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Assessment and monitoring of the health status of the Talassemtane fir forest (Western Rif, Morocco)

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Abstract. The endemic Talassemtane fir forest (northern Morocco) represents an ecosystem of great ecological and socioeconomic values, but has not been subject of any phytosanitary monitoring. This monitoring is crucial for providing information on forest health and supporting conservation actions. We sampled 200 trees from ten plots at the Talassemtane fir forest, measured their dendrometric features, and assessed forest dysfunction (branch mortality, leaf deficit, pruning, and biotic and abiotic damages) and stability indicators (Relative Crown Length and Index of Biodiversity Potential) from 2015 to 2018. The distribution of the sampled trees according to the circumference and total height classes revealed continuous stand regeneration. We found a gradual improvement in the crown status for almost all sampled trees. The pruning was low in 2015 and absent between 2016 and 2018. The most common damages were the abnormal colouring and consumption of leaves, especially by pine processionary moth and looper outbreaks. Lichens colonized about 40% of the sampled trees, reflecting environmental and microclimatic conditions, while biotic damages did not exceed 1.5% of the trees. The majority of plots present a high number of trees with a Relative Crown Length greater than half of the total height. The sampled trees showed significant vigour and high vitality, which would express a stable environmental equilibrium. The Index of Biodiversity Potential revealed a good forest capacity to host biodiversity and significant stability. Our pioneer permanent plot network should be continuously monitored to help the long-term management and conservation of this endemic ecosystem.

Keywords: Moroccan fir; *Abies marocana*; Talassemtane national park; ecosystem health; systematic monitoring; defoliation; permanent plot.

1. Introduction

The forest is a complex ecosystem (Gosselin & Paillet, 2016) containing plant and animal biocenoses which interact with each other, with their biotopes, thus promoting a dynamic equilibrium in perpetual renewal (Oughilass, 2012). Because of their longevity, forest ecosystems are subject to numerous environmental changes, the most profound and rapid of which are ongoing climate changes (Salhi et al., 2022), having impacts that can disrupt their fragile balance (Ghallab, 2018). Indeed, climate stressors act by various mechanisms and can deeply impact tree vigour (Bracalini et al., 2024). Maintaining the goods and services offered by forest ecosystems is essential for the living organisms and humans who depend on them.

Currently, at an international scale, monitoring forest health has become essential for the sustainable management of these ecosystems (Ferretti, 1997; Wang et al., 2020). To this end, different countries worldwide have developed monitoring programs which rely on networks of measurement and observation sites to assess forest health status, e.g., permanent plots (Oughilass, 2012). Monitoring networks of forest ecosystem health are expensive tools; in terms of planning, use and/or maintenance (Samalens 2009). The performance of these networks requires that all its components be optimized, in particular, plot and tree sampling as well as the scoring procedures, which often constitute the majority of the effort provided (Engeman, 1998 *in* Samalens, 2009). These networks use simple, quick-to-evaluate, and reliable indicators to provide information on forest health (Assali, 2009). The permanent assessment of forest health status is generally based on operational criteria which make it possible to assess earlier the signs (symptoms, changes, etc.) of possible declines in the vitality and vigour of forest stands (Assali, 2009; Oughilass, 2012).

The phytosanitary inventory is based on the determination of several descriptors such as those relating to the vitality and forest stability. The vitality of a tree is defined as its capacity to assimilate resources, develop, adapt to changes, and reproduce (Dobbertin & Brang, 2001). It can be estimated using numerous criteria such as branch mortality, leaf deficit, pruning, biotic and abiotic damages, etc. The health status of a tree or forest stand cannot be assessed by considering only the presence or absence of aggressors (climatic events, parasites, and pathogens, etc.), the manifestation of their activities (symptoms and damages) or the presence of dead or destroyed trees (Samalens, 2009), but also depends on the competition with other neighbouring trees (Ferretti, 1997). Competition occurs in many models of growth and forest dynamics (Prévosto, 2005). In Morocco, studies focusing on plant-plant competition are rare. In the Rif, it is only recently that this type of study was conducted by Navarro-Cerrillo et al. (2020) and Ben-Said et al. (2020, 2022). In addition, many biotic (e.g., parasites and pathogens) and/or abiotic (e.g., mineral deficiency and extreme climatic events) factors can lead to a decline in tree vitality (Castagne, 2022). They result in deterioration, deformation of organs or alteration of tissues, often compromising the vitality of affected trees (Laouina & Mahé, 2013). The estimation of tree vitality is a practical procedure, feasible in the field, and considered sufficient for a phytosanitary inventory (Oughilass, 2012).

In Morocco, forest health monitoring has for a long time been limited to some well-known defoliating insects such as *Thaumetopoea pityocampa* (Denis & Schiffermüller) (pine processionary moth), being the most studied Mediterranean defoliating species, and *Lymantria dispar* (bombyx disparate) (FAO, 2011; Bracalini et al., 2024). Since the monitoring of damages caused by other abiotic and biotic factors has rarely been carried out, the gaps in understanding the extent of damage caused are still huge for managers (Assali, 2009). For several years, the unexpected emergence of health problems has seriously affected several important Moroccan forests such as *Quercus suber* L. (cork oak) in the Moroccan Central Plateau (Dallahi et al., 2023), *Cedrus atlantica* (Endl.) Manetti ex Carrière (Atlas cedar) in the Middle Atlas (e.g., Aoubouazza, 2017), *Quercus ilex* L. (holm oak) in the High Atlas (Gharnit et al., 2025), and *Abies marocana* Trab. (Moroccan fir) (Laaribya & Alaoui 2025; Lamrhari et al., 2025). It is in this context that Morocco, through the Water and Forests Agency, has developed, with the assistance of FAO and the collaboration of the French Forest Health Department, a national strategy for monitoring and surveillance of the forest ecosystem health (Assali, 2009), which relied on three elements: the systematic network, phytosanitary monitoring, and specific systems for evaluating and monitoring the status of Moroccan forests' health (FAO, 2011). As a result, a plot (35°11.48' N; - 5°12.91' W) of the systematic network was installed by a specialist team from the Water and Forests Agency (National Forest Health Office and local forest managers) at the scale of the Talassemtane fir forest. However, a single plot was insufficient to draw statistical conclusions on the health status of this forest.

The Moroccan fir forest illustrates an original endemic ecosystem in the Western Rif landscape. It covers nearly 3760 ha (DPEFLCD, 2012) where the particular bioclimatic conditions have allowed its conservation (Oughilass, 2012). Melhaoui (1990) mentioned two main causes limiting the regeneration of *A. marocana*: water stress and overgrazing. However, recently, Ben-Said et al. (2020, 2022) reported remarkable regeneration dynamics of *A. marocana* and *C. atlantica*. Moreover, Castello et al. (2016) concluded that *A. marocana* populations appear to be structurally sustainable.

However, this endemic ecosystem has not been subject to any phytosanitary monitoring, which raises many questions about its current health status, which thus should be urgently assessed, as long as its sustainable management presupposes objective knowledge of its dynamic. Our present field-based study aims to assess the health status of the Talassemtane fir forest. Indeed, we visually estimated the status of the trees sampled within ten plots, during the period of vegetative activity over four years (2015 to 2018), by monitoring certain criteria (leaf deficit, branch mortality, and pruning), along with monitoring, for one year, other symptoms and phytosanitary damages (e.g. abnormal colouring, deformation of branches and barking of the trunk), inferring their potential causes, as well as the evaluation of the equilibrium of the Talassemtane fir forest, through the measurement of two ecosystem stability indices.

2. Materials and methods

2.1. Sampling of plots and trees

In 2012, Oughilass developed three grid scenarios (1 km x 1 km, 2 km x 2 km and 4 km x 4 km) to analyse their representativeness of the entire Moroccan fir forest (Talassemtane and Tazaout). The author showed that a large part of the forest escapes sampling for the 2 km x 2 km and 4 km x 4 km scenarios, with respectively four and only one potential plot to be installed; while the systematic 1 km x 1 km grid, which consists of installing 31 potential plots, allows covering the total fir forest (Oughilass, 2012). Based on these results, we chose the 1 km x 1 km grid to collect the maximum amount of information in a representative manner. To create this systematic grid, we proceeded as follows (Fig. 1): i) based on the shapefile of the Talassemtane fir forest contour already established, we developed the theoretical square systematic grid of 1 km x 1 km using the "*Fishnet*" tool in ArcGIS software (version 10.2.2); and ii) the superposition of this shapefile (as a background) with that of the nodes of the 1 km x 1 km grid, where each node corresponds to the location of a sample plot. Based on this grid, we identified 28 potential plots (Fig. 1).

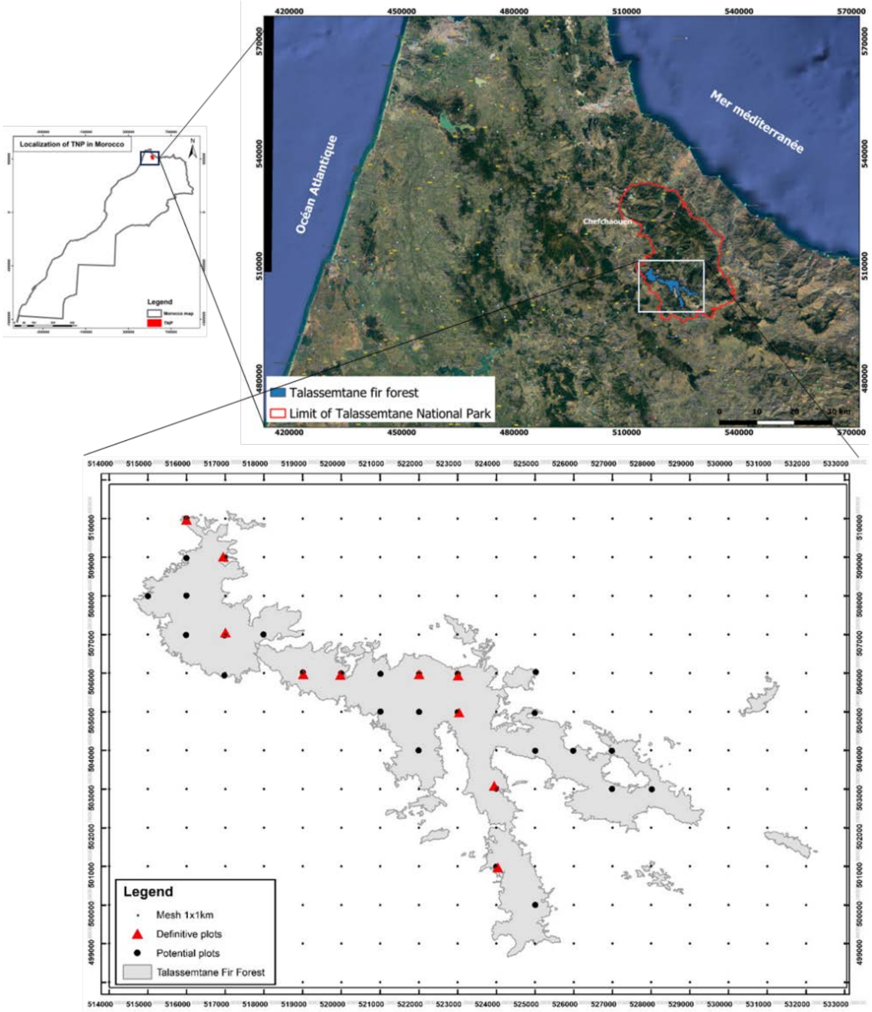


Figure 1. The 1 km x 1 km grid scenario at the Talassemtane fir forest showing the location of the 28 potential plots (black), including the ten (red) sampled plots in the field.

The choice of plots and sample trees was generally carried out according to the protocol standardized by the national forest health monitoring and surveillance strategy implemented in Morocco, which proved to be an effective tool for forest surveillance (Ramzi et al., 2009). After the setup of the systematic 1 km x 1 km grid, we positioned the potential plots (planned before installation; Fig. 1) at the nodes of the grid and identified their coordinates, then they were established on the topographical map at 1/50,000 before being installed in the field. We identified 28 potential plots across the entire study area (Fig. 1). In the field, we used the global positioning system (GPS) to precisely identify the points marked on the topographical map. The prospection and plot installation were carried out during May, 2015.

The observation plots installed met two criteria (Assali, 2009): i) they are located in the fir forest, with an area of at least 0.5 ha; and ii) they contain, within a maximum of 60 m radius, at least twenty living stems, of all woody species, dominant or co-dominant, of all circumferences, with a height greater than 1 m, and whose crown is not broken.

The installation of the systematic network resulted in the effective materialization of only ten observation plots on the field (Fig. 1). Indeed,18 of the 28 potential plots were excluded because: i) some of them do not meet the two criteria mentioned above; ii) their inaccessibility due to very perilous topography (cliffs, summit, ridge); and iii) the high density of forest stands (tree crowns are not observable at the ground level).

The plots to be installed were chosen so that they included a fixed number of trees and not a fixed area, mainly due, on the one hand, to the possibility of lacking the required number of trees to be observed on a plot with a fixed surface area (Assali, 2009), and on the other hand, to meet the requirements linked to the compensation of felled or dead trees by other trees to ensure the network sustainability (Ferretti, 1997). To have statistical robustness, we sampled twenty stems per plot (Ramzi et al., 2009). In the field, the centre of each plot was marked using a strip of yellow paint around the trunk at breast height (1.30 m), and the first sample stem chosen (1) was the one closest to the centre. Then, the neighbouring trees of the first tree spotted were numbered from 2 to 20, moving away from them in a spiral manner (Ramzi et al., 2009).

In each plot, we determined stationary data (coordinates, slope, altitude, and aspect), stand type (pure or mixed)), as well as tree attributes (species, circumference at 1.30 m, total height, phytosanitary status: healthy, declined, or dry tree). Table 1 summarizes the main characteristics of the ten plots. The majority of plots are oriented towards the northwest and north. Five plots (2, 4, 7, 8, and 10) have steep slopes (≥ 32°) while the others have moderate slopes (Table 1).

Table 1. Geographic and topographical characteristics of the ten sampled observation plots.

Plots	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Latitude (N)	35°10926	35°12796	35°14542	35°15356	35°15360	35°15428	35°15437	35°16413	35°18438	35°19044
Longitude (W)	-5°13475	-5°13622	-5°14559	-5°14569	-5°15654	-5°17919	-5°18961	-5°21169	-5°21098	-5°22276
Elevation (m a.s.l.)	1610	1694	1813	1552	1504	1640	1667	1810	1706	1658
Aspect	North-west	South-east	East	North	North-west	North-west	North	North	South-east	North-east
Slope (°)	24	35	30	36	24	18	36	35	26	32

For dendrometric measurements, we measured the circumference at breast height (1.30 m) and the total height of the sampled trees using a measure tape and the lumberjack's cross, respectively. These measurements were made only the first time when we installed the plots.

2.2. Phytosanitary inventory

Each sample tree was visually examined according to the standardized protocol of Ramzi et al. (2009). For this phytosanitary inventory, two categories of data were estimated: descriptors related to the apparent forest vitality, and descriptors of the ecosystem stability. To estimate the vitality of a tree, we determined four criteria: branch mortality, leaf deficit (i.e., defoliation), pruning, as well as biotic and abiotic damages, while identifying, if possible, the causes of these damages. For stability, we determined two indices: the index of Relative Crown Length (RCL) and the Index of Biodiversity Potential (IBP).

Branch mortality (a branch is dead if it no longer has leaves in summer) was estimated for the notable crown (parts of the crown that are generally exposed to light; Ramzi et al., 2009). The leaf deficit was estimated from the percentage of foliage missing at the notable crown level, compared to an “ideal” reference tree (Fig. 2), having complete foliage (defoliation is 0%), and growing in the same stationary and silvicultural conditions where the observation is carried out (Ramzi et al., 2009; Dogan Ciftci et al., 2024). The defoliation is considered severe when the percentage of leaf loss exceeds 25% (Ferretti, 1997; Landmann & Bouhot-Delduc, 1995). Thus, the sampled trees were grouped into two categories: trees presenting a leaf loss of less than 25% and those greater than 25%.

Figure 2. Examples of “ideal” reference trees (black arrow) of *Abies marocana* (Photo by Lamrhari H., 2018).

To determine the effect of topographical factors (altitude, aspect, and slope) and stand type (pure or mixed) on trees with defoliation less or greater than 25%, a multivariate analysis of variance (MANOVA) and a one-way analysis of variance (ANOVA) were conducted. To this end, we took into account the following factors as independent variables: altitude (two classes: 1500–1700 m and 1700–1800 m), slope (three classes: 10–20%, 21–30%, and 31–40), aspect [north, northwest, southeast, east, and northeast], and the stand type [pure *A. marocana* stand (Am), mixed stand: *A. marocana* and *Quercus rotundifolia* Lam. (green oak) (Am–Qr), *A. marocana* and *C. atlantica* (Am–Ca), and *A. marocana*, *Pinus nigra* Arnold subsp. *mauretanica* (Maire & Peyerimh.) Heywood (black pine), and *P. pinaster* subsp. *hamiltonii* (Ten.) H. del Villar var. *maghribiana* H. del Villar (Maghreb maritime pine) (Am–Pn–Pm)], and as dependent variables, the two categories of trees (defoliation lesser or greater than 25%). The normal distribution of trees with defoliation less than or greater than 25% in each class of independent variables was tested using the Shapiro-Wilk normality test (Shapiro & Wilk, 1965), while the homogeneity of variance was checked using the Levene test (Levene, 1960). All statistical analyses were performed using IBM SPSS Statistics 20.0 software (Armonk, NY, USA).

Pruning refers to an action of limbing or topping carried out by the local population for firewood and livestock feed, thus reflecting a common anthropic action in Moroccan forests, which should be systematically monitored (Assali, 2009) to assess its impact on the forest health status. For other observed damages, the assessment was carried out using the description of (Oughilass, 2012): i) the type of visible and abnormal symptoms; ii) the affected organ (leaves, twigs, branches and trunk); and iii) the quantification of damages. Moreover, the causal agents were identified when possible, according to Ramzi et al. (2009).

In our study, this phytosanitary inventory was conducted from mid-June to mid-July in the summer of 2015, 2016, 2017, and 2018 for certain descriptors (i.e., leaf deficit, branch, and pruning mortality), and the summer of 2018 for others (i.e., biotic and abiotic damages or symptoms and causal agents).

The index of Relative Crown Length (RCL) is an indirect measure of competition and reflects the tree’s vitality and vigour, to the extent that vigour increases with the length of the crown (Becker et al., 1994). Since the direct measurement of competition is problematic; this is why the RLC, due to the simplicity of its implementation, is widely used (Prévosto, 2005). The RCL represents the green part of a tree, it is obtained by the ratio of the crown length (CL) to the total height of each tree (H_{total}) (Lhafi et al., 2017):

$$\text{RCL (\%)} = \frac{CL}{H_{total}}$$

According to the classification of WSL (1994), the sampled trees were grouped into three classes: i) long crown: the CL value exceeds half of the H_{total}; ii) average crown: CL is between 1/4 and 1/2 of the H_{total}; and iii) short crown: CL is less than 1/4 of the H_{total}.

The Index of Biodiversity Potential (IBP) evaluates the potential taxonomic diversity of a forest stand, which corresponds to its capacity to support species (plants, animals, fungi) independently of their actual presence (Larrieu & Gonin, 2008). The IBP makes it possible to better take into account biodiversity in the sustainable management of European temperate forests, subsequently extended to the Mediterranean region (Larrieu & Gonin, 2008). It has been applied in several temperate regions (e.g., Zeller et al., 2022). To evaluate the IBP, we materialized specific plots (called IBP plots hereafter) within the ten phytosanitary observation plots of the systematic network, at the rate of one IBP plot per phytosanitary plot. The sampling of the IBP plots was carried out according to the procedures described by Gonin and Larrieu (2013, 2015, 2017). Indeed, the IBP survey was based on the determination of the score of ten factors, seven of which are management-related factors and the other three are context-related factors (Larrieu & Gonin, 2008). The results are represented as graphs that can be produced in a spreadsheet (file downloadable from the website of the "*Centre National de la Propriété Forestière*") (https://www.cnpf.fr/nos-actions-nos-outils/outils-et-techniques/ibp-indice-de-biodiversite-potentielle/realiser-des) [Accessed at 02/10/2018].

3. Results

3.1. Composition of the sampled plots

The woody species present in the plots are fairly well representative of the species present in the Moroccan fir forest: i) conifers include *A. marocana* which was the most abundant species (65%), followed by *C. atlantica* (11%), in addition to other less abundant species, that are *P. mauretanica* (4%), *Juniperus oxycedrus* L. (prickly juniper; 2.5%) and *Taxus baccata* L. (Common Yew; 0.5%); and ii) broadleaved trees include *Q. rotundifolia* (6.5%), *Acer opalus* subsp. *granatense* Mill. (Spanish Maple, 10%), and *Crataegus laciniata* Ucria (cutleaf hawthorn; 0.5%) (Fig. 3).

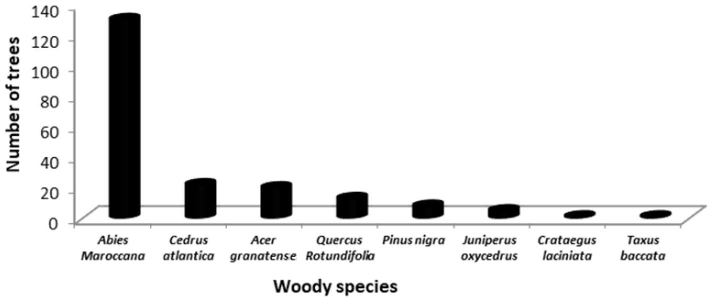


Figure 3. Total number of woody species present in the ten sampled plots.

Plots 1, 4, 5, 6, 7, 8, 9, and 10 are all dominated by *A. marocana*, while plot 3 by *C. atlantica* (85%), and plot 2 is codominated by *A. marocana* and *A. granatense* with a proportion of 45% each (Appendices 1 and 2).

3.2. Dendrometric characteristics of the sample trees

The abundance of *A. marocana*, other conifers, and broadleaved trees varies depending on the circumference classes (Fig. 4). Indeed, *A. marocana* is present in different classes, with a higher percentage (15%) in the 61–80 cm class and lower (1%) in the 201–220 cm class. Coniferous trees follow a perfectly similar trend. Beyond 180 cm in circumference, the number of coniferous trees, including *A. marocana*, clearly decreases. Broadleaved trees are absent in classes 5–20, 201–220, and 221–240 cm with a high abundance in the 81–100 cm class and low in the 41–60 cm class (24% and 3%, respectively). Beyond 140 cm of circumference, the number of broadleaved trees decreases (Fig. 4).

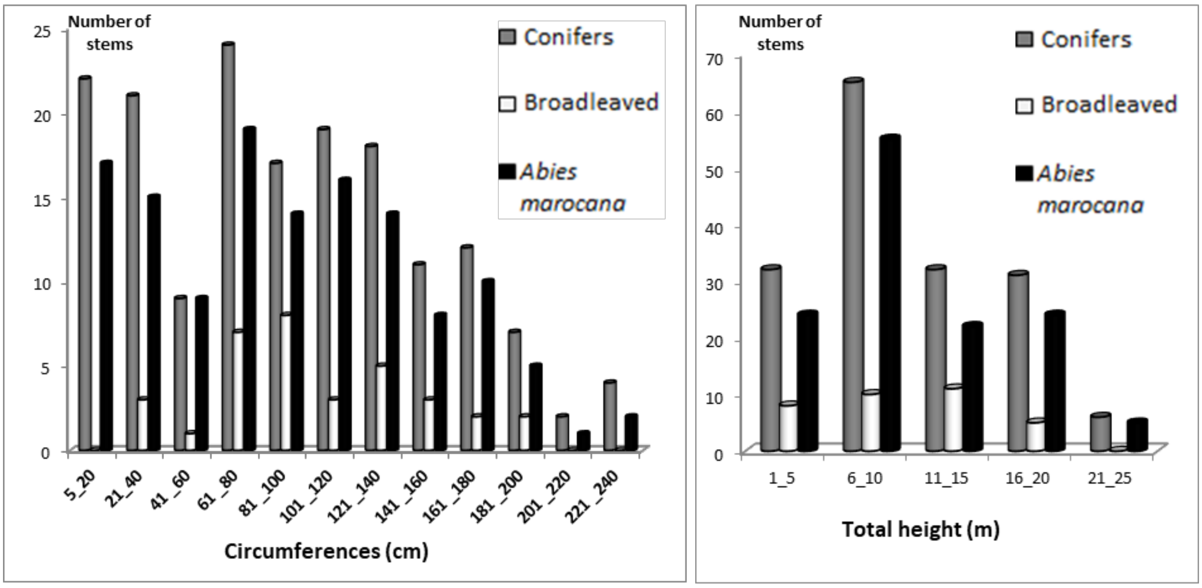


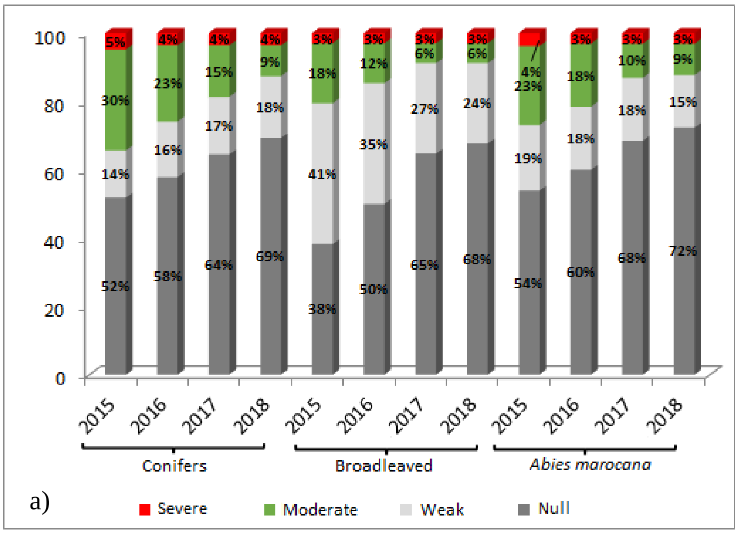
Figure 4. Distribution of the total numbers of *A. marocana*, other conifers and broadleaved trees according to classes of circumference at 1.30 m (cm) and total height (m) in all the observation plots. Conifers include *C. atlantica*, *P. mauretanica*, *J. oxycedrus*, and *T. baccata,* while broadleaved trees are represented by *Q. rotundifolia*, *A. granatense*, and *C. laciniata*.

As for the total height distribution, *A. marocana* and other conifers trees are present in all height classes (Fig. 4), with a higher abundance in the 6–10 m class (42.31% and 39.16% of *A. marocana* and other conifers, respectively), and lower in the 21–25 m class (3.85% and 3.61% of *A. marocana* and other conifers, respectively). Broadleaved trees have relatively similar abundances in the 6–10 m and 11–15 m classes, are absent in the 21–25 m height class, and low in the 16–20 m class. As a result, it appears that tall trees were less represented for both conifers (including *A. marocana*) and broadleaved trees (Fig. 4).

3.3. Phytosanitary inventory

3.3.1. Evolution of branch mortality and defoliation of the sample trees

During the study period (2015 to 2018), the number of dead branches in notable crowns was determined in the observation plots. In 2015, 161 trees (i.e., 49% of the stems sampled), all species combined, showed signs of branch mortality (Fig. 5a). In 2018, this number decreased to 98 (i.e., 30%). Taken separately, for the null class, the mortality of *A. marocana* branches, other conifers, and broadleaved trees increased from 54%, 52%, and 38% in 2015 to 72%, 69%, and 68% in 2018, respectively. For the severe class, the proportion of *A. marocana* and other conifers decreased from 4% and 5% in 2015 to 3% and 4% in 2018, respectively; while it remained stable at 3% between 2015 and 2018 for broadleaved trees (Fig. 5a). The percentages of the two other classes have also decreased for all the sampled trees.



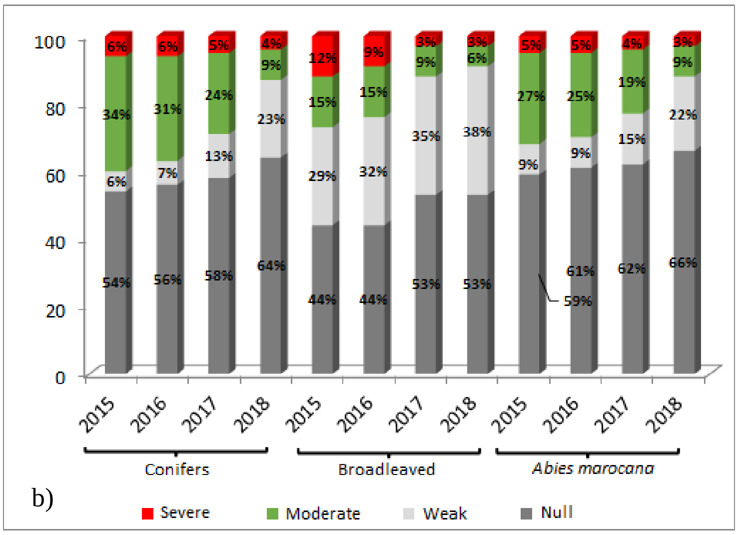


Figure 5. Evolution of the percentage of branch mortality (a) and leaf deficit (b) observed in all trees sampled (all species combined) in the ten plots studied from 2015 to 2018.

For the null leaf deficit class (defoliation of 0 to 5%), the proportion of *A. marocana* trees and other conifers gradually increased during the study period, from 59% and 54% in 2015 to 66% and 64% in 2018, respectively (Fig. 5b). For broadleaved trees, trees showing null leaf deficit remained stable at 44% between 2015 and 2016 and increased to 53% in 2017, then stabilized in 2018. The second largest category observed in conifers (including *A. marocana*) was moderate (i.e., 26% < defoliation < 50%). Indeed, the proportion of moderately damaged trees *A. marocana*, other conifers, and broadleaved decreased from 2015 to 2018. A progressive increase in the proportion of trees in the weak defoliation class was observed for all species studied. For the last class, only a small proportion of *A. marocana*, other conifers and broadleaved trees showed severe defoliation, but it decreased during the observation period (Fig. 5b).

The average values of trees (all species combined) showing defoliation less than 25% and of those greater than 25% were high in altitude classes of 1500–1700 m and 1700–1800 m, slopes of 21– 30% and 31–40%, north/northwest and south-east aspects, and pure *A. marocana* (Am) and mixed *A. marocana–Q. rotandifolia* (Am–Qr) stands, respectively (Appendix 3). Conversely, they are low in altitude classes of 1700–1800 m and 1500–1700 m, slopes of 10–20%, eastern and north-eastern aspects, and mixed *A. marocana–Q. rotandifolia*, mixed *A. morocana–C. atlantica*, *A. marocana–P. mauretanica–P. maghribiana* stands, respectively (Appendix 3).

The results of the MANOVA revealed that altitude, slope, aspect, and stand type significantly explain respectively 52%, 22%, 37% and 83% of the variations observed in the two defoliation categories (i.e., less or greater than 25%), and the *p*-values are less than 0.05 (Tab. 2). This indicates that the studied environmental variables and stand types have a significant effect on tree defoliation.

Table 2. Results of the MANOVA test to assess the effect of environmental factors on tree defoliation.

Independent variable	Wilks' Lambda	F	P-value	Partial eta-squared
Altitude	0.48	9.18	0.002	0.52 (52 %)
Slope	0.61	3.65	0.011	0.22 (22 %)
Aspect	0.39	6.56	0.000	0.37 (37 %)
Stand type	0.17	86.78	0.000	0.83 (83 %)

p ≤ 0.05: significant; p ≤ 0.01: highly significant; p ≤ 0.001: very highly significant

The ANOVA showed a very highly significant (p ≤ 0.001) effect of aspect and stand type and a significant (p ≤ 0.05) effect of slope on trees showing defoliation less than 25% (Tab. 3). While it revealed a very highly significant effect (p ≤ 0.001) of altitude and a significant effect of stand type on trees showing defoliation greater than 25%.

Table 3. Results of the ANOVA test to evaluate the effect of environmental variables on tree defoliation.

Environmental variable	Percentage of defoliation	F	P-value
Altitude	< à 25 %	0.065	0.802
	> à 25 %	19.29	0.000
Slope	< à 25 %	5.37	0.011
	> à 25 %	2.28	0.122
Aspect	< à 25 %	13.14	0.000
	> à 25 %	2	0.112
Stand type	< à 25 %	9.76	0.000
	> à 25 %	3.56	0.024

p ≥ 0.05: not significant; p ≤ 0.05: significant; p ≤ 0.01: highly significant; p ≤ 0.001: very highly significant.

3.3.2. Pruning, damages and symptoms assessment of the sampled trees

Out of the 200 trees sampled (all species combined), 27 were pruned in 2015, with a low intensity of pruning (Appendix 4). The majority of pruned branches are located in the lower part of the crowns. However, no crown cutting was observed from 2016 to 2018. Generally, conifers show less pruning than broadleaved trees. For trees, the most broadleaved species affected by pruning were *Q. rotandifolia* (17%) followed by *A. granatense* (9%). For conifers, *A. marocana* seems to be the most affected by pruning (7%), followed by *C. atlantica* (3%) and *J. oxycedrus* (1 %).

For other damages and symptoms, abnormal colouring was the most encountered symptom on the leaves of both conifers (including *A. marocana*) and broadleaved trees, i.e., 45% and 41%, respectively (Appendix 4), while the consumption of leaves by a defoliator was the most marked type of damage in broadleaved trees (56%) compared to all conifers (8%). Trunk injuries were more frequently noted in broadleaved trees (18%) than in conifers (7%). However, a very limited number of both tree groups showed breaks, deformation and peeling of branch bark, resin leaks and barking of the trunk and microphyllia (Appendix 4).

3.3.3. Assessment of lichen patterns and impact of pests on the sampled trees

Four biotic causes of damage were essentially noted on the studied trees: mistletoe (*Viscum album*), witches' brooms, insect nests (*Coccinellidae Latreille*, *Thaumetopoea pityocampa,* and *Cynips* L.), and insects (*Geometridae* Leach, *Apion* Herbst and *Carabidae* Latreille). Figure 6 illustrates the percentage of observed organisms associated with trees. Other damages were observed with a very low percentage, not exceeding 1.5% of trees. On the other hand, lichens (*Pseudevernia furfuracea* Zopf, *Evernia prunastri* Acharius and *Lecanora intumscens* Rabenh) colonize 40% of the stems recorded (all species combined).

Taken separately, we found that 54.62% of *A. marocana* trees hosted lichens, whereas only 0.77% showed the presence of insects or insect nests. *Abies marocana* was not affected by witches’ brooms or mistletoe. Other conifers also exhibited a high occurrence of lichens (48.8%), while insects (1.2%), insect nests, witches’ brooms and mistletoe (each 0.6%) were rarely observed (Appendix 5). Broadleaved trees were less frequently colonized by lichens (8.82%) and insect nests (2.94%).

It should be emphasized that lichens were recorded as bioindicators of environmental and microclimatic conditions rather than as harmful agents. Two lichen species were identified on *A. marocana* (branches, twigs and trunks): *Pseudevernia furfuracea* and *Evernia prunastri*. Their presence was locally associated with reddening and needle loss on colonized branches, while needles remained intact on non-colonized portions (Fig. 6 and 7).

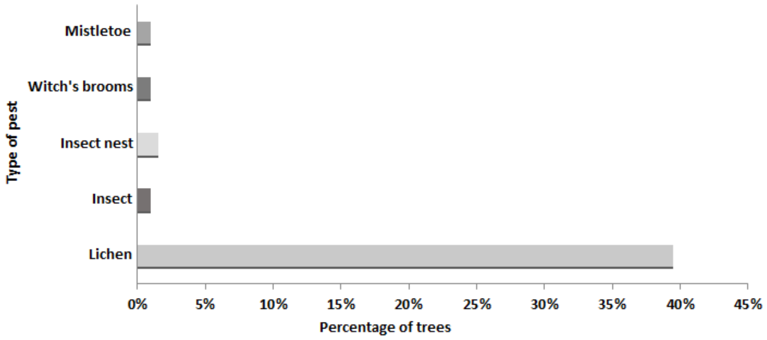


Figure 6. Percentage of observed organisms associated with trees (irrespective of the species concerned). Please note that lichens have been included in this graph as part of the organisms identified on the sampled trees, despite being bioindicators of environmental quality and tree physiological status.

Figure 7. Illustration of the proliferation of the lichen thallus on a branch of *A. marocana* (Photo by Lamrhari H, 2018).

3.3.4. Assessment of ecosystem stability

The distribution of sample trees by Relative Crown Length (RCL) classes shows that 92% of *A. marocana*, 93% of other conifers, and 79% of broadleaved trees had a long crown (RCL > 50%) (Fig. 8), while a very small proportion had a short crown with RCL < 25% (1% of conifers, including *A. marocana*, and 3% of broadleaved trees). In addition, all the observation plots had a high percentage of trees with a crown length greater than half of the total height (Appendix 9). Indeed, plots 3, 4, 6, and 8 contained only trees with a long crown, plots 1, 2, 7, and 9 are formed by two classes of RCL (long and medium crowns), and plots 5 and 10 presented the three RCL classes (long, medium and short crowns). This indicates that all the plots studied contain a high number of trees with satisfactory vigour.

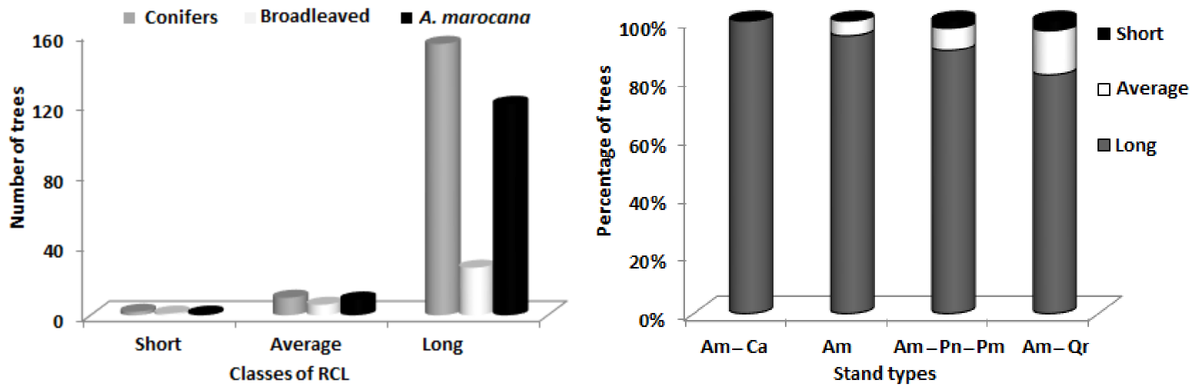


Figure 8. Distribution of the number of *A. marocana*, other conifers, and broadleaved trees by classes of Relative Crown Length (RCL) and of the percentage of RCL classes (all species combined) according to stand types. Am: *A. morocana*; Ca: *C. atlantica*; Qr: *Q. rotundifolia*; Pn: *P. mauretanica*, Pm: *P. maghribiana*.

Likewise, all stand types showed a high percentage of trees (all species combined) with long crowns (Fig. 8), especially the *A. morocana–C. atlantica* (Am–Ca) mixed stands, while this percentage is slightly reduced in *A. marocana–Q. rotandifolia* (Am–Qr) mixed stands. In addition, the percentage of trees with a short crown was very low and present mainly in the "Am–Qr" stands. Here, it appears that all stand types also contain a significant number of trees which are characterized by satisfactory vigour.

According to the leaf deficit, the average RCL was high for 93% of *A. marocana*, 94% of other conifers, and 91% of broadleaved trees that have a null foliar deficit, while it was low (i.e., 55%, 22% and 57%, respectively) for those showing severe defoliation (Appendix 10). Indeed, the studied conifers (including *A. marocana*) showed better vitality for RCLs above 80%, and the best vitality among broadleaved trees was noted for RCLs above 70%.

For the Index of Biodiversity Potential (IBP), and taking into account management-related factors by plot, we emphasize from the graphs in Appendix 11 that:

- The richness of autochthonous tree genera is maximum for all the plots, half of which (plots 1, 3, 5, 6, and 8) are characterized by the presence of more than 5 genera (*Abies, Cedrus, Pinus, Quercus, Juniperus, Pistacia* and *Crataegus,* etc.) (Appendix 12a);

- The presence of four vertical layers in all the plots (except for plot 7 with 3 layers: shrub, low canopy, and high canopy) (Appendix 12b);

- Large standing deadwood (≥ 120 cm of circumference) was high in plots 2, 8, and 10, present with 1 to 2 stems/ha in plots 1, 5, and 6, while absent in the remaining plots (Appendix 12c). Large lying deadwood was high in plots 8 and 10, present with 1 to 2 stems/ha in plots 1, 5, 7, and 9, and absent in the rest (Appendix 12d). Very large living wood (≥ 220 cm of circumference) was generally well represented in all plots (Appendix 12e), with 5 stems/ha in plot 1.

- The number of living trees with at least one tree-related microhabitat was 1 to 4 stems/ha in plots 1, 2, 5, and 6 to 10, while absent in the rest (Appendix 12f, g).
- Openness is well represented in plots 2, 3, 5, 6, and 8 as clearings (2 and 5), edges (3), and gaps (6 and 8). Moreover, small clearings are observed in the rest of the plots.

For context-dependent factors, *A. marocana* forest is a relict forest (Appendix 13). The aquatic environment only occurred in plot 2. The presence of rocky habitats (Appendix 14a,b) was high in plots 6, 8, and 10. However, only one type of rocky environment exists in the other plots (rocky outcrops in plots 1 and 9, scree in plots 2 and 4, and chaos of blocks in plots 3 and 7) (Appendix 14c).

According to the stand type, for the “Am–Qr” stands, plot 10 contains fairly high IBP, whereas plots 1 and 9 have average biodiversity (Appendix 15) because they were less rich in lying deadwood and rocky environments compared to the former. For the “Am” stands, plot 8 had a strong IBP, while plots 2 and 6 had a fairly strong IBP. On the other hand, plot 7 is characterized by an average potential biodiversity, due to the presence of small clearings and the absence of standing dead trees, herbaceous, and shrub layers. For the “Am–Pn–Pm” stands, plots 4 and 5 are characterized by average and fairly high IBP, respectively. Plot 4 had small clearings, lying dead trees, and micro-habitats were absent. Finally, plot 3 (i.e., Am–Ca) presented an average IBP since standing, lying dead trees, and micro-habitats were absent.

4. Discussion

In our study, we targeted a certain number of indicators of forest health to assess, for the first time, the phytosanitary status of the Talassemtane fir forest.

4.1. Dendrometric characterization of the sample trees

The analysis of the frequency distribution of the circumference at 1.30 m and the total height of conifers and broadleaved trees showed that the former was present in all dendrometric classes, while the latter was absent in the classes 5–20 and 201–240 cm of circumference and in class 21–25 m of total height (Fig. 4). This indicates an active stand dynamic of the study plots, mainly for conifers, compared to previous reports made by Melhaoui (1990) that indicated the dominance of old trees and the absence of middle circumference classes. In addition, our field observations highlighted a high abundance of coniferous trees less than 10 cm in circumference and 0.5 m in height in almost all plots. Similar results were recently reported by Navarro-Cerrillo et al. (2020) and Ben-Said et al. (2020, 2022). Navarro-Cerrillo et al. (2020) mentioned the absence of legal logging, domestic wood collection, and grazing in the Talassemtane National Park. On the other hand, we observed a low number of large trees for all the species recorded (Fig. 4), which can be explained by the fact that the Rif forests were excessively overexploited during the protectorate period (Benabid, 2002).

4.2. Health status of the Talassemtane fir forest

The evolution of branch mortality observed in the sampled trees during the study period (2015–2018) showed a progressive improvement since 2016, with essentially a decrease in the proportion of trees in classes 2 and 3 (i.e., moderate and severe branch mortality), and an increase in that of classes 0 and 1 (null and low; Fig. 5). This could be linked to the improvement in climatic conditions (particularly precipitation) during the 2016–2018 period and the reduction in anthropogenic pressure (Navarro-Cerrillo et al., 2020; Lamrhari et al., 2025). These results may indicate that there was a gradual improvement in the forest health during the study period and that the severe leaf deficit (i.e., class 3) can be reversible. The spatio-temporal evolution of NDVI (Normalized Difference Vegetation Index) showed a decrease in declining vegetation over time, with very low and low NDVI values occupying an area of 369.27 ha in 2009, but reduced to 100.08 ha in 2019 (Lamrhari et al., 2025). Similar results have been reported in a recent study by Laaribya and Alaoui (2025), who found that the NDVI and EVI (Enhanced Vegetation Index) values have increased between 2001 and 2024 in the western part of the Talassemtane National Park, including our study area, although some other eastern parts of the park showed declining trends. In the Türkish Mediterranean region, Dogan Ciftci et al. (2024) also observed no increasing defoliation during the 2008–2020 period, despite the high interannual variability of precipitation, with *Cedrus libani* showing the lowest defoliation rate, and thus being more resistant to climate variabilities and drought. In Italy, Bussotti et al. (2024), however, found a significant increase in defoliation and mortality since 2010 in conifers and broadleaves. These contrasting results indicate that defoliation is a context-dependent phenomenon.

In addition, the leaf deficit of *A. marocana* generally was very close to that observed for the other conifers, unlike broadleaved trees. Bussotti et al. (2024) also found that conifers and broadleaves showed slightly different trends in defoliation, with the former experiencing a significant increase in defoliation during the 2001-2022 period, while the latter did so during 2010-2022. In the temperate zones, it has been reported that the most important defoliation occurrences overlapped with the drought periods, and only partly recuperating later (Bussotti et al., 2024). Recent studies have shown that *A. marocana* growth is limited by precipitation deficit and temperature increase (Ghallab, 2018; Navarro-Cerrillo et al., 2020; Alaoui et al., 2021). Studies carried out on several species within monitoring networks across Europe have shown that growth is negatively and significantly linked to defoliation (Jacquet et al., 2012). In France, Goudet and Nageleisen (2011) obtained similar results for *Fagus sylvatica* L. (European beech) forests, showing a recovery of the tree crown because climatic conditions became better, after having suffered from a strong leaf deficit. Additionally, according to Goudet and Nageleisen (2011), in the case of a punctual disturbance over time, and growth conditions become favourable to vegetation with the absence of an aggravating factor, trees can gradually recover if they are sufficiently vigorous or little affected by previous stress. On the other hand, it has been suggested that trees with a very severe leaf deficit (> 75%) are most likely to die in the short term (Mirabel & Gaertner, 2023).

The results of the one-way analysis of variance revealed that the stand type and the topographical variables (i.e., altitude, aspect, and slope) have a significant effect ($p \leq 0.05$) on tree defoliation (Tab. 2). Trees showing a leaf deficit less than 25% and those greater than 25% were abundant in pure *A. marocana* (Am) and *A. marocana–Q. rotundifolia* (Am–Qr) mixed stands, respectively (Tab. 3). In the latter, we suggest that there is a competition between trees for resources necessary for their growth (light, water, and nutrients). These stands present a relatively closed canopy. Aafi (1995) noted that these stands generally show vegetation cover of around 90%, which could limit the availability of resources, especially for the understorey trees. Ben-Said et al. (2020) found that dense stands contained the highest density of suppressed and dead trees, without demonstrating a significant intraspecific competition in pure *A. marocana* stands. Similarly, Gharnit et al. (2025) found that mixed holm oak shrubs suffered from significant decline than pure shrubs in the central High Atlas. Indeed, a denser stand will potentially have a higher mortality rate due to a more intense uptake of water resources, which will be quickly depleted (Linares et al., 2009).

In addition, trees showing a leaf deficit greater than 25% were more abundant in the 1700–1800 m altitudinal range. At high altitudes in Talassemtane National Park, precipitation and snow amounts are significant (Ghallab, 2018). In France, Tallieu (2020) linked the degradation of the crown of *Picea* (spruce) stands at high altitudes to thermal constraints. In our study area, Ben-Said et al. (2020) found that tree density was higher at higher elevations and associated with a high abundance of dead trees. Moreover, we found that on the north and northwest slopes, the abundance of stems with less than 25% of leaf deficit is higher compared to the southeast slope (Tab. 3). This result supports the prosperity of *A. marocana* on the northern and western slopes (Melhaoui, 1990; Aafi, 1995). In Algeria, Guit et al. (2016) found that *P. halepensis* shows greater growth on the northern than southern slopes in the Senalba Chergui massif, where evapotranspiration is more intense (Linares et al., 2009). Generally, in Mediterranean environments, north-facing slopes favour vegetation development (Rodrigues et al., 2024). We found that the number of trees with more than 25% of leaf deficit was higher on steep slopes (Tab. 2; Appendix 3). Indeed, the local topography plays an important role since it strongly water conditions of the site (Cailleret, 2011). Therefore, our results corroborate the significant influence of slope, observed in numerous studies on different species and carried out at different spatial scales (e.g., Marty et al., 2019).

The results showed that tree pruning by the local population was low in 2015 and was not practised in subsequent years. This can be explained by the positive impact of the "*Mouhsine ovens*" initiative, established by the DPEFLCD of Chefchaouen, which consisted of the distribution of 2000 oven units (150 units/year) to forest users, between 2015 and 2024, and aimed at mitigating forest resources overlogging by the rural population. In addition, the DPEFLCD (2012) reported that since the establishment of the Talassemtane National Park, the livestock there has gradually been reduced and is limited in certain places to a very limited number of cattle.

For the other damages recorded in the fir forest, abnormal colouring constitutes the most common symptom encountered on conifers (45% of their total number), but the proportion of trees showing discolouration of more than 10% was relatively low (Appendix 4). Indeed, any alteration in the foliage colour is not necessarily considered abnormal or dramatic because this phenomenon is frequently reversible (Roloff, 1987), mainly due to nutrient depletion, but can also be induced by atmospheric pollutants (Landmann & Bouhot-Delduc, 1995), pathogen outbreaks and/or unfavourable climatic conditions (Cailleret, 2011). For example, in the Brussels Sonian Forest, 68% of *Quercus robur* L. (pedunculate oak) trees showed abnormal colouring in 2012; however, in 2016, they regained their normal colouring (Hugues, 2017).

For broadleaved trees, the consumption of leaves by defoliating insects constitutes the most marked damage in our study area (56% of their total number), but trees showing more than 10% of leaf consumption were very low (Appendix 4). This could indicate that there are few defoliators in the studied plots. The other damages (i.e., microphyllia and breakage, deformation, bark peeling of branches and injuries, resin flow, and trunk barking) were only observed on a limited number of conifers and broadleaved trees (i.e., 23.5 % of all the sampled trees; Appendix 4). Similar results were obtained by Assali (2009) for conifers [*C. atlantica*, *Tetraclinis articulata* (Vahl) Masters (Sandarac tree), and *J. oxycedrus*] and broadleaved [*Q. rotundifolia, Q. faginea* (zen oak), and *Q. suber*] in the Middle Atlas. Taken separately, *A. marocana* is, however, the species most affected by damage (Appendices 4 and 5). This may be because this species is the most sensitive of the codominant conifers, such as *C. atlantica* and *P. mauretanica*, to the wet and cold conditions of the previous late winter, and the latter two species have less responsiveness to climate (Navarro-Cerrillo et al., 2020). Unlike *C. atlantica,* growing on all types of soil, *A. marocana* is essentially limited to moist brown forest soils on calcareous-dolomitic substrates (Alaoui et al., 2021). For the other species present in the fir forest, we can point out that *J. oxycedrus* is remarkably resistant to drought and can develop in semi-arid bioclimates, with plasticity about the soil nature and fertility (Ouaar et al., 2022). *Q. rotundifolia* also has bioclimatic and edaphic plasticity (Barbero & Loisel, 1980). In Italy, Bussotti et al. (2024) found no significant defoliation in holm oak, which has contributed to the ability of sclerophyllous species to manage hydric stress recovery during drought periods. *T. baccata* can develop on either calcareous or basalt substrates (in the Rif and the Middle Atlas, respectively; Romo et al., 2017), and the distribution area of *A. granatense* is vast and widespread from the mountains of Algeria to the Middle Atlas in North Africa (Dobignard, 2002).

Furthermore, lichens colonized 40% of the sampled trees. Insect nests and other damage causes (i.e., mistletoe, witches' brooms, and insects) did not surpass 1.5% of all trees (Fig. 6, Appendix 6). Similar results were reported by the HCEFLCD (2017) in the Middle Atlas cedar forest, where 71% of the stems were colonized by lichens while witches' brooms and caterpillar nests only infected a limited number of trees.

We mainly observed the presence of insect nests, mistletoe, witches' brooms and defoliating insects [*T. pityocampa, Lambdina fiscellaria fiscellaria* (Guen.) (hemlock looper)] on trees with a leaf deficit greater than 25%. In France, Cailleret (2011) found that the reduction in the leaf area of *A. alba* is induced by mistletoe. In Algeria, repeated attacks by *T. pityocampa* led to massive defoliation or even total leaf loss of *C. atlantica* (Sebti, 2011). Furthermore, Martel (1999) highlighted that the stem defoliation of *Abies balsamea* (L.) Mill. (Balsam fir) by the hemlock looper affected their radial growth over a long period. Witches' brooms are rusts that cause excessive development of branches, from the same point on a branch, which gives it an abnormal appearance and causes stunting of the tree, but rarely its death (Solla et al., 2006). Tallieu (2020) attributed the deformations of *A. alba* in France to the presence of mistletoe or witches' brooms. Mistletoe is a hemiparasite that takes water and nutrients necessary for its growth from the raw sap of the host tree (Cailleret, 2011), which can cause a reduction in the rate of branching and the needle length (Rigling et al., 2010), thus, crown degradation and the weakening of the infested tree (Durand-Gillmann et al., 2014). *T. pityocampa* moth feeds on the needles (which turn yellow) of *Pinus* spp. and *Cedrus* spp. (Brinquin & Martin, 2017). This can lead to a considerable reduction in radial growth with a significant weakening of the trees during the attack, but also in subsequent years (Buntgen et al., 2009). In our study area, it appears that witches' brooms and mistletoe are respectively associated with branch deformations and microphyllia observed in *P. mauretanica*, while the abnormal colouring observed on an *A. marocana* stem and at the shoot tips of a *C. atlantica* stem were assigned to *L. fiscellaria* and T. *pityocampa*, respectively. In general, conifers were relatively more affected than broadleaved trees, which is in line with previous studies (e.g., Bussotti et al., 2024).

Lichens are highly resistant epiphytic cryptogams capable of surviving significant temperature variations and resisting very strong desiccations (Adli & Dennine, 2019). Given their slow growth, lichens tend to develop on branches with low turnover and stable bark. Their presence is therefore favoured on older or slow-growing branches, as well as in more open canopies that receive more light (Johansson & Ehrlén, 2003). Our results show that lichens are ubiquitous across all circumference classes, from the smallest class (5–20 cm) to the largest (240 cm; Appendix 7), and large trees are all colonized. Lichens colonize all *A. marocana,* presenting a leaf deficit of classes 2 and 3, and branch mortality (Appendix 8). These results are in line with those observed in *Q. ilex*, *Q. pyrenaica* Willdenow (tauzin oak; Bouaid & Vicente, 1998) and *Picea mariana* Mill., Britton, Sterns & Poggenb. (Black spruce) in Canada (Simard & Payette, 2001). Therefore, the apparent link between the presence of lichens and defoliation should be interpreted as a correlation rather than a causal relationship. Lichens do not invade the crown following defoliation, nor do they cause it, but both phenomena can result from similar structural and microclimatic conditions. A comparable case was reported in the Middle Atlas cedar forest by Et-Tobi (2008).

4.3. Stability of the Talassemtane fir forest

Concerning the relative crown length (RCL) index, we noted a high percentage of trees having an RCL greater than half of the total height (more than 91% of all sampled trees had a long crown; Fig. 8; Appendix 10). This indicates that the trees are characterized by significant vigour, which would be largely an expression of an equilibrium between trees and their environment. Generally, the studied trees seem to have better vitality for an RCL greater than 70%. Indeed, the RCL is the result of competition and trees with long crowns have a greater probability of being healthy than those with short crowns (Bert et al. 1990). This indicates that there is low inter-tree competition in our study plots. Our results are consistent with those recently found on the biotic relationships of *A. marocana*. Indeed, Na:varro-Cerrillo et al. (2020) revealed that competition with *P. mauretanica* appears to have a positive to neutral effect on the growth of *A. marocana* in mixed stands. The presence of a high percentage of trees with long crowns in pure *A. marocana* and in Am–Ca mixed stands is consistent with the findings by Ben-Said *et al*. (2020, 2022), who concluded that *A. marocana* has a strong positive intraspecific association and facilitative effect with *C. atlantica*. However, the lower percentage of trees with long crowns in Am–Qr mixed stands suggests more competitive effects.

The Index of Biodiversity Potential (PBI) revealed a good hosting capacity of biodiversity and significant stability in all sampled plots (Fig. 13, 14). Deadwood plays an important role as a reservoir of biodiversity; it hosts nearly 25% of forest biodiversity (Bouget 2007). Saproxylic beetles and fungi constitute the most important organisms colonizing deadwood (Bouget 2021). As a result, the conservation of lying deadwood, standing deadwood, and living trees with tree-related microhabitat seems to be crucial (Fig. 15 and 16). Living trees with related microhabitats also play a remarkable role in biodiversity because they shelter specific taxa such as birds (Gosselin *et al*. 2006, Larrieu and Gonin 2008). The presence of small gaps in denser stands could attract numerous species of birds, reptiles, mammals, as well as insects (Gosselin *et al*. 2006). However, a good number of autochthonous trees (alive or dead trees), vertical layers and large trees should be maintained in all plots. Large trees offer heterogeneous habitats, allowing many specialist species to survive and fulfil various functions (Larrieu and Gonin 2008).

5. Conclusion

The assessment of the health status based on 200 trees in ten plots within the Talassemtane fir forest allowed us to fill a huge gap in our knowledge. The analysis of defoliation and branch mortality evolution over the study period (2015–2018) indicated that there is a gradual improvement in the crown health of most of the stems sampled; this may be linked to the good climatic conditions during this period and the reduction in anthropogenic pressure. We assume that the "*Mouhsine oven*s" initiative and the reduction in livestock since the establishment of the Talassemtane National Park had a positive effect on the reduction in the intensity of pruning practised by the population.

Abnormal colouring and leaf consumption by defoliators constitute the most common damage in the study area. Several aggressors (i.e., mistletoe, witches' brooms, insects, and insect nests) have been identified, but the proportion of trees affected was low. We found that witches' brooms are associated with branch deformation and breakage, mistletoe is responsible for branch deformation and needle microphyllia, while the abnormal colouring was attributed to *L. fiscellaria* and *T. pityocampa*. On the other hand, a significant proportion of trees of varying circumferences, especially large stems, was colonized by lichens. This colonization reflects favourable environmental and microclimatic conditions rather than a harmful or mechanical effect on trees. The ecosystem stability indicators (RCL and IBP) revealed a satisfactory status of the Talassemtane fir forest stability.

The results of our original study should be reinforced by regular monitoring of the plots set up to help managers in conservation and management plans. Despite the significant contribution of our pioneer study, several aspects remain to be explored in the future. Indeed, among the important factors that have been reported to have an influence on forest damage and have not been investigated in the present study are mainly the stand age and the plot localization (e.g., distances from plots to the forest edge and human settlements, wet *vs* dry sites, etc.). In addition, taking into account an exhaustive analysis of the correlation between climatic factors in the study area and the observed damages would be of paramount importance to understand the incidence of different damages to be considered in management plans.

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