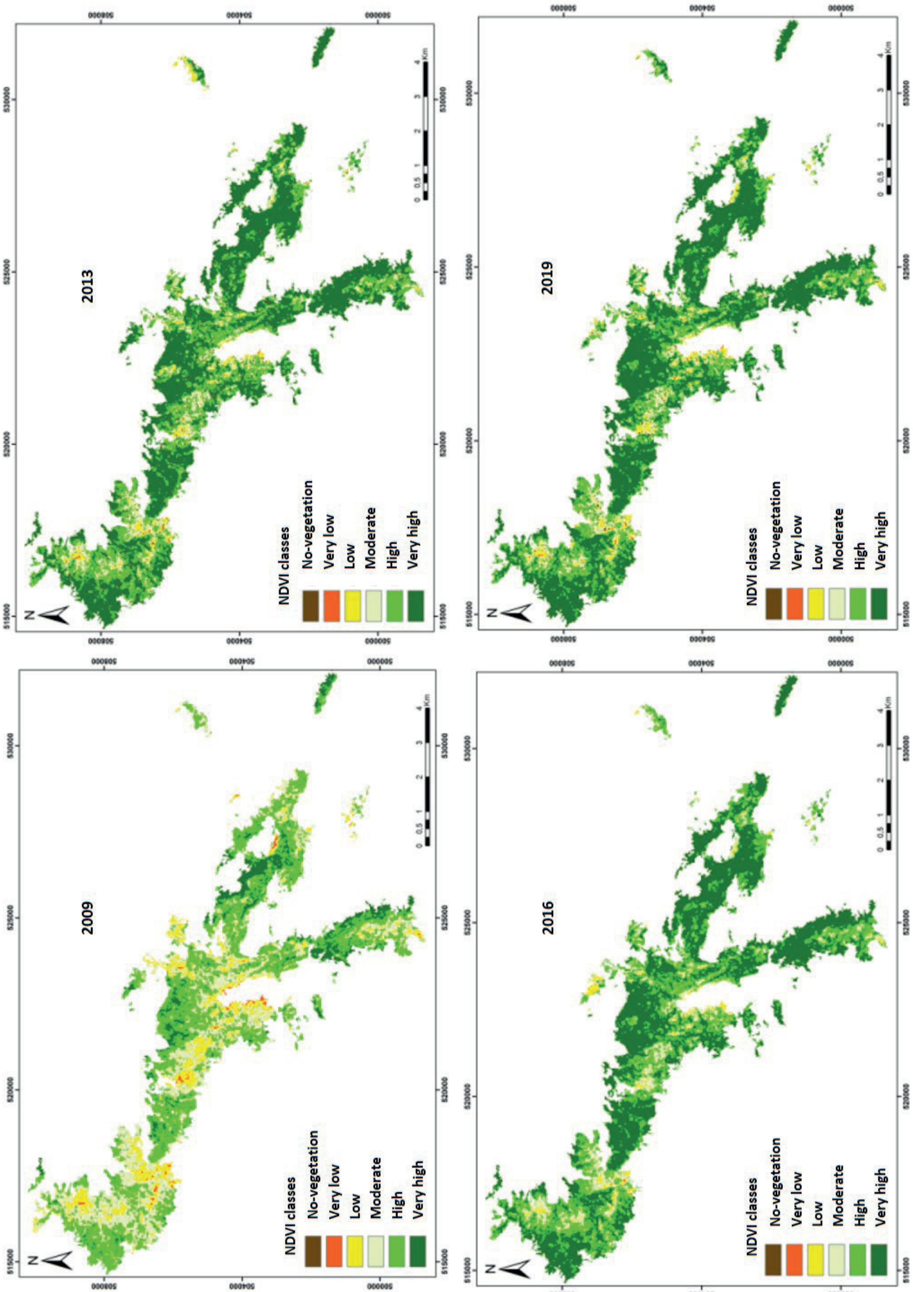

Fig. 6. Evolution of NDVI in the Talassemtane fir forest, 2009–2019

Table 7. Dieback characterisation in the six sampled mountains

MountainS	Severity class	Area affected (ha)	Incidence (%)	Occurrence of declining trees	Damages observed on leaves, branches and/or trunk
Jbel Bouslimane	4	> 1	60	Patches	Branch mortality Very severe leaf deficit
J. Lakraa	4	> 1	60	Patches	Drying with bark peeling Wilting of leaves Descent of crown
J. Talassemtane	3	> 10	17	Sparse	Branch mortality Severe leaf deficit
J. Taloussisse	4	< 2	40	Isolated and sparse	Branch mortality Very severe leaf deficit Very marked abnormal colouring
J. Sfiha Telj	2	> 10	6	Isolated	Abnormal colouring
J. Abdoune	3	> 10	15	Isolated and sparse	Branch mortality Severe leaf deficit

descent of tree crown) were exclusively observed on J. Lakraa, where dead trees of different ages were, notably, completely invaded by lichens.

Discussion

This study represents a first attempt to assess vegetation dieback in an endemic Talassemtane fir forest (western Rif, Morocco) through an integrated approach combining long-term remote-sensing data (NDVI) with on-the-ground field assessments. By analysing spatio-temporal NDVI patterns alongside tree-level symptoms, we aimed to better understand the multifactorial drivers of forest health in this sensitive Mediterranean ecosystem.

Variations in NDVI and the effect of climatic factors

We examined the interannual and seasonal variations in NDVI and the effects of climatic factors (precipitation and temperature) on the Moroccan fir forest from 2009 to 2019. We found a significant increase in NDVI, a non-significant increase in mean precipitation and a significant decrease in mean temperature (Fig. 1). This indicates that higher temperature and higher precipitation had a negative and a positive effect on the NDVI, respectively. Spring temperature and precipitation have a strong impact on vegetation cover during the subsequent summer (Table 3, Fig. 3). Spring and summer precipitation had a positive effect on mesophilic vegetation in summer and autumn, respectively, while spring and summer temperatures showed a negative effect on summer and autumn NDVI. The climatic conditions before the growing season have a predominant influence on the onset of vegetation activity (Liu et al. 2021) because early-season climate sets physiological thresholds, mainly by regulating soil water content (Camarero et al. 2015). For example, Camarero et al. (2021a) found that dry previous-November conditions negatively affected tree growth. Similar results were recently reported by Dallahi et al. (2023) on cork oak forest where NDVI had a positive and negative correlation with mean annual precipitation and mean annual temperature, respectively, indicating its capacity to forecast phenotypic changes in tree species.

Spatiotemporal evolution of vegetation dieback based on NDVI

The use of remote-sensing data is becoming essential to monitor plant decline over time in different geographical areas (Ogaya et al. 2015).

Vegetation indices remarkably contribute to the identification and discrimination of dieback signs in forests and shrublands, and thus to the monitoring of ecosystem health (Castellaneta et al. 2022; Miletić et al. 2024). As a greenness vegetation index, NDVI is calculated by estimating the captured photosynthetically active radiation and it is widely applied to evaluate vegetation health (Tucker 1979). Several studies used NDVI to assess forest health. Ogaya et al. (2015) reported that NDVI was an efficient indicator of dieback in a Mediterranean holm oak forest. Among five common vegetation indices, Ghavidel et al. (2021) found that NDVI was valuable for detecting forest disease spread. For example, in drought-prone *P. pinaster* forests, it has been reported that the dieback was mostly associated with the trends of vegetation indices (Moreno-Fernández et al. 2021). In a *Pinus pinea* forest located in Central Spain, Moreno-Fernández et al. (2022) found that low dieback levels showed higher values in NDVI, while high dieback stands experienced lower values over the period 2011–20. In the Moroccan Central Plateau, Dallahi et al. (2023) found that interannual NDVI variations were significantly related to dieback severity, which indicates that NDVI is an important tool for forest monitoring. In Spain and Italy, Castellaneta et al. (2022) found that NDVI values were lower in dieback stands than in non-dieback ones, with declining trees presenting a lower performance and a reduced radial growth, which may indicate an increase in their vulnerability to other stress factors such as insect and fungal attacks.

The results of the spatio-temporal evolution of NDVI and its relationship with forest vegetation dieback revealed that the area of declining vegetation regressed over time (very low and low NDVI values being of 369.27 ha in 2009 to 100.08 ha in 2019) (Table 6, Fig. 6). High NDVI values indicate an increase in leaf surface area and thus photosynthetic activity, reflecting favourable ecological conditions for plant development (Warrag 2019). In Spanish *A. pinsapo* forests, Cortés-Molino et al. (2022) found an increase in photosynthetic activity based on NDVI since the mid-2000s and in the forest cover in recent years at mid and high elevations. The authors reported that this unpredicted resilience to climate-change-related dieback in *A. pinsapo* forests might be supported by compensation processes such as (i) *A. pinsapo* regeneration; (ii) facilitation interactions with other species; and (iii) a "release effect" whereby surviving individuals can prosper with weak competition for resources. Indeed, vegetation cover in the study area experienced a remarkable enhancement which could be due to the conservation measures related to the establishment of the Talassemtane National Park in 2004, reinforced by the creation of the Mediterranean Intercontinental Biosphere Reserve of Morocco and Spain in 2006. These conservation measures probably promoted favourable conditions for natural regeneration in the study area (Ben-Said et al. 2020, 2022).

Several studies found that the change in NDVI values varied according to altitude (Tikvić et al. 2008; Cortés-Molino et al. 2022). We found high NDVI values at the lower and mid-altitudes range (<1800 m a.s.l.) and very low values at the highest range (>1800 m a.s.l.; Table 4). The altitudinal distribution of NDVI was consistent with that of vegetation belts previously defined in the study area (Benabid 1982; Aafi 1995). At lower and medium altitudes, the forest is mainly dominated by *Q. rotundifolia and A. marocana*, respectively, with a dense canopy (70% to 90%), which is reflected by the high NDVI values. By contrast, tree density decreases at high altitude (>1800 m a.s.l.), which explains the relatively low NDVI values (Fig. 5). Our results were inconsistent with those reported by Gazol et al. (2020), who found that forest dieback prevailed at low altitudes, where there is a smaller amount of rainfall during summer compared to forests with no dieback symptoms in Pyrenean silver fir (*Abies alba* Mill.) forests.

Our results revealed high NDVI values for the northern aspect, which is shaded and has higher soil moisture content, allowing optimal vegetation growth compared to the drier aspects (i.e., eastern and southern; Table 5). In *Pinus pinaster* forest in north-eastern Spain, the dieback was more intense in south-facing aspects that receive more sunlight and are dry and warmer (Moreno-Fernández et al. 2021). Tikvić et al. (2008) also found similar results in silver fir in Croatia. In these south-facing aspects, however, the severity of the dieback process is not uniform but arises in patches showing variable levels of crown damage and tree mortality (Moreno-Fernández et al. 2021). In contrast, Ghailoule et al. (2012) observed that dieback of *C. atlantica* was more obvious on the northern compared to the southern aspect within the same valley in the Azrou region (Middle Atlas). This was explained by competition being the main factor of decline on the northern slope (where cedar density is high) compared to the southern slope, local heterogeneity of the soil and therefore of water reserves, and also by the existence of intraspecific genetic variability of the cedar resulting in different sensitivity to water deficit (Ghailoule et al. 2012). Sánchez-Salguero et al. (2010) considered southern aspect to be a factor that predisposes to dieback. Nepstad et al. (2007) found that aspect was the main factor controlling the distribution of pest-induced dead trees in an Amazon forest.

Several other factors have been reported to be responsible for forest dieback. For example, Moreno-Fernández et al. (2021) found that decreases in NDVI were consistent with recurrent droughts. Moreno-Fernández et al. (2022) found that dieback levels were not correlated to stand attributes (i.e., mean tree diameter, stand density and basal area). Similarly, Dallahi et al. (2023) found that neither substrate, nor slope, nor stand age and density had any influence on cork oak dieback in the Moroccan Central Plateau. In contrast, Derak et al. (2008) found that Atlas cedar dieback was linked to high densities and pure stands of cedar in the Central Middle Atlas, while healthy stands are less dense, and those in which cedar is mixed with holm oak or in which oak may even be abundant. In the study area, the density of Moroccan fir in J. Bouslimane is high (unpublished data), which could induce tree decline. The fir forest dieback may also be due to the increasing pressure of fires and land-use conversion, mainly the expansion of cannabis crops (Boubekraoui et al. 2024; Chergui et al. 2024).

Field characterisation of dieback symptoms

Our field observations revealed that all six investigated mountains (Jbel Bouslimane, J. Talassemtane, J. Taloussisse, J. Abdoune, J. Sfiha Telj and J. Lakraa) were affected by dieback symptoms (Table 7). Indeed, 60% of trees showed dieback symptoms of class-4 severity over an area between 1 and 2 ha in J. Bouslimane, J. Lakraa and J. Taloussisse. Additionally, class-3 severity was observed on 17% and 15% of trees in J. Talassemtane and J. Abdoune, respectively, over an area of more than 10 ha. By contrast, 6% of trees presented a class-2 severity over more than 10 ha in J. Sfiha Telj. This may indicate that dieback is not currently at an alarming level in the study area, which seems to contradict the excessive dieback reported in many European fir forests in recent decades (Camarero et al. 2015; Jankowiak et al. 2016).

With the exception of J. Lakraa, where Atlas cedar is the species most affected by dieback, Moroccan fir seems to be the one suffering most from dieback on almost all the mountains (J. Bouslimane, J. Talassemtane, J. Taloussisse, J. Akroud and J. Sfiha Telj). This may be related to the species' higher sensitivity to climatic drought compared to other conifers (e.g., *C. atlantica* and *P. nigra*; Navarro-Cerrillo et al. 2020). This climatic sensitivity may have a significant impact on its future dynamic under the warming trend and decrease in precipitation predicted for the upcoming decades (Ghallab 2018; Moukrim et al. 2022).

According to the managers of the study area, pre-existing diebacks followed the drought of 2001 (Oughilass 2012). Klesse et al. (2022) reported that the severity of crown damage was significantly correlated with soil water availability at the stand level. We assume that the dieback of Moroccan fir trees located at the top of J. Bouslimane is linked to the unfavourable ecological conditions expressed by the soils being more superficial and stonier on steep slopes (predisposing factor) and thus having fewer water reserves (triggering factor). According to Wermelinger et al. (2008), water stress reduces production and changes resin content, thereby making trees more susceptible to bark beetle attacks. Furthermore, at J. Lakraa, it is suggested that pine processionary caterpillars, which have been rampant since 2010 in the Talassemtane fir forest according to local foresters, are involved in the process of dieback of Atlas cedar. However, in J. Taloussisse, we believe that witches' brooms and mistletoe contribute to the dieback of maritime pine. Idžojtic et al. (2008) highlighted that mistletoe acts as a predisposing factor in the dieback of fir in Croatia.

Moreover, at J. Taloussisse, we revealed the intervention of a wood-eating insect belonging to the genus *Phaenops sp.* as an aggravating factor in the dieback of a fir tree presenting the following symptoms: loss of bark, subcortical galleries, denudation, drying and breakage of twigs and branches, and reddening of the needles which become greyish over time. Defoliation was reported to be a predictor of mortality in *P. abies* and *P.*

sylvestris underneath dry conditions and infection by pathogens (Gomez-Gallego et al. 2022). Bark beetle outbreaks have led to high mortality in many forests across the world, such as in the western US (Spruce et al. 2019). According to Mouna and Fabre (2005), xylophagous insects act as an aggravating factor and often intervene in the last phase of dieback by accelerating this process, leading in the majority of cases to the death of trees. This suggests that Moroccan fir trees exhibiting similar symptoms and attacked by wood-boring insects are in irreversible decline. Furthermore, at J. Talassemtane, J. Sfiha Telj and J. Abdoune, no biotic symptoms were observed on the declining trees, suggesting that abiotic agents are involved in their dieback.

Overall, Moroccan fir forest dieback is linked to abiotic factors, including drought conditions, unfavourable soils and biotic causes, including pests and pathogen attacks such as pine processionary and bark beetle, as well as to other factors such as forest conversion to croplands.

Conclusions and perspectives

The field- and remote-sensing-based assessments used to analyse the spatio-temporal dynamics of forest dieback in the Talassemtane fir forest helped to fill significant gaps in our knowledge regarding the dynamic status of this endemic forest, which will be useful for managers and conservation strategies. The area of declining trees decreased during the study period (2009–2019), which could be related to the conservation measures undertaken since the establishment of the Talassemtane National Park and the increasing awareness of the importance of forest protection, which may have improved natural regeneration. The enhancement of climatic factors could be also involved. The vegetation cover is influenced by the climatic conditions of the previous season. The NDVI values on the northern and western aspects are relatively high at an altitudinal range of 1229–1800 m. The NDVI values were consistent with the altitudinal distribution of forest vegetation at the study area.

The factors involved in the detected diebacks are far from being categorically identified and require further investigation, although the observed dieback is relatively limited. Many abiotic (e.g., recurrent drought, topographic constraints) and biotic (e.g., pine processionary caterpillars, looper caterpillars, witches' brooms, mistletoe and xylophage insects) factors appear to be involved in the dieback in the study area. Identifying whether a factor is predisposing, triggering or aggravating requires long-term monitoring. Moroccan fir seems to be the species most affected by dieback compared to other co-occurring species, which indicates its vulnerability to climatic hazards and its sensitivity to pathogen attacks.

Our study is a first step toward a deeper understanding of Moroccan fir forest dieback, one of the most threatened ecosystems of the western Mediterranean. However, our preliminary findings are still descriptive and limited and do not sufficiently describe the overall dieback status of the Talassemtane forest, since it does not cover the other main Moroccan fir population, i.e., Tazaout. Further efforts should be carried out in the stands showing symptoms of decline, especially of the first severity classes, to gain insight into the factors underlying the dieback, along with the mapping of the decline risks in the forest. Future studies should also combine greenness and wetness indices to gain insight into forest drought-related responses. A deeper understanding of decline in the Talassemtane fir forest should include analysis of edaphic properties (texture, structure, depth, water reserve), tree ecophysiological properties, and growth patterns of declining vs non-declining trees.

Disclosure statement

No potential conflict of interest was reported by the authors

Author contributions

Study design: HL, TA, HB; data collection: HL, TA; statistical analysis: HL; result interpretation: HL, TA, MB, HB; manuscript preparation: HL, MB; literature review: HL, MB.

Acknowledgments

The authors are grateful to Pr Abdallah Aouadi for his valuable assistance in the statistical analyses and for his constructive comments on an earlier version of the manuscript. We thank the three anonymous reviewers for their thoughtful comments, suggestions, and language correction.

References

AADEL T, ROCHDI A and ZINE EL ABIDINE A, 2021, Explaining the Atlas Cedar (Cedrus atlantica M.) dieback by studying Water relations of young plants subject to an edaphic drought. *E3S Web of Conferences* 234: 00100. DOI: https://dx.doi.org/10.1051/e3sconf/202123400100 .

AAFI A, 1995, Contribution à l'étude phytoécologique et à la cartographie des groupements végétaux du Parc Naturel de Talassemtane. Dissertation, National School of Forest Engineers, Morocco.

ALAOUI A, LAARIBYA S and AYAN S, 2025, Floristic Diversity and Conservation Status of Strictly Endemic Taxa of Talassemtane National Park in Morocco. *Forestist* 75: 1-11. DOI: https://dx.doi.org/10.5152/forestist.2025.25001.

AOUBOUAZZA M, 2017, Influence des propriétés hydrodynamiques du sol sur la sensibilité au dépérissement du cèdre dans le Causse moyen-atlasique central marocain (Influence of soil hydrodynamic properties on the susceptibility of cedar trees to decline in the central Middle Atlas region of Morocco – in French). *Revue Marocaine des Sciences Agronomiques et Vétérinaires* 5: 293-303.

ASSALI F, 2009, *Études de cas sur l'évaluation de la dégradation des forêts. Surveillance et suivi de la sante des forêts au Maroc* (Case studies on assessing forest degradation. Monitoring and tracking forest health in Morocco – in French). FAO, Rome.

BENABID A, 2000, *Flore et écosystèmes du Maroc : Evaluation et préservation de la biodiversité* (Flora and ecosystems of Morocco: Assessment and preservation of biodiversity – in French). Ibis Press. Paris.

BENABID A, 1985, Les écosystèmes forestiers préforestiers et presteppiques du Maroc : Diversité, répartition biogéographique et problèmes posés par leur aménagement (Pre-forest and pre-steppe forest ecosystems in Morocco: Diversity, biogeographical distribution, and issues raised by their management – in French). *Forêt méditerranéenne* VII : 53-64.

BENABID A, 1982, *Etudes phytoécologique biogéographique et dynamique des associations et séries sylvatiques du Rif Occidental* (Phytoecological, biogeographical, and dynamic studies of forest associations and series in the Western Rif Mountains – in French). Dissertation, University of St Jérome-Marseille.

BEN-SAID M, GHALLAB A, LAMRHARI H, CARREIRA JA, LINARES JC and TAÏQUI L, 2020, Characterizing spatial structure of Abies marocana forest through point pattern analysis. *Forest Systems* 29: e014. DOI: https://dx.doi.org/10.5424/fs/2020292-16754.

BEN-SAID M, LINARES JC, CARREIRA JA and TAÏQUI L, 2022, Spatial patterns and species coexistence in mixed Abies marocana–Cedrus atlantica forest in Talassemtane National Park. *Forest Ecology and Managemment* 506: 119967. DOI: https://dx.doi.org/10.1016/j.foreco.2021.119967.

BEN-SAID M and SAKAR EH, 2023, A systematic review on the endemic Moroccan fir (Abies marocana Trab.) and its implications for conservation and future research perspectives. *Folia Geobotanica* 58(1): 31-53. DOI: https://dx.doi.org/10.1007/s12224-023-09434-5.

BEN-SAID M, EL AICH N, BERRAD F and GHALLAB A, 2024, Etat des connaissances de la sapinière endémique du Maroc (Abies marocana Trab.): acquis, lacunes et nouveaux axes de recherche (State of knowledge on Morocco's endemic fir forest (Abies marocana Trab.): achievements, gaps, and new avenues for research – in French). *Bulletin de l'Institut Scientifique, Rabat, Section Sciences de la Vie* 46: 01–16.

BOUBEKRAOUI H, MAOUNI Y, GHALLAB A, DRAOUI M and MAOUNI A, 2024, Deforestation Drivers in Northern Morocco: An Exploratory Spatial Data Analysis. *Environmental Research Communications* 6: 071005. DOI: https://dx.doi.org/10.1088/2515-7620/ad5ad6.

CAMARERO JJ, GAZOL A, SANGÜESA-BARREDA G, OLIVA J and VICENTE-SERRANO SM, 2015, Special Feature. Forest resilience, tipping points and global change processes. To die or not to die: early warnings of tree dieback in response to a severe drought. *Journal of Ecology* 103: 44–57. DOI: https://dx.doi.org/10.1111/1365-2745.12295.

CAMARERO JJ, COLANGELO M, GAZOL A, and AZORÍN-MOLINA C, 2021a, Drought and cold spells trigger dieback of temperate oak and beech forests in northern Spain. *Dendrochronologia* 66: 125812. DOI: https://dx.doi.org/10.1016/j.dendro.2021.125812.

CAMARERO JJ, SÁNCHEZ-SALGUERO R, SANGÜESA-BARREDA G, LECHUGA V, VIÑEGLA B, SECO JI, TAÏQUI L, CARREIRA JA and LINARES JC, 2021b, Drought, axe and goats. More variable and synchronized growth forecasts worsening dieback in Moroccan Atlas cedar forests. *Science of the Total Environment* 765: 142752. DOI: https://dx.doi.org/10.1016/j.scitotenv.2020.142752.

CASTELLANETA M, RITA A, CAMARERO JJ, COLANGELO M and RIPULLONE F, 2022, Declines in canopy greenness and tree growth are caused by combined climate extremes during drought-induced dieback. *Science of the Total Environment* 813: 152666. DOI: https://dx.doi.org/10.1016/j.scitotenv.2021.152666.

CASTRO I., STAN AB, TAIQUI L, SCHIEFER E, GHALLAB A, DERAK M and FULÉ PZ, 2022, Detecting fire-caused forest loss in a Moroccan protected area. *Fire* 5: 1–14.

CHEMCHAOUI A, ISMAILI ALAOUI H, GHAZI S, BOUKITA H, BRHADDA N and ZIRI R, 2025, Assessing forest dynamic in Talassemtane National Park: A 34-year land cover change analysis using Google Earth Engine. *Ecological Engineering & Environmental Technology* 26(5): 107–122. DOI: https://dx.doi.org/10.12912/27197050/202873.

CHERGUI B, FAHD S, SANTOS X and PAUSAS JG, 2024, Moroccan cannabis farms threaten biodiversity. *Science* 385(6712): 941. DOI: https://dx.doi.org/10.1126/science.adq5140.

COLANGELO M, CAMARERO JJ, BATTIPAGLIA G, BORGHETTI M, DE MICCO V, GENTILESCA T, and RIPULLONE F, 2017, A multi-proxy assessment of dieback causes in a Mediterranean oak species. *Tree Physio*logy 37: 617–631. DOI: https://dx.doi.org/10.1093/treephys/tpx002.

CORTÉS-MOLINO Á, LINARES JC, VIÑEGLA B, LECHUGA V, SALVO-TIERRA AE, FLORES-MOYA A, FERNÁNDEZ-LUQUE I. and CARREIRA JA, 2022, Unexpected resilience in relict Abies pinsapo Boiss forests to dieback and mortality induced by climate change. *Frontiers in Plant Science* 13: 991720. DOI: https://dx.doi.org/10.3389/fpls.2022.991720.

DALLAHI Y, BOUJRAF A and MELIHO M 2023, Ashianga Orlando C. Assessment of forest dieback on the Moroccan Central Plateau using spectral vegetation indices. *Journal of Forestry Research.* 34: 793–808. DOI: https://dx.doi.org/10.1007/s11676-022-01525-x.

DERAK M, M'HIRIT O, MOUFLIH B and ET-TOBI M, 2008, Influence de la densité et du type de peuplement sur le dépérissement du Cèdre à Sidi M'Guild (Moyen Atlas marocain)(Influence of density and type of stand on cedar decline in Sidi M'Guild (Moroccan Middle Atlas) – in French). *Forêt méditerranéenne* 29: 23-32.

FENNANE M, IBN TATTOU M, MATHE J, OUYAHYA A and EL OUALIDI J (ed.), 1999, *Flore pratique du Maroc. Volume 1. Pteridophyta, Gymnospermae, Angiospermae (Lauraceae–Neuradaceae)*(Practical Flora of Morocco. Volume 1. Pteridophyta, Gymnospermae, Angiospermae (Lauraceae–Neuradaceae) – in French). Institut Scientifique, Agdal: Rabat.

GAZOL A, SANGÜESA-BARREDA G and CAMARERO JJ, 2020, Forecasting Forest Vulnerability to Drought in Pyrenean Silver Fir

Forests Showing Dieback. *Frontiers in Forests and Global Change* 3: 36. DOI: https://dx.doi.org/10.3389/ffgc.2020.00036.

GHAIOULE D and LUMARET JP, 2020, Current knowledge on the dieback of the Barbary thuja, Tetraclinis articulata (Vahl) Mast. *ecologia mediterranea* 46: 83-96.

GHAILOULE D, ROSSI J-R and LIEUTIER F, 2012, Caractérisation spatio-temporelle du dépérissement du cèdre (Cedrus atlantica Manetti) dans deux peuplements du Moyen Atlas marocain : Résultats préliminaires. Paper presented at the MEDINSECT 3 "Entomological Research in Mediterranean Forest Ecosystems" conference, Tunis. *Annales de l'INRGREF* 17: 145-156.

GHALLAB A, 2018, *Modélisation de la distribution potentielle actuelle des espèces forestières majeures dans le Rif occidental du Maroc et prédiction de l'impact du changement climatique* (Modeling the current potential distribution of major forest species in the western Rif Mountains of Morocco and predicting the impact of climate change – in French). Dissertation, University of Abdelmalek Essaadi.

GHALLAB A, BOUBEKRAOUI H, LAARIBYA S and BEN-SAID M, 2024, Potential natural vegetation pattern based on major tree distribution modeling in the western Rif of Morocco. *iForest – Biogeosciences and Forestry* 17(6): 405–416. DOI: https://dx.doi.org/10.3832/ifor4602-017.

GHAVIDEL M, BAYAT P and FARASHIANI ME 2021, Satellite image processing of the Buxus hyrcana Pojark dieback in the Northern Forests of Iran. *Journal of Forest Science* 67: 71–79.

GOMEZ-GALLEGO M, GALIANO L, MARTÍNEZ-VILALTA J, STENLID J, CAPADOR-BARRETO HD, ELFSTRAND M, CAMARERO JJ and OLIVA J, 2022, Interaction of drought- and pathogen-induced mortality in Norway spruce and Scots pine. *Plant, Cell & Environment* 45(8): 2292-2305. DOI: https://dx.doi.org/10.1111/pce.14360.

IDŽOJTIC M, PERNAR R, GLAVAŠ M, ZEBEC M and DIMINIC D, 2008, The incidence of mistletoe (Viscum album ssp. abietis) on silver fir (Abies alba) in Croatia. *Biologia* 63: 81–85. DOI: https://dx.doi.org/10.2478/s11756-008-0014-2.

JANKOWIAK R, BILAŃSKI P, PALUCH J and KOŁODZIEJ Z, 2016, Fungi associated with dieback of Abies alba seedlings in naturally regenerating forest ecosystems. *Fungal Ecoloy* 24: 61e69. DOI: http://dx.doi.org/10.1016/j.funeco.2016.08.013.

KLESSE S, WOHLGEMUTH T, MEUSBURGER K, VITASSE Y, ARX GV, LÉVESQUE M, NEYCKEN A, BRAUN S, DUBACH V, GESSLER A, GINZLER C, GOSSNER MM, HAGEDORN F, QUELOZ V, SAMBLÁS VIVES E, RIGLING A and FREI ER, 2022, Long-termsoilwater limitation and previous tree vigor drive local variability of drought-induced crown dieback in Fagus sylvatica. *Science of the Total Environment* 851: 157926. DOI: http://dx.doi.org/10.1016/j.scitotenv.2022.157926.

MÉDAIL F and DIADEMA K, 2009, Glacial refugia influence plant diversity patterns in the Mediterranean Basin. *Journal of Biogeography* 36: 1333-1345.

MILETIĆ BR, MATOVIĆ B, ORLOVIĆ S, GUTALJ M, ĐOREM T, MARINKOVI´C G, SIMOVIĆ S, DUGALIĆ M and STOJANOVIĆ DB, 2024, Quantifying Forest Cover Loss as a Response to Drought and Dieback of Norway Spruce and Evaluating Sensitivity of Various Vegetation Indices Using Remote Sensing. *Forests* 15: 662. DOI: https://dx.doi.org/10.3390/f15040662.

MORENO-FERNÁNDEZ D, VIANA-SOTO A, CAMARERO JJ, ZAVALA MA, TIJERÍN J and GARCÍA M, 2021, Using spectral indices as early warning signals of forest dieback: The case of drought-prone Pinus pinaster forests. *Science of the Total Environment* 793: 148578.

MORENO-FERNÁNDEZ D, CAMARERO JJ, GARCÍA M, LINES ER, SÁNCHEZ-DÁVILA J, TIJERÍN J, VALERIANO C, VIANA-SOTO A, ZAVALA MÁ and RUIZ-BENITO P, 2022, The Interplay of the Tree and Stand- Level Processes Mediate Drought- Induced Forest Dieback: Evidence from Complementary Remote Sensing and Tree-Ring Approaches. *Ecosystems* 25: 1738–

1753. DOI: https://dx.doi.org/10.1007/s10021-022-00793-2.

MOUKRIM S, LAHSSINI S, RHAZI M, MENZOU K, EL MADIHI M, RIFAI N, BOUZIANI Y, AZEDOU A, BOUKHRIS I. and RHAZI L, 2022, Climate change impact on potential distribution of an endemic species Abies marocana Trabut. *Ekológia* 41: 329–339.

MOUNA M and FABRE J-P, 2005, Pests insects of cedars: Cedrus atlantica Manetti, C. libani A. Richard and C. brevifolia Henry in the Mediterranean area. In: LIEUTIER F and GHAIOULE D (eds.), *Entomological Research in Mediterranean Forest Ecosystems*, Science Update Series, INRA: Paris.

NAVARRO-CERRILLO RM, MANZANEDO RD, RODRIGUEZ-VALLEJO C, GAZOL A, PALACIOS-RODRÍGUEZ G and CAMARERO JJ, 2020, Competition modulates the response of growth to climate in pure and mixed Abies pinsapo subsp. Maroccana forests in northern Morocco. *Forest Ecology and Management* 459: 117847.

NEPSTAD DC, TOHVER I.M, RAY D, MOUTINHO P and CARDINOT G, 2007, Mortality of large trees and lianas following experimental drought in an Amazon forest. *Ecology* 88: 2259–2269.

NI M, WU Q, LI G and LI D, 2025. Remote Sensing Technology for Observing Tree Mortality and Its Influences on Carbon–Water Dynamics. *Forests* 16: 194. DOI: https://dx.doi.org/10.3390/f16020194.

OGAYA R, BARBETA A, BAŞNOU C, and PEÑUELAS J, 2015, Satellite data as indicators of tree biomass growth and forest dieback in a Mediterranean holm oak forest. *Annals of Forest Science* 72: 135–144. DOI: https://doi.org/10.1007/s13595-014-0408-y.

OUGHILASS L, 2012, *Caractérisation de l'état de santé de la sapinière marocaine (Talassemtane, Chefchaouen) en 2012*. Dissertation, National Forest School of Engeeners, Sale, Morocco.

RAMZI H, STIKI A, LAHLOU M, and ASSALI F, 2009, *Stratégie nationale de surveillance et de suivi de la santé des forêts* (National Strategy for Forest Health Monitoring and Surveillance – in French). HCEFLCD et FAO, Rabat.

RIPULLONE F, CAMARERO JJ, COLANGELO M and VOLTAS J, 2020, Variation in the access to deep soil water pools explains tree-to-tree differences in drought-triggered dieback of Mediterranean oaks. *Tree Physiology* 40: 591–604. DOI: https://dx.doi.org/10.1093/treephys/tpaa026.

SÁNCHEZ-SALGUERO R, NAVARRO RM, CAMARERO JJ and FERNÁNDEZ-CANCIO Á, 2010, Drought-induced growth decline of Aleppo and maritime pine forests in south-eastern Spain. *Forest Systems* 19: 458-470. DOI: https://dx.doi.org/10.5424/fs/2010193-9131.

SÁNCHEZ-SALGUERO R, CAMARERO, JJ, CARRER M, GUTIÉRREZ E, ALLA AQ, ANDREU-HAYLES L, HEVIA A, KOUTAVAS A, MARTÍNEZ-SANCHO E, NOLA P, PAPADOPOULOS A, PASHO E, TOROMANI E, CARREIRA JA and LINARES JC, 2017, Climate extremes and predicted warming threaten Mediterranean Holocene firs forests refugia. *Proceedings of the National Academy of Sciences of the USA* 114: E10142–E10150. DOI: https://doi.org/10.1073/pnas.1708109114.

SARMOUM M, NAVARRO-CERRILO R and GUIBAL F, 2019, Bilan actuel et rétrospectif du dépérissement du cèdre de l'Atlas dans le Parc national de Theniet El Had (Algérie)(Current and retrospective assessment of the decline of Atlas cedar in Theniet El Had National Park (Algeria) – in French). *Bois et Forêts des Tropiques* 342: 29-40. DOI: https://dx.doi.org/10.19182/bft2019.342.a31636.

SELLERS PJ, 1987, Canopy reflectance, photosynthesis and transpiration: II. The role of biophysics in the linearity of their interdependence. *Remote Sensing of Environment* 21: 143-183.

SPRUCE JP, HICKE JA, HARGROVE WW, GRULKE NE and MEDDENS AJH, 2019, Use of MODIS NDVI Products to Map Tree Mortality Levels in Forests Affected by Mountain Pine Beetle Outbreaks. *Forests* 10: 811. DOI: https://dx.doi.org/10.3390/f10090811.

TIKVIĆ I, SELETKOVIĆ Z, UGARKOVIĆ D, POSAVEC S and ŠPANJOL Ž, 2008, Dieback of Silver Fir (Abies alba Mill.) on Northern Velebit. *Periodicum Biologorum* 110: 137–143.

TUCKER CJ, 1979, Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment.* 8: 127-150.

WARRAG EI, MALLICK J, SINGH RK and KHAN RA, 2019, Status of dieback of Juniperus procera (African pencil cedar) in natural stands and plantation in Alsouda Highlands, Saudi Arabia. *Applied Ecology and Environmental Research* 17: 2325-2338.

WERMELINGER B, RIGLING A, SCHNEIDER MATHIS D and DOBBERTIN M, 2008, Assessing the role of bark- and wood-boring insects in the decline of Scots pine (Pinus sylvestris) in the Swiss Rhone valley. *Ecological. Entomology* 33: 239–249.

ZINE EL ABIDINE A, LAMHAMEDI MS and AADEL T, 2013, Water relations of healthy and declining trees of Cedrus atlantica M. in Tabular Middle Atlas in Morocco. *International journal of tropical geology, geography and ecology* 37: 157-176.

Received 25 May 2025
Accepted 21 August 2025