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Stand factors influencing *Pinus halepensis* decline in north-western Spain

By A. V. Sanz-Ros[1,2,4] F. Valladares[3] and J. J. Diez[1]

[1]Sustainable Forest Management Research Institute, University of Valladolid-INIA, Avenida Madrid, 44, Campus La Yutera, Building E, 34071, Palencia, Castilla y León, Spain; [2]Centro de Sanidad Forestal de Calabazanos (Junta de Castilla y León), Polígono Industrial de Villamuriel, Villamuriel de Cerrato, Palencia, Spain; [3]Departamento de Biodiversidad y Biología Evolutiva, CSIC, Museo Nacional de Ciencias Naturales, Madrid, Spain; [4]E-mail: asanzros@gmail.com (for correspondence)

Summary

Although decline of Aleppo pine was observed long ago and several climatic and biotic factors have been previously associated with this complex process, site factors involved in this decline remain poorly understood. The objective of the work described here was to identify site factors associated with canopy condition. Canopy condition was estimated both by a visual estimation of defoliation, and by an indirect estimation of leaf area index (LAI) and other stand- and light-related parameters through the analysis of hemispherical photographs. A high percentage of damaged trees (81%) along with high levels of defoliation in plots (up to 53%) and trees (up to 85%) were recorded. Regression models showed that the site factors associated with defoliation were basal area, age, crown depth and elevation, while those associated with LAI were diameter at breast height, tree density and canopy openness. Analysis of hemispherical photographs proved to be a useful method for LAI estimation, but not for estimation of defoliation due to heterogeneous defoliation patterns caused by fungal pathogens detected in the study area. Soils and climatic conditions were common to all plots, so their influence could not be tested, but poor soil conditions and climatic restraints are known in this area, including low soil productivity, frequent summer droughts and high numbers of frost days. The results obtained suggest that several factors were associated with the decline of *Pinus halepensis*, including age, basal area, canopy openness, diameter, height and tree density. These factors can influence canopy condition, and thus, they might be acting as predisposing factors for the decline. The modulation of these factors is possible if suitable forest management strategies are applied, which could lead to a decrease of the decline incidence.

1 Introduction

Aleppo pine (*Pinus halepensis* Miller) is the most widespread pine species in the Mediterranean region, representing a distinctive and fundamental element of Mediterranean forests (Serrada et al. 2008). Aleppo pine can grow in poor soils and tolerate extreme dry and hot conditions (Cámara 1999). Although the species is susceptible to late spring or autumn frosts (Muñoz et al. 2007), it is able to grow well even under such climatic conditions. For this reason, it has been used for afforestation and stabilization of slopes delimiting high calcareous plateau borders in north-western Spain, which represents the north-western limit of *P. halepensis* distribution in the Iberian Peninsula and the western limit in Europe (Gil et al. 1996).

A severe decline of *P. halepensis* has been observed for many years (Muñoz 1999; Santamaría et al. 2003). The causes of this problem, however, appear to be complex and are not completely understood. The main symptoms observed in declining forest stands are dieback, branch death and high levels of defoliation, resulting in a significant reduction in the tree canopy with consequent reduction in tree growth and vigour. Several biotic agents have been found in association with the decline of this species, including *Sirococcus conigenus* in central Spain (Muñoz 1997, 1999) and *Gremmeniella abietina* as primary pathogens in northern forest stands (Martínez 1933; Santamaría et al. 2003, 2007a,b; Botella et al. 2010). In addition, secondary pathogens, such as *Sclerophoma pithyophilla, Thyriopsis halepensis or Cenangium ferruginosum,* are also present (Sutton and Waterston 1970; Sinclair et al. 1987; Phillips and Burdekin 1992). However, infections by these organisms do not fully explain the decline. It is likely, therefore, that other site factors must play a role, for example those related to soils, topography, climate or resources, that is light, water and nutrients, as well as disturbance factors, including those associated with silvicultural management (Barnes et al. 1998). Combinations of these factors may present a stressful environment for the tree, favouring decline.

Trees under stress frequently show reductions in the canopy, which can be estimated through the use of indicators, defoliation being one of the most common. The term defoliation is defined as the defoliating effects of biological agents, premature needle loss or reduction in the needle holding period (Ferretti 1994). Furthermore, defoliated trees have a low chance of survival and are prone to attack by root pathogens and bark beetles (Houston 1992). Thus, defoliation has become the most widely used indicator of forest health and canopy condition, for instance since 1986 in the International Co-operative Program for the Intensive Monitoring of Forest Ecosystems (ICP Forests: Ferretti 1997; Eichhorn et al. 2010; Fischer et al. 2010).

On the other hand, the amount of canopy, which is one of the most general indicators of stress (Waring 1985), has been most commonly estimated by leaf area index (LAI). This parameter is directly influenced by the water, carbon and energy exchange in a stand (Norman 1992). Many ecological processes in a stand, such as transpiration, competition, growth and self-thinning, determine total stand leaf area (Waring 1983; Long and Smith 1984; Dean and Long 1985).

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Although LAI can be estimated by destructive sampling, this process is extremely time-consuming and labour intensive in pine stands. Thus, indirect methods are required to increase the speed of LAI determination and avoid destructive tree harvesting. Different approaches have been used for LAI estimation: remote sensing (De Santis and Chuvieco 2009; Somers et al. 2010), airborne laser scanning (LIDAR) (Riaño et al. 2004; Solberg et al. 2006) and ground-based methods. Certain ground-based methods use photosynthetic active radiation (PAR) for LAI estimation (Chazdon and Field 1987; Himmler 1996; Chen and Cihlar 2000), while hemispherical photography (Chen et al. 1991) uses canopy light interception to estimate leaf area optically. This optical technique has been widely used in studies of canopy structure and forest light transmission (Valladares and Guzman 2006; Montes et al. 2007), but application to the assessment of canopy condition studies has not been previously evaluated.

The aim of the work described in this study was to identify site factors affecting canopy condition in declining *P. halepensis* stands located in north-western Spain by the estimation of defoliation and LAI using visual and hemispherical photography methods, respectively. The hypothesis was that site factors are influencing canopy condition.

2 Materials and methods

2.1 Study area

The studied area is located in the south-east of Palencia Province (Castilla y León, Spain) within latitudes 41°52′52″N-41°56′9″N and longitudes 4°20′35″W-4°28′51″W, where *P. halepensis* suffers a severe decline. The study area is characterized by the presence of calcareous high plains with marlaceous slopes and gypsum deposits. The altitude ranges between 775 and 965 m.a.s.l. The climate is Mediterranean with continental features of hot summers and cold winters, where frost days are common (60 per year). Mean annual temperature is 12.3°C, and annual precipitation is 400 mm. Soils are stony, with a low percentage of organic matter and high calcium content (Oria Rueda et al. 1996), and are classified as Inceptisol, Ochrept, Xerochrept following the Soil Taxonomy classification system (USDA 1987).

2.2 Sampling method and data collection

During summer 2007, thirty circular plots of 15 m of radius were established in *P. halepensis* declining forests. In each plot, the 15 trees nearest to the plot centre were evaluated following a spiral track (Fig. 1), giving a total of 450 trees for inspection. All plots were established over the same soil type (described above). Locations of plots and other plot features are shown in Table 1. In order to identify the site factors related to defoliation and LAI, each plot was characterized by a number of variables related to tree growth and canopy structure. Variables were calculated as the average value for the 15 evaluated trees (Table 2) and included the following: diameter at breast height (DBH), calculated as the mean value of two orthogonal stem diameters at 1.30 m above ground level; mean height (MH), as the arithmetic mean of tree height,

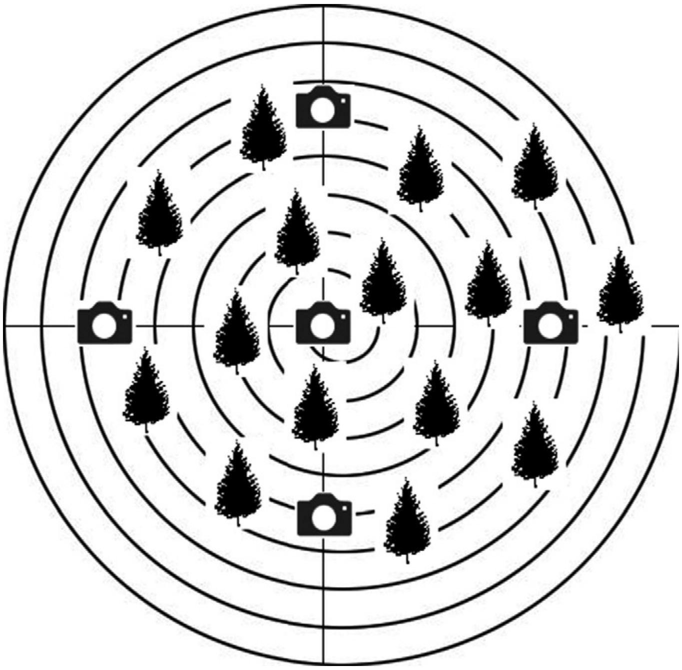

Fig. 1. Distribution of the 15 evaluated trees following a spiral path, and the five sampling points where hemispherical photographs were taken in each plot.

estimated using a Vertex III hypsometer (Haglöf), also used for canopy depth (CDe), the average height from the lowest live branch to the top of the crown; mean tree age (Age); tree density (D), expressed as the number of trees per hectare; basal area (BA) measured with a relascope; and elevation (E), obtained using a portable GPS.

2.3 Evaluation of canopy condition

Canopy condition was determined through estimations of plot defoliation and leaf area index (LAI). Defoliation was calculated as mean defoliation (MDef) of the 15 evaluated trees per plot, and was estimated visually with 5% intervals, following the ICP Forest methodology (Ferretti 1994; Eichhorn et al. 2006) from a distance at least equal to the height of the evaluated tree and avoiding facing the sun during the evaluation. The estimates were compared with reference tree photographs for *P. halepensis*. The reference tree is the best tree crown condition for this species in Mediterranean areas, with a maximum amount of foliage, which provides comparable data for *P. halepensis* through the Mediterranean region.

Leaf area index was estimated through analysis of hemispherical photographs. A total of 150 photographs (5 per plot, Fig. 1) were taken as follows: one in the centre of the plot and one at each cardinal point (N, S, E, W) at a distance from the plot centre equal to half of the radius of the plot (7.5 m). Hemispherical photographs were taken with a Nikon Coolpix 4500 digital camera (Nikon Corporation Imaging Company, Tokyo, Japan) equipped with a Nikon Fc-E8 fisheye adapter and mounted on a tripod with a levelling head, oriented to magnetic north at a height of 1 m above the ground (and above understory vegetation). Photographs were taken skywards at sunrise or sunset, or sometimes during the day, under overcast conditions and homogeneously distributed clouds, so that direct sunbeams were not captured in the photographs. An automatic exposure setting was used.

Hemispherical photographs were analysed with Gap Light Analyzer software (version 2.0, Simon Fraser University, Burnaby, British Columbia, and the Institute of Ecosystem Studies, Millbrook, NY, USA) (Frazer et al. 1999); . The blue channel was used to maximize contrast between sky and canopy elements. A threshold level was selected for each photograph to distinguish between visible sky and vegetal elements, such as foliage, branches and stems. The uniform overcast distribution model (UOC) and a clear sky transmission value of 0.65 were used. The data obtained were combined to produce indirect estimates of growing-season light transmission and parameters related to canopy structure: effective leaf area index (MLAI), computed from 0° to 75° from the zenith, as defined by Welles and Norman (1991); mean canopy openness (MCOp), defined as the percentage of visible sky across the whole hemisphere; transmittance, defined as the percentage of

Table 1. Characteristics of *Pinus halepensis* plots examined in this work.

Plot	coorX[1]	coorY[2]	Age (years)	Elevation (m.a.s.l)
1	387 176	4 640 637	42.5	888
2	387 243	4 640 642	33.0	883
3	387 406	4 640 594	28.0	887
4	387 316	4 640 466	41.0	879
5	387 425	4 640 293	44.0	965
6	387 340	4 640 313	40.0	885
7	387 258	4 640 587	45.0	892
8	387 407	4 640 242	45.0	863
9	387 329	4 640 220	38.7	885
10	387 222	4 640 338	36.0	878
11	387 261	4 640 396	44.5	880
12	384 478	4 639 008	35.5	884
13	384 496	4 638 959	38.5	885
14	384 349	4 638 984	25.5	878
15	384 242	4 638 925	30.5	879
16	384 350	4 638 884	38.0	887
17	384 193	4 638 842	38.0	894
18	384 328	4 638 802	36.5	884
19	384 424	4 638 817	25.0	874
20	384 425	4 638 899	35.0	883
21	384 510	4 638 887	29.0	883
22	386 415	4 637 153	27.0	797
23	386 244	4 637 069	31.0	806
24	385 591	4 643 447	36.3	832
25	385 630	4 643 401	45.5	828
26	377 651	4 639 996	36.7	782
27	377 782	4 639 795	39.5	799
28	377 615	4 640 137	30.7	783
29	377 734	4 639 484	27.0	775
30	377 694	4 639 545	31.0	780

[1] CoorX, UTM coordinates X.
[2] CoorY, UTM coordinates Y.

Table 2. Description, abbreviations and units of plot parameters measured in field conditions and light-related variables obtained from the analysis of hemispherical photographs.

Variable	Description	Units
Age	Mean tree age	Years
BA	Basal area	m^2/ha
CDe	Mean canopy depth	m
D	Density	Trees/ha
E	Elevation	m.a.s.l
DBH	Mean tree diameter at breast height	cm
MH	Mean tree height	m
MDef	Mean defoliation	%
MCOp	Mean canopy openness	%
MLAI	Mean effective leaf area index	m^2/m^2
MDirT	Mean direct transmittance	%
MDifT	Mean diffuse transmittance	%
MTT	Mean total transmittance	%

transmitted direct, diffuse and total radiation (MDirT, MDifT and MTT) incident on a horizontal surface when light is blocked by the surrounding topography and overlying forest canopy (Frazer et al. 1999).

2.4 Statistical analysis

A descriptive analysis was made at tree and plot levels and the Kolmogorov–Smirnov test used to assess data normality. Variables which did not meet this assumption were logarithm, inverse or squared transformed. Secondly, a multivariate principal components analysis (PCA) was carried out in order to reduce the dimensions of the observations, to identify gradients that explained the largest variations in the data, and to identify key factors potentially associated with the response variables defoliation and LAI. The PCA was based on the correlation matrix, and the components were rotated according to the *Varimax* method. Finally, a multiple regression model was built for each of the response variables (defoliation and LAI), using the forward stepwise selection method. For the defoliation model, all variables were included (Stand and hemispherical photography analysis) as explanatory variables, while for the LAI model only the stand variables were used (excluding those obtained by hemispherical analysis). The Durbin–Watson test was used to assess residual autocorrelation, and variance inflation factors (VIFs) were examined to assess colinearity. The statistical package STATISTICA 6.0 (Statsoft, Tulsa, OK, USA) was used for statistical analyses.

3 Results

3.1 Defoliation and LAI

Visual assessments of the canopies in *P. halepensis* stands revealed a high level of defoliation in general, and a high percentage of damaged trees. The high defoliation levels found in the study area were mainly located in the upper part of the crown, and in some cases, a severe dieback downwards was observed. The mean defoliation of plots ranged from 22 to 53% (Table 3), while defoliation at the tree level ranged from 15 to 85%. The mean defoliation value was 37.74% in both tree and plot levels, although standard deviation of plots (plot SD) was 8%, while tree SD was 12%. The assessment also showed that 19% of the evaluated trees had between 10 and 25% defoliation, (Defoliation Class 1: DC1), whereas 77.85% of trees were 25–60% defoliated (DC 2) and 3.13% were over 60% defoliated (DC 3).

Leaf area index values of plots, determined by analysis of hemispherical photographs, ranged from 0.36 to 2.92 m^2/m^2 (Table 3), and the mean value was 1.71 (+0.48, standard deviation) m^2/m^2. A Pearson correlation analysis suggested a very low correlation between defoliation and LAI ($R = 0.075$; $p > 0.05$: Fig. 2).

3.2 Multivariate analysis

Principal components analysis (PCA) identified three main axes which accounted for 80.96% of the total variance (Table 4). The first principal component (40.12% of the total variance) was related to the light environment under the canopy, having high factor loadings for variables such as transmittance (MTT), canopy openness (MCOp), leaf area index (MLAI), density (D) and basal area (BA) (Table 4). The second component was interpreted as being related to canopy condition and associated factors, because high factor values were obtained for defoliation (MDef), elevation (E) and age (Age). The third component was related to stand growth and canopy development: factor values were higher for mean height (MH), mean diameter (DBH) and canopy depth (CDe). Some abiotic factors, such as soil and rainfall, were homogeneous across all plots; therefore, these were not included in the analysis.

Summarizing the results, PCA (Fig. 3) suggested that the light environment, canopy condition and stand growth were the main components associated with canopy condition. This analysis showed a relationship between defoliation and factors

Table 3. Stand parameters measured in the field and those obtained from analysis of hemispherical photographs. Values given as averages are presented with standard deviation (±SD). Abbreviations are described in Table 2.

	Stand parameters				Digital image analysis parameters				
Plot	MDef (%)	Density (trees/ha)	BA (m^2/ha)	CDepth (m)	MLAI	MCOp	MTT	MDirT	MDifT
1	37.86 ± 5.45	198.1	12	3.06 ± 0.87	0.36 ± 0.06	58.20 ± 2.68	22.93 ± 1.30	73.39 ± 4.94	70.08 ± 4.56
2	42.33 ± 7.53	339.5	23.5	4.26 ± 1.88	1.11 ± 0.12	31.40 ± 2.24	11.98 ± 1.34	37.82 ± 10.28	37.12 ± 3.15
3	36.67 ± 6.17	863.0	20	3.45 ± 1.24	1.80 ± 0.09	17.93 ± 0.94	8.61 ± 1.35	27.76 ± 7.67	26.09 ± 1.60
4	48.00 ± 9.78	1004.4	28	3.13 ± 1.24	1.82 ± 0.16	17.07 ± 1.69	7.85 ± 0.32	24.51 ± 3.53	24.56 ± 2.22
5	53.33 ± 7.24	1867.4	36.5	2.33 ± 0.95	2.12 ± 0.26	14.77 ± 1.78	7.20 ± 0.36	22.67 ± 1.49	22.37 ± 1.56
6	53.00 ± 7.26	1103.5	22	2.61 ± 0.77	1.81 ± 0.19	16.97 ± 2.13	7.25 ± 0.16	20.62 ± 2.67	24.70 ± 2.04
7	46.15 ± 8.70	183.9	10.5	4.03 ± 1.02	0.56 ± 0.14	48.25 ± 3.95	20.10 ± 2.94	64.37 ± 11.85	61.38 ± 7.68
8	47.67 ± 6.51	1457.1	36.5	2.19 ± 0.50	1.75 ± 0.15	17.89 ± 1.20	8.28 ± 0.53	26.1 ± 3.64	25.65 ± 1.22
9	43.00 ± 7.75	1145.9	33	2.65 ± 0.99	1.60 ± 0.11	19.65 ± 1.63	8.68 ± 1.01	26.99 ± 7.16	27.31 ± 1.64
10	39.33 ± 8.21	1414.7	26.5	2.78 ± 1.45	1.87 ± 0.07	15.87 ± 0.72	6.04 ± 0.56	22.12 ± 4.94	24.53 ± 1.05
11	47.67 ± 11.93	1244.9	50	2.41 ± 0.89	1.99 ± 0.12	15.70 ± 1.18	5.37 ± 0.24	15.59 ± 1.86	23.30 ± 1.90
12	38.00 ± 11.31	1174.2	45	2.87 ± 1.22	2.22 ± 0.17	14.84 ± 1.05	5.71 ± 0.43	17.49 ± 2.90	22.03 ± 0.49
13	44.67 ± 16.95	1287.4	46	2.27 ± 0.74	2.23 ± 0.08	14.59 ± 0.78	5.87 ± 0.60	28.88 ± 3.03	14.44 ± 1.38
14	32.67 ± 9.80	1216.6	33	3.34 ± 1.27	1.69 ± 0.15	21.03 ± 3.31	7.32 ± 0.72	21.74 ± 2.03	28.98 ± 6.38
15	38.33 ± 6.73	1358.1	42	2.33 ± 0.56	1.62 ± 0.14	24.18 ± 1.69	12.31 ± 1.09	42.29 ± 5.63	36.02 ± 2.93
16	37.67 ± 12.08	1782.5	43	2.62 ± 1.13	2.92 ± 0.26	13.23 ± 0.72	11.22 ± 0.47	31.61 ± 2.47	21.45 ± 0.59
17	31.00 ± 7.37	1315.7	40	3.64 ± .082	1.81 ± 0.18	19.25 ± 1.99	13.06 ± 1.74	34.94 ± 6.77	26.81 ± 2.50
18	34.67 ± 7.67	933.7	44	2.25 ± 0.75	2.02 ± 0.11	16.43 ± 0.65	6.86 ± 0.70	22.71 ± 5.23	24.82 ± 1.12
19	30.00 ± 6.55	778.1	24	3.72 ± 0.78	1.08 ± 0.08	31.79 ± 2.21	13.11 ± 1.81	45.77 ± 10.95	44.99 ± 3.47
20	41.67 ± 8.16	1301.5	49.5	2.94 ± 0.88	2.13 ± 0.21	18.00 ± 1.66	7.87 ± 0.94	26.44 ± 4.30	28.05 ± 2.37
21	39.00 ± 21.40	735.6	37.5	3.03 ± 1.14	1.87 ± 0.13	16.36 ± 1.33	8.39 ± 0.77	28.70 ± 3.97	23.77 ± 1.61
22	36.00 ± 5.41	1061.0	26	3.97 ± 1.06	1.47 ± 0.15	24.57 ± 1.83	13.04 ± 1.95	39.26 ± 7.88	36.30 ± 4.36
23	22.33 ± 5.30	721.5	25	5.14 ± 1.43	1.79 ± 0.46	20.54 ± 7.50	8.14 ± 2.75	22.53 ± 4.61	25.88 ± 13.22
24	25.33 ± 6.67	749.8	39	5.87 ± 1.10	1.66 ± 0.05	18.93 ± 1.05	9.67 ± 1.28	31.01 ± 8.37	26.50 ± 1.52
25	30.00 ± 8.86	1174.2	60	4.07 ± 1.25	2.07 ± 0.14	14.44 ± 0.92	6.28 ± 0.30	18.69 ± 1.84	19.58 ± 0.16
26	30.00 ± 8.66	1216.6	30	3.36 ± 1.4	1.58 ± 0.19	20.81 ± 2.38	8.90 ± 0.70	29.12 ± 2.72	27.92 ± 3.02
27	37.33 ± 9.61	820.5	36	3.04 ± 0.93	1.63 ± 0.07	19.59 ± 1.20	6.58 ± 0.36	20.36 ± 3.42	26.23 ± 1.68
28	33.00 ± 5.61	1358.1	31	4.05 ± 1.55	1.77 ± 0.14	18.42 ± 1.36	8.65 ± 0.89	27.32 ± 4.29	25.37 ± 1.51
29	32.33 ± 9.61	1103.5	35	3.31 ± 1.26	1.71 ± 0.16	18.28 ± 1.31	9.26 ± 0.92	30.37 ± 5.07	25.69 ± 0.79
30	24.33 ± 6.23	749.8	33.5	3.85 ± 1.08	1.52 ± 0.18	21.45 ± 2.58	9.99 ± 1.02	30.45 ± 6.24	29.13 ± 2.06

such as elevation, age, tree height and crown depth. There was also a positive relationship between LAI and density and basal area, and a negative relationship with transmittance or canopy openness.

3.3 Defoliation and LAI regression models

General regression models (GRM) were built for defoliation (Eq. 1) and LAI (Eq. 2) in order to identify the key factors associated with canopy condition. The regression model for defoliation included variables such as age (Age), elevation (E), basal area (BA), and canopy depth (CDe). On the other hand, the LAI regression model includes canopy openness (MCOp), mean diameter (DBH) and density (D).

The multiple regression model for defoliation (Eq. 1) was significant ($F = 14.71$; $p < 0.0001$), with no colinearity (variance inflation factors (VIFs) <3) and the residuals followed a normal distribution (Durbin–Watson, p-value > 0.1). The regression provided a reasonable fit ($R^2 = 70.18\%$), and the adjusted correlation coefficient (R^2_{adj}) was 65.42%.

$$\text{MDef} = -2.671 - 4.39 \times \text{CDe} + 0.427 \times \text{Age} - 0.178 \times \text{BA} + 0.0531 \times \text{E} \qquad (1)$$

where MDef = mean defoliation; CDe = canopy depth; BA = basal area; Age = mean age; E = elevation. In this model, basal area (BA) and canopy depth (CDe) were negatively related to mean defoliation (MDef), while age (Age) and elevation (E) were positively related to this variable. Defoliation values were lower in plots with high BA, high tree density and thus composed of young trees. In addition, defoliation values were higher in older (ca. 40–45 years) stands and those at higher altitudes.

The multiple regression model for LAI (Eq. 2) was also significant ($F = 35.78$; $p < 0.0001$), with no colinearity (VIFs < 2); the residuals followed a normal distribution (Durbin–Watson, p-value > 0.1). The regression model provided a good fit ($R^2 = 72.61\%$), and the R^2_{adj} was 70.57%.

$$\text{MLAI} = 0.396 + 0.00065 \times \text{D} + 0.0183 \times \text{BA} \qquad (2)$$

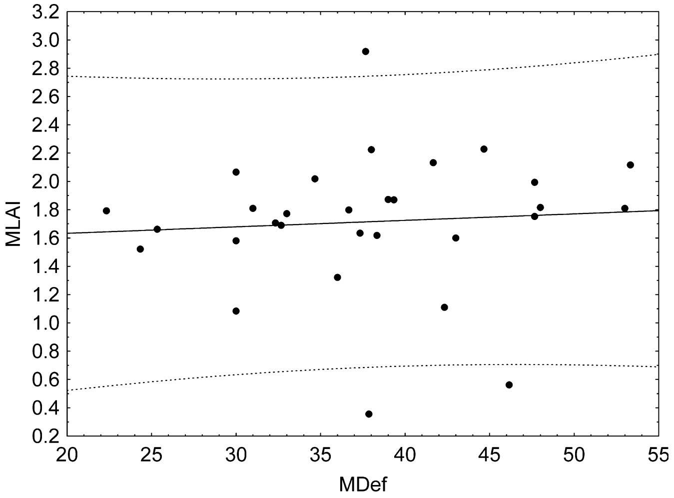

Fig. 2. Scatter plot between defoliation and leaf area index. The continuous line represents the simple regression line for defoliation, using MLAI (obtained by analysis of hemispherical photographs) as the independent variable. Dashed lines represent the 95% confidence interval.

Table 4. Principal components with eigen values and explained variance, and PCA factor loadings of variables. Bold numbers represent highest factor loadings of variables in each component. Abbreviated variables are described in Table 2.

Variable	Factor 1	Factor 2	Factor 3
MCOp	−**0.898**	−0.313	0.139
MTT	−**0.861**	−0.291	0.186
CDe	−0.535	0.451	−**0.551**
DBH	−0.355	−0.458	−**0.693**
E	0.186	−**0.731**	0.243
Age	0.210	−**0.767**	−0.205
MDef	0.277	−**0.757**	0.428
MH	0.289	−**0.696**	−0.561
BA	**0.777**	0.051	−0.399
D	**0.869**	0.091	0.259
MLAI	**0.926**	0.147	−0.139
Eigen value	4.413	2.809	1.684
%TV[1]	40.116	25.539	15.309
%CTV[2]	40.116	65.656	80.966

[1] %TV, percentage of total explained variance.
[2] %CTV, percentage of cumulative total explained variance.

where MLAI = mean effective leaf area index; D = stand density; BA = basal area.

BA and D were positively related to LAI, indicating that plots with a higher amount of canopy were also those with high density of large trees.

4 Discussion

The percentage of *P. halepensis* trees categorized as 'damaged' when assessed using the ICP Forests protocols, that is those trees in defoliation classes DC2 and DC3 (Eichhorn et al. 2006), represented 81% of the evaluated trees. This percentage is far higher than the percentage (15.7%) for *Pinus* spp. reported by the ICP Forest monitoring networks throughout Spain (Fischer et al. 2010).

The high defoliation levels observed in the upper part of the crowns and the presence of dieback were previously associated with biotic agents, including *G. abietina*, *S. pithyophila, T. halepensis* and *C. ferruginosum* (Santamaría et al. 2003, 2007 a,b; Botella et al. 2010). The type and location of symptoms were consistent with those caused by these fungal pathogens, including death of needles and branches in the upper part of the crown, which leads to increased defoliation and gradual dieback from the upper part of the crown (Santamaría et al. 2003, 2007a,b). However, the presence of those agents alone does not fully explain the decline, and the aetiology of the decline may be very complex.

The results of the work reported here suggested that a number of site factors are associated with canopy condition and may act as decline predisposing factors leading to decline. The models built in this work indicated that variations in defoli-

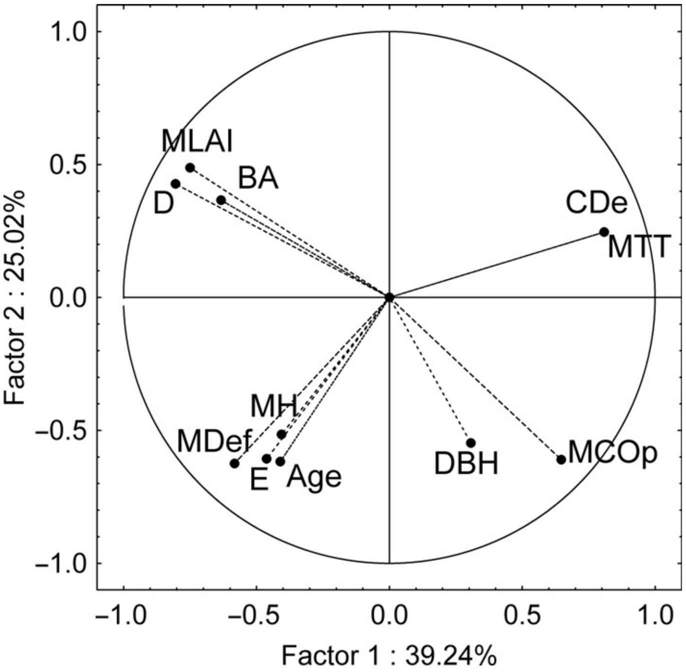

Fig. 3. Biplot obtained from principal components analysis (Component 1 *vs.* 2). Variables are described in Table 1.

ation may be explained by several stand factors (Eq. 1), while variation in LAI is explained by different factors (Eq. 2). These models support the hypothesis, demonstrating that site factors are associated with poor crown condition.

The factors identified as affecting defoliation (Age, BA, CDe and E) were consistent with the concepts of decline presented by Manion (1991), which states that only mature dominant trees will go into decline. Usually those mature trees are in stands with a low basal area, due to a low density of large trees. On the other hand, for *P. halepensis* stands, elevation may be related to a high exposure to frost of the more elevated plots compared to those located at lower altitudes. It is well known that *P. halepensis* usually displays twig tip wilting and general discoloration due to frost (Muñoz et al. 2007), and the area investigated has a high number of frost days (Santamaría et al. 2007a,b). Moreover, some authors have recommended avoiding cold and wet locations for the establishment of *P. nigra* and *P. sylvestris* plantations, with the aim of preventing damage caused by fungal pathogens (Karadžić and Milanović 2008).

LAI values were high, as expected, in plots with a high density of large trees where the percentage of visible sky is very low. The mean LAI values of plots were 1.71 ± 0.48 (SD) m^2/m^2, whereas other studies on healthy *P. halepensis* trees of similar diameter range have reported mean LAI values of 2.69 m^2/m^2 (López-serrano et al. 2000). This reduction in LAI may be due to defoliation, but a cause–effect relation cannot be established, as stand structural parameters (Long and Smith 1984; Ford 1985) or the method of estimating LAI (Fassnacht et al. 1994; Chen 1996) may influence this relationship. Furthermore, the use of LAI as a health indicator requires reference values, as variations in LAI may be caused by factors other than defoliation, such as forest structure (Jack and Long 1991; Dean and Baldwin 1996; O'Hara 1996), silvicultural treatments (Waring 1985; Solberg et al. 2006) or forest fires (De Santis and Chuvieco 2009).

Comparisons between defoliation and LAI revealed poor relationship between the two variables, despite the fact that the contrary was expected: the models, however, showed that the factors determining these two parameters were different. This low correlation may be due to the heterogeneous defoliation pattern observed in this work, as most damage occurred in the upper part of the crown, thus supporting the idea that fungal pathogens contribute to the decline. Given that LAI was estimated from photographs taken vertically from the ground towards the zenith, the overlapping of needles, twigs and branches may have impeded the detection of dieback in the upper part of the crown. It was noted that Aleppo pines retained lower dead branches and that natural pruning did not occur, thus increasing the superposition of branches and reducing the correlation between both variables.

Previous work on defoliation of *Pinus sylvestris* L. after insect outbreaks related defoliation to changes in LAI, measured by airborne laser scanning; this method could represent a useful tool for the early detection of canopy damage (Waring 1985; Solberg et al. 2006; Eklundh et al. 2009), but this case represents a different situation than that of Aleppo pine in northern Spain.

The hemispherical photography analysis is a suitable method for estimating LAI (Valladares et al. 2006; Montes et al. 2007); however, it was not appropriate to estimate defoliation. Hemispherical photography, and probably other ground-based methods for canopy assessment, such as LAI 2000, might not be suitable for the detection of some defoliating agents, such as fungal pathogens causing dieback from the upper part of the crown. On the other hand, it is likely that other methods such as remote sensing or airborne laser scanning were neither able to detect heterogeneous defoliation patterns, mainly due to the problem with background vegetation. However, more research is needed to test the ability of these methods for the detection of heterogeneous defoliation patterns. These results emphasize the complexity of forest health assessments highlighting the need for skilled evaluators in the field.

Overall, three kinds of factors were associated with the decline of *Pinus halepensis*: (i) predisposing factors, such as poor soil conditions. The soils in the affected areas are xeric Inceptisols (Xerochrept), characterized by low productivity under a xeric climate (Soil Survey Staff USDA 1987). The summer combination of high temperatures and low rainfall has been related to high defoliation levels in conifer species (Sanz-Ros et al. 2008), and will undoubtedly produce a negative impact on tree physiology and growth (Borghetti et al. 1998). The results of the present work suggest that stand factors, such as age, basal area, canopy openness, diameter, height or tree density, can influence canopy condition, and may also be considered predisposing factors. ii) Inciting factors suggested by the results presented here include defoliation and frost damage. Although defoliation is caused by the combination of biotic and abiotic factors, the reduction in canopy led to a decrease in photosynthetic activity, carbon sequestration and tree growth (Wiley et al. 2013; Pinkard et al. 2014), therefore reducing resources and vigour, and rendering defoliated trees prone to attack by pests and diseases (Houston 1992). The trees at higher altitudes were exposed to frosts and showed tip wilting, as previously described by Muñoz et al. 2007;. Both factors may incite tree decline. iii) Contributing factors, such as the presence of primary and weak fungal pathogens, previously isolated in this same area, which may result in severe defoliation of trees (Santamaría et al. 2003, 2007a,b; Botella et al. 2010.

Climate scenarios predicted for Spain will probably increase the incidence of predisposing and inciting factors of decline, as climate models suggest an increase in temperature and a decrease in rainfall (Kattenberg et al. 1996; Parry 2000; Mossman 2002; IPCC 2013). In addition contributing factors also may be enhanced, as the combination of climatic factors may enhance the activity of weak pathogens.

In conclusion, the results of this work suggest that a number of site factors, including age, basal area, canopy openness, diameter, height and tree density, can influence canopy condition in *P. halepensis*. This influence might determine the final response of trees to stress and the severity of the observed decline. Even when contributing factors are present, only declining trees are unable to recover from attack. Thus, suitable forest management strategies could be designed to modify certain site factors with the aim of decreasing the incidence of the decline.

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