iForest
Biogeosciences and Forestry

Research Article
doi: 10.3832/ifor4587-018
vol. 19, pp. 237-243

Assessing the environmental factors affecting the natural regeneration of *Cedrus libani* A. Rich. in Jawbat Burghal, Syria

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Remote Sensing (RS) and Geographic Information Systems (GIS) technologies are valuable tools for managing forest ecosystems today. This study employed a Binary Logistic Regression Model to analyze the environmental factors influencing the natural regeneration of *Cedrus libani* A. Rich. within its native habitat in the Jawbat Burghal forest of Syria. The effects of various environmental factors (spatial and forest structure, topography, and spectral indicators) were assessed both individually and collectively to understand their impact on the probability of *C. libani* seedling presence in Jawbat Burghal. The model's accuracy significantly improved when considering the combined effects of these factors, reaching 94.3%, exceeding the accuracy of the other models evaluated (none of which surpassed 85%). Higher stone density, increased broadleaved tree cover, and favorable summer soil moisture were found to promote the natural regeneration of *C. libani* in Jawbat Burghal.

Keywords: Natural Regeneration, Environmental Factor Modeling, Remote Sensing, Geographic Information Systems (GIS), Forest Structure, *Cedrus libani*

Introduction

Native populations of Lebanon cedar (*Cedrus libani* A. Rich.) are confined to the Eastern Mediterranean region, where they once formed extensive and magnificent forests in Syria, Lebanon, and Turkey, and were an important source of wood for successive human civilizations (Loffet 2004). Today, only small and fragmented forest populations remain as a result of more than 5,000 years of intensive human exploitation, mainly through logging, burning, and goat grazing (Boydak 2003). These populations have been genetically isolated since the last Quaternary glacial cycle; they have been threatened with extinction since the 19th century (Fady et al. 2008) and have been classified in national records as endangered, threatened, and at risk of extinction (Khouzami et al. 1996). In Syria, due to increasing human pressure, *C. libani* populations are now confined to a highly restricted area in the northern part of the Syrian coastal mountain range (Khuri et al. 2000).

Currently, Syrian *C. libani* forests are degraded and fragmented, found only in the northwestern regions of Slenfeh and Jawbat Burghal (Khouzami & Nahal 1983). These remaining forests suffer from a severe lack of natural regeneration, threatening their long-term sustainability (Nahal 2003, Hajar et al. 2010).

Regeneration is a multiphase process involving several sequential life history stages (*i.e.*, seeds, seedlings, saplings) connected by transitional processes (*i.e.*, predispersed seed, dispersed seed, germination, emergence, survival) which are affected by various environmental factors (*e.g.*, litter, drought, diseases, insects, etc.) (Gómez-Aparicio 2008). Many environmental factors govern the success of the regeneration process, especially within microsites, defined by environmental characteristics at the spatial scale of individual seeds or seedlings (Wangchuk 2007). Seedling establishment is the critical stage in a plant's life history, during which the survival and growth of the tree species are more sensitive to microenvironmental site conditions (Gray et al. 2005).

Satellite imagery at various spatial and temporal scales plays a vital role in studying dynamic phenomena such as natural regeneration following disturbances (climate change, fires, land-use change, volcanoes, etc.) over specific periods using vegetation biomass or remote sensing indices (Carlson & Ripley 1997). Remote sensing technology has been used to monitor natural regeneration patterns in forests after fires, particularly shrub cover regeneration in the Mediterranean region (Hernández-Clemente et al. 2009).

The study aims to: (i) assess the current state of *C. libani* natural regeneration in its native habitat in Syria (Jawbat Burghal); (ii) identify the potential causes of regeneration weakness by developing a mathematical model to evaluate the effects of spatial and forest structure, topographic variables, and spectral indicators; (iii) predict the likelihood of *C. libani* occurrence in Jawbat Burghal based on environmental factors influencing its natural regeneration.

Material and methods

Study area

This study was conducted in a specific region within the natural distribution range of *Cedrus libani*, located in the Jawbat Burghal area of Syria's Lattakia Governorate. The site, officially designated as the "Cedar and Fir Protected Area" since 1996, lies between 36° 10′ and 36° 17′ E and 35° 29′ and 35° 41′ N, on the eastern slopes of the northern Syrian coastal mountain range, encompassing the Slenfeh and Jawbat Burghal regions.

In Syria, *C. libani* naturally grows in soils developed over hard Jurassic limestone formations, composed primarily of limestone and dolomite, both calcareous rocks (Martini 1989). These cedar forests are confined to the cold perhumid bioclimatic zone on the eastern slopes of the coastal mountain range, at elevations ranging from 900 to 1,562 m a.s.l. A detailed study

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Received: Feb 14, 2024 - Accepted: Dec 06, 2025

Citation: Ibrahem A, Koubaily E, Thabeet A (2026). Assessing the environmental factors affecting the natural regeneration of *Cedrus libani* A. Rich. in Jawbat Burghal, Syria. iForest 19: 237-243. - doi: 10.3832/ifor4587-018 [online 2026-06-14]

Communicated by: Maurizio Marchi

by Ibrahem et al. (2015) accurately mapped the distribution of *C. libani* in Syria, identifying 35.29 ha in Slenfeh and 219.43 ha in Jawbat Burghal, totaling 254.72 ha of *C. libani* stands across both these regions.

Image acquisition and processing

Image data used in this study were obtained from the United States Geological Survey (USGS) Earth Explorer Landsat archive (http://earthexplorer.usgs.gov/). A Landsat 8 OLI_TIRS Level 1 image, systematically and terrain-corrected (L1T/G), was acquired on August 24, 2014, with a spatial resolution of 30 m. The study site falls within Path 174, Row 35 of the World Geographic System (WGS). The image was geometrically rectified to the Universal Transverse Mercator (UTM) coordinate system, Zone 37 N, using the WGS 1984 Datum. Top-of-atmosphere (TOA) correction was applied to convert raw image data into TOA reflectance values (USGS 2014).

A Digital Elevation Model (DEM) with a 30 m resolution was used to derive topographic variables for the study area. All satellite images were resampled to a 5 m resolution using bilinear interpolation to match the spatial resolution of the RapidEye 532 high-resolution image, acquired on June 24, 2011. Supervised classification of the RapidEye image was performed to estimate the cover of *Cedrus libani*, broadleaved trees, and open areas (vegetation cover < 30%) within the study site.

Field survey

In summer 2014, field surveys were conducted to evaluate natural regeneration using a random sampling method. A total of 198 sample plots were distributed along the eastern slopes of the Syrian coastal mountain range in the Jawbat Burghal region. Each plot measured 5 × 5 m and was used to record data on trees, shrubs, saplings, and seedlings.

The geographic coordinates of the sample plots were recorded using a Global Positioning System (GPS) and converted into a GIS point data layer. Within each plot, the presence or absence of *Cedrus libani* seedlings (height < 50 cm) was recorded, as well as their density. Additionally, the number of *Cedrus* saplings (height ≥ 50 cm and ≤ 130 cm) and seedlings of other forestry species were registered.

For *C. libani* seedlings, additional measurements were taken, including height, estimated age, vitality, and microsite conditions (exposed, semi-exposed, shaded, or under the parent tree's crown).

Data preparation for the models

The impact of environmental variables on *C. libani* natural regeneration was recorded across 198 plots in Jawbat Burghal, which were divided into 3 groups (see below).

Spatial and forest structure variables

Type of predominant forest cover (type): type1, *C. libani*; type2, conifers (except cedar); type3, *Quercus* spp.; type4, broadleaved (except oaks); type5, mixed forest stands; type6, open area. The tree coverage (cover, in %). Type of predominant shrub cover (shrub_type): shrub_type0, no shrubs; shrub_type1, *C. libani* shrubs; shrub_type2, conifers shrubs (except cedar); shrub_type3, *Quercus* spp.; shrub_type4, broadleaved shrubs (except oaks); shrub_type5, mixed shrub species. The shrub coverage (shrub, in %). The litter thickness (litter_thick). The litter type (litter_type): litter_type1, conifers; litter_type2, broadleaved; litter_type3, mixed conifer-broadleaved litter. The stone size (stone_size): stone_size1, small; stone_size2, medium; stone_size3, large; stone_size4, varied size. The stone coverage (stone, in %) and the fruiting intensity (fruit), according to the number of cones on the tree: (0) cones absent; (1) fewer than 20 cones; (2) number of cones between 20 and 50; (3) number of *C. libani* cones > 50 cones. The distance from mature cedar trees (distance_cedar), the distance from broadleaved trees (distance _broad), and the distance from forest roads (distance_ roads) were calculated in ArcGIS® v. 9.3 using Euclidean distances in Spatial Analyst Tools.

Topographic variables

The DEM was used to derive the following topographic variables layers in ArcGIS 9.3 using Spatial Analyst Tools. The elevation was classified manually into 10 classes in meters: (570-900), (900-950), (950-1000), (1000-1050), (1050-1100), (1100-1150), (1150-1200), (1200-1250), (1250-1300) and (1300-1350). The slope was divided into 5 classes (in degrees): slope1 (0-10), slope2 (10-20), slope3 (20-30), slope4 (30-40), and slope5 (40-50). The aspect was divided into 9 classes (in degrees): north (0-22.5), northeast (22.5-67.5), east (67.5-112.5), southeast (112.5-157.5), south (157.5-202.5), southwest (202.5-247.5), west (247.5-292.5), northwest (292.5-337.5), and north (337.5-360). The curvature of the earth-shaped layer was divided into 3 classes: 0, flat ground; 1, concave shape; 2, convex shapes. The hillshade layer was divided into two layers: 0 - shade, which is values less than 127° (shade), and 1 - light, which is values greater than 127° (light). The solar radiation layer was divided into 9 classes by using the natural break method (Jenks). The eastness, which is the east-west trend (sinaspect), and cell values range from -1 to +1 (Bader & Ruijten 2008). The northness, which is the north-south trend (cosaspect), and cell values range from -1 to + 1 (Bader & Ruijten 2008).

Remote sensing indicators

Satellite data from Landsat 8 were used to derive the following remote sensing indicators. The Normalized difference vegetation index (NDVI) was computed by the following equation (Tucker 1979 - eqn. 1):

$$NDVI = \frac{NIR - R}{NIR + R} \quad (1)$$

The Normalized Difference Water Index (NDWI), calculated as follows (Gao 1996 - eqn. 2):

$$NDWI = \frac{NIR - G}{NIR + G} \quad (2)$$

The Normalized Difference Moisture Index (NDMI), which was computed as (Wilson & Sader 2002 - eqn. 3):

$$NDMI = \frac{NIR - MIR}{NIR + MIR} \quad (3)$$

The Modified Soil Adjusted Vegetation Index (MSAVI), which is defined by the following equation (Qi et al. 1994 - eqn. 4):

$$MSAVI = \frac{2\,NIR + 1 - \sqrt{(2\,NIR+1)^2 - 8(NIR - R)}}{2}$$

The Disturbance Index (DI) was calculated as (Amiro & Chen 2003 - eqn. 5):

$$DI = MIR / NIR \quad (5)$$

while the simple ratio (SR) was obtained as follows (Knipling 1970 - eqn. 6):

$$SR = NIR / R \quad (6)$$

and the structure index (SI) using the equation (Fiorella & Ripple 1993 - eqn 7):

$$SI = NIR / MIR \quad (7)$$

where NIR is the near infrared spectral wavelength, R is the red spectral wavelength, G is the green spectral wavelength, and MIR is mid-infrared spectral wavelength. The soil moisture index (SMI) was computed using the following equation (Lambin & Ehrlich 1996 - eqn. 8):

$$SMI = \frac{LST_{max} - LST}{LST_{max} - LST_{min}} \quad (8)$$

where $LST_{max} = a_1 \times (NDVI) + b_1$, $LST_{min} = a_2 \times (NDVI) + b_2$; LST_{max} is the maximum earth surface temperatures corresponding to the value of the NDVI considered, LST_{min} is the minimum earth surface temperatures corresponding to the value of the NDVI considered, LST is the surface temperature at the target pixel corresponding to the value of the NDVI considered; a_1, a_2 are the slope coefficients in the linear regression model representing the relationship between surface temperature and NDVI, and b_1, b_2 are constants in the linear regression model.

All final GIS database layers were in raster format. After preparing these layers, the sample plot locations were overlaid on the maps to extract the corresponding predictor variables for further analysis (see Supplementary material).

Data analysis

In order to model the effects of environmental variables on the natural regeneration of *Cedrus libani* in the Jawbat Burghal region, all examined spatial, forest structure, topographic, and spectral variables were treated as continuous, except for the following, which were considered categorical: dominant forest type, shrub cover, litter type, stone size, slope, aspect, hillshade, and curvature. Binary Logistic Regression (BLR) analysis was performed in SPSS® v. 20 (IBM Corp., Armonk, NY, USA) using a backward-elimination algorithm based on the maximum-likelihood ratio test. Raster-based remote sensing data were converted into ASCII format and subsequently imported into SPSS for statistical modeling of the presence or absence of *C. libani* seedlings.

The logistic regression model is expressed in the equation (Lee & Pradhan 2007 - eqn. 9):

$$P=\frac{1}{1+e^{-Z}} \qquad (9)$$

where *P* is the estimated probability of occurrence of the dependent variable; its value ranges between 0 and 1, and the cut-off value is 0.5. *Z* is the linear relationship between the predictor variables that take values from -∞ to +∞; its values are given as follows (eqn. 10):

$$Z=b_0+b_1X_1+b_2X_2+\ldots+b_kX_k \qquad (10)$$

where b_0 is the constant logistic regression model, b_1-b_k are slope coefficients in the logistic regression model, and X_1-X_k are independent variables.

A multicollinearity test was conducted to ensure the independence of predictor variables and eliminate redundancy prior to model implementation. Variables with a Variance Inflation Factor (VIF) > 10 were excluded from the model to enhance the reliability of parameter estimates and overall model performance

Data evaluation

The significance of the logistic regression model was assessed using the Omnibus χ^2 test at a 5% significance level. Model performance was evaluated through several key indicators: Nagelkerke R^2, which reflects the proportion of variance in the dependent variable explained by the independent variables; the Hosmer-Lemeshow test, where a p-value greater than 0.05 indicates good model calibration and fit; overall classification accuracy, determined based on a specified cut-off value (*e.g.*, 0.05); and the ROC (Receiver Operating Characteristic) curve along with AUC (Area Under the Curve) values, which range from 0.5 to 1.0.

The relationship between AUC values and model prediction accuracy can be interpreted as follows: values between 0.9 and 1.0 indicate excellent performance; between 0.8 and 0.9, very good; between 0.7 and 0.8, good; between 0.6 and 0.7, moderate; and between 0.5 and 0.6, poor or weak performance (Yesilnacar 2005).

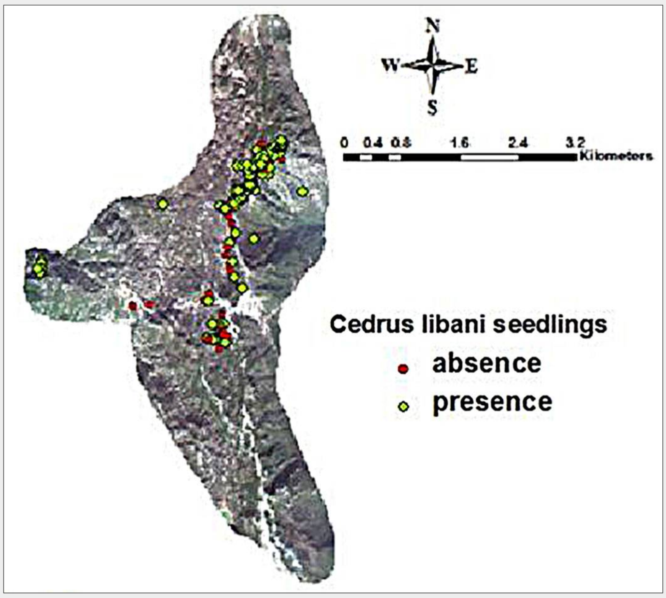

Fig. 1 - Sample plots of natural regeneration of *C. libani* in Jawbat Burghal.

Results and discussion

Current status of natural regeneration of C. libani

The mean density of *Cedrus libani* seedlings in the Jawbat Burghal forest was 11.75 individuals per 25 m^2, equivalent to approximately 4,700 individuals per hectare, with a presence probability of 71% (Fig. 1). Seedling age ranged from 1 to 5 years, with an average of 3 years, while height varied between 10 and 45 cm, averaging 25 cm. Saplings were aged between 15 and 30 years, with heights ranging from 50 to 250 cm.

A high proportion (98%) of *C. libani* seedlings were healthy. Regarding microsite distribution, 71% of seedlings were found in open areas, 16% in semi-exposed areas, and 13% under cedar crowns. This pattern reflects the species' light-demanding nature, although it can tolerate partial shade during early growth stages and occasionally at tree ages between 30 and 70 years (Boydak 2003).

Among other conifer seedlings, *Juniperus oxycedrus* L. and *Juniperus drupacea* Labill. showed the highest densities after cedar seedlings (61.5%), followed by *Quercus* spp. (38.5%), with an overall presence probability of 12.2% in the Jawbat Burghal forest.

The natural regeneration of *C. libani* in Jawbat Burghal is considered fair, with an average seedling density of 4,700 individuals ha^{-1}. However, the average sapling density (111 ind. ha^{-1}) remains lower than the adult tree density (330 ind. ha^{-1} – Sukumar et al. 1992), indicating potential limitations in seedling establishment and progression (Teketay 1997, Tesfaye et al. 2010). Such constraints are common in Mediterranean forests, where young woody species often experience slow growth due to climatic stress, resulting in longer transition periods from seedling to sapling than in tropical or temperate forests (Castro et al. 2006).

Logistic regression model analysis for the presence of C. libani seedlings

Spatial and forest structure model

The binary logistic regression model assessing spatial and forest structure variables was statistically significant (χ^2 = 0.0001, P < 0.05), explaining 59% of the total variation in *Cedrus libani* seedling presence (Nagelkerke R^2). The model effectively predicted the actual probability of seedling occurrence in the Jawbat Burghal forest, as confirmed by the Hosmer-Lemeshow goodness-of-fit test (χ^2 = 0.965, P > 0.05). An overall classification accuracy of 82.8% indicates strong model performance (Tab. 1).

Although tree and shrub cover did not significantly affect seedling presence, two variables emerged as significant predictors: stone coverage and distance from broadleaved trees. Their regression coefficients (B = 0.078 and 1.419, respectively – Tab. S1 in Supplementary material) suggest that higher stone coverage and greater distance from broadleaved trees positively influence the likelihood of *C. libani* seedling establishment. This finding aligns with Boydak (1996), who reported that *C. libani* seedlings thrive on bare karstic terrain with 70%-75% stone cover, which reduces evaporation and enhances seedling survival. Additionally, distance from broadleaved trees may reduce competition for water and nutrients while providing partial shade during

Tab. 1 - Classification accuracy of spatial and forest structure model.

Observed	Predicted		Perc. Correct
	Abs	Pres	
Absence	37	10	78.7
Presence	17	93	84.5
Overall Perc.	-	-	82.8

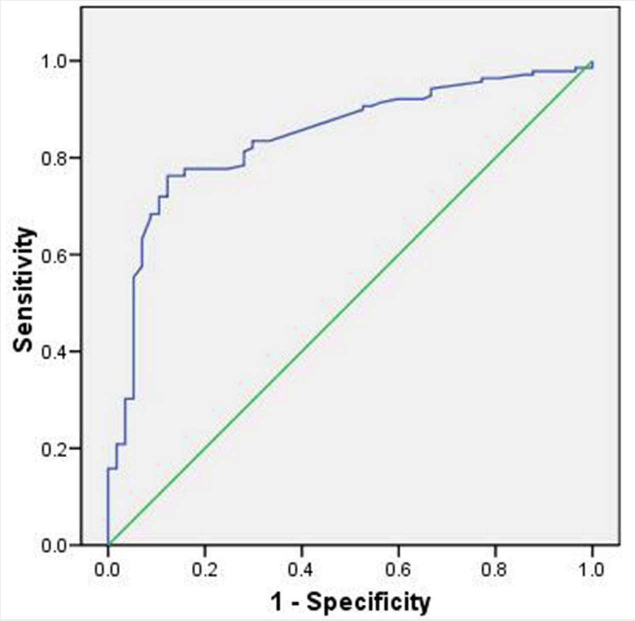

Fig. 2 - Area under the ROC curve for the spatial and forest structure model.

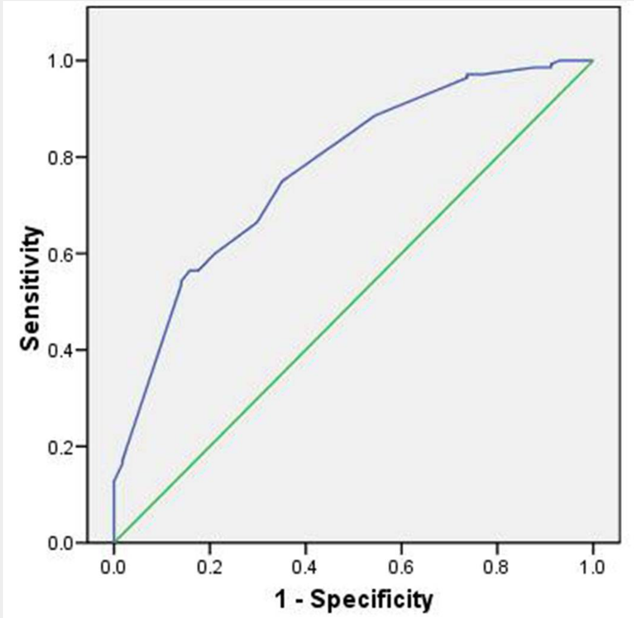

Fig. 3 - Area under the ROC curve for the topographic model.

hot, dry periods. Nahal (1962) observed that *C. libani* seedlings often establish under oak trees, benefiting from improved soil conditions and water uptake. However, broadleaved species can also act as strong competitors, especially in open areas, due to their rapid reproduction and shoot development (Bachir 2007).

The spatial relationships between plant species (competition, facilitation) can change over time; this temporal dynamics alters the relative sizes of individuals and their impacts on growth conditions and local climate fluctuations, thus the balance between competition and facilitation depends on the stages of plant life (Adili et al. 2013). The final logistic regression model is expressed as (eqn. 11):

$$Z=17.480+0.078(stone) +1.419(distance\_broad) \quad (11)$$

where *stone* and *distance_broad* are the stone coverage (%) and the distance from broadleaved trees, respectively.

Model performance, evaluated using the ROC curve, was rated as very good, with an AUC value of 0.84, indicating high predictive accuracy (Fig. 2).

Topographic model

The binary logistic regression model for topographic variables was statistically significant (χ^2 = 0.0001, P < 0.05), explaining 29% of the total variation in the presence of *Cedrus libani* seedlings (Nagelkerke R^2). The model effectively predicted the probability of seedling occurrence in the Jawbat Burghal forest, as confirmed by the Hosmer-Lemeshow goodness-of-fit test (χ^2 = 0.928, P > 0.05). An overall classification accuracy of 76.1% indicates that the model performs well at predicting the presence of *C. libani* seedlings (Tab. 2).

Tab. 2 - Classification accuracy of the topographic variables model.

Observed	Predicted		Perc. Correct
	Abs	Pres	
Absence	15	42	26.3
Presence	5	135	96.4
Overall Perc.	-	-	76.1

Among the topographic variables, aspect (particularly north-facing slopes), the second slope class (10-20°), and concave landforms were statistically significant contributors to model accuracy. In general, aspect had a negative influence on seedling presence, except for southwest-facing slopes, which showed a positive effect with a regression coefficient B of 18.721 (Tab. S2 in Supplemetary material). This finding aligns with Nahal (1962), who reported that *C. libani* prefers moist, wind-protected environments. Boydak (1996) also observed higher seedling mortality on sunny exposures than on shaded ones, suggesting that seed dispersal on sunny slopes must be 1.5 to 2 times greater than on shaded slopes under similar ecological conditions.

All slope classes positively influenced seedling presence, with the second slope class (10-20°) being particularly significant. The land shape had no significant effect generally on the probability of the presence of the *C. libani* seedlings; the convex land shape had an insignificant positive effect (B = 0.420) while the concave land shape had a significant negative impact (B = -3.038 – Tab. S2), likely due to increased erosion risk compared to convex terrain.

C. libani is considered a fairly light-demanding species, capable of growing under partial shade during its early stages and sometimes even during the tree stage between 30 and 70 years (Kalipsiz & Eler 1984). It can tolerate canopy cover up to 70 years of age, maintaining normal height growth, and adapts well to both vertical and lateral shading (Aksoy 1987). The resulting model is as follows (eqn. 12):

$$Z=24.036-4.837(north) +1.711(slope\,2)-3.038(curvature\,1) \quad (12)$$

where *north, slope2*, and *curvature1* are aspect (0-22.5°), slope (10-20°), and concave shape, respectively.

The model performance, evaluated using the ROC curve, was 0.77, indicating good predictive capability (Fig. 3).

Remote sensing indicators

The binary logistic regression model based on remote sensing indicators was statistically significant (χ^2 = 0.0001, P < 0.05), explaining 23% of the total variation in the presence of *Cedrus libani* seedlings (Nagelkerke R^2). The model effectively predicted seedling occurrence in the Jawbat Burghal forest, as confirmed by the Hosmer-Lemeshow goodness-of-fit test (χ^2 = 0.80, P > 0.05). An overall classification accuracy of 68.9% suggests that the model performs well in predicting *C. libani* seedling presence (Tab. 3).

Several spectral indicators were statisti-

Tab. 3 - Classification accuracy of spectral variables model.

Observed	Predicted		Perc, Correct
	Abs	Pres	
Absence	23	33	41.1
Presence	23	101	81.5
Overall Perc.	-	-	68.9

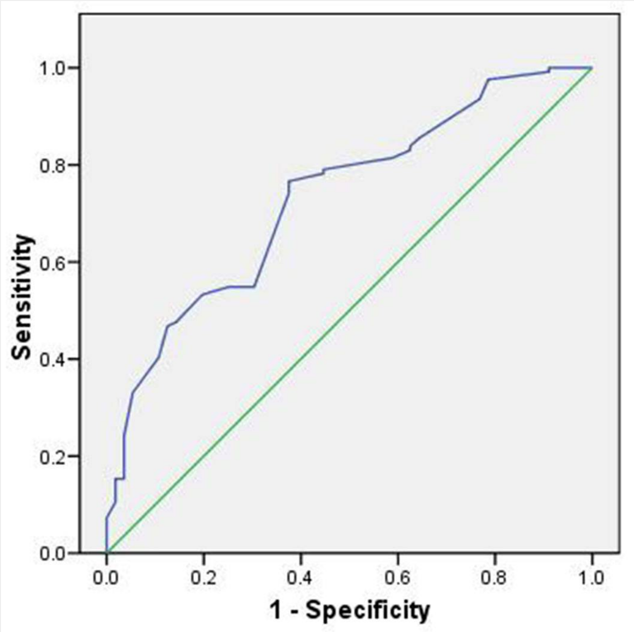

Fig. 4 - Area under the ROC curve for the spectral model.

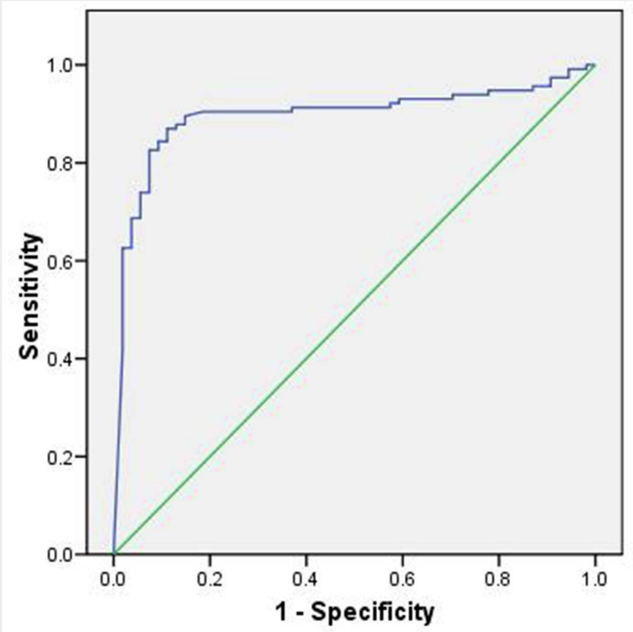

Fig. 5 - Area under the ROC curve for the environmental model.

cally significant, including NDWI, NDMI, MSAVI, and SMI. While NDWI, NDMI, and MSAVI exhibited negative effects on seedling presence, SMI demonstrated a positive influence. The corresponding regression coefficients B were -1.552, -1.225, -1.423, 1.318, respectively (Tab. S3 in Supplementary material). Higher soil moisture levels, indicated by elevated SMI values, were positively associated with *C. libani* seedling presence. This may be attributed to the presence of Jawbats, which are low-lying areas that retain water, creating favorable soil conditions, and contributing to increased precipitation rates in the region (Nahal 2003). Conversely, lower values of NDWI, NDMI, and MSAVI, indicating reduced moisture and overall vegetation health, were associated with higher probabilities of seedling presence. This pattern may reflect the vulnerability of forest cover to summer water stress in Jawbat Burghal (Goodwin et al. 2008) and suggests that *C. libani* seedlings can thrive in areas with reduced vegetation competition and potentially greater light availability (Nahal 2003).

Additionally, the frequent fog and cloud cover in the region contribute to elevated relative humidity, thereby enhancing growing conditions for *Cedrus libani* even during hot, dry periods (Nahal 2003). Peyre (1979) observed a strong correlation between high August temperatures and fog formation, which is favorable for *Cedrus* species. Notably, *C. libani* is found on the western slopes of the Lebanon mountain range overlooking the Mediterranean Sea but is absent from the eastern slopes. This absence is likely due to the absence of favorable environmental conditions, such as fog and cloud accumulation, which increase relative humidity and mitigate summer water loss, thereby supporting the survival of *C. libani*. The final logistic regression model is expressed as (eqn. 13):

$$Z = -13.480 - 1.552(NDWI) - 1.225(NDMI) - 1.423(MSAVI) + 1.318(SMI) \quad (13)$$

where NDWI, NDMI, MSAVI, and SMI are the normalized difference water index, normalized difference moisture index, modified soil adjusted vegetation index, and soil moisture index, respectively.

The model's performance, evaluated using the ROC curve, demonstrated good predictive capability (AUC = 0.73 – Fig. 4).

Tab. 4 - Classification accuracy of the environmental variables model. The cut value is .500

Observed	Predicted		Perc. Correct
	Abs	Pres	
Absence	42	4	91.3
Presence	4	91	95.8
Overall Perc.	-	-	94.3

All combined environmental variables

The combined binary logistic regression model, incorporating all environmental variables, was highly significant (χ^2 = 0.0004, $P < 0.05$) and explained 87% of the total variation in the presence of *Cedrus libani* seedlings (Nagelkerke R^2). The model demonstrated excellent predictive ability, as confirmed by the Hosmer-Lemeshow test (χ^2 = 0.979, $P > 0.05$), and achieved an overall classification accuracy of 94.3%, indicating that the model is only 5.7% away from perfect prediction (Tab. 4). This underscores its effectiveness in estimating the actual probability of *C. libani* seedling presence in the Jawbat Burghal forest.

Several environmental variables had a statistically significant positive effect on seedling presence, including: the third slope class (20-30°), distance from broadleaved trees, soil moisture index (SMI), shrub coverage percentage, coniferous litter, broadleaved litter, and stone coverage. Their respective regression coefficients B were 40.204, 7.094, 21.684, 1.352, 10.788, 40.646, and 0.415 (Tab. S4 in Supplementary material). Conversely, the following variables had significant negative effects: elevation, eastness layer, NDMI index, *C. libani* tree cover, coniferous shrub cover (except cedar), broadleaved shrub cover (except oaks), and litter thickness. Their regression coefficients B were -10.252, -12.293, -13.814, -36.676, -28.400, -67.792, -9.652, respectively (Tab. S4 in Supplementary material).

The positive relationship between shrub coverage and seedling emergence aligns with findings from Mediterranean forest studies. For example, Gómez-Aparicio et al. (2005) demonstrated a strong correlation between shrub presence and the emergence and survival of *Acer opalus* ssp. *granatense* seedlings. Similarly, Keyes & Maguire (2005) reported that shrub cover enhances the survival of *Pinus ponderosa* seedlings during the critical early weeks of establishment, particularly in summer when mortality rates are highest. Forest litter may inhibit initial seedling emergence but contributes positively to survival and long-term establishment (Ibáñez & Schupp 2002). The final regression model is expressed as (eqn. 14):

$$Z = -54.159 + 40.204(slope3) + 7.094(distance\_broad) + 21.684(SMI) + 1.352(shrub) + 10.788(litter\_type1) + 40.646(litter\_type2) + 0.415(stone) - 10.252(elevation) - 12.293(eastness) - 13.814(NDMI) - 36.676(type1) - 28.400(type\_shrub2) - 67.792(type\_shrub4) - 9.652(litter\_thick)$$

where *slope3* = slope (20°-30°), *distance_broad* = distance from broadleaved trees, *SMI* = soil moisture index, *shrub* = shrub coverage (%), *litter_type1* = coniferous litter, *litter_type2* = broadleaved litter, *stone* = stone coverage (%), *elevation* = elevation (m a.s.l.), *eastness* = eastness layer, NDMI = normalized difference moisture index, *type1* = *C. libani* tree cover, *type_ shrub2* = coniferous cover (except cedar shrub), *type_ shrub4* = broadleaved shrub cover (except oaks), *litter_thick* = litter thickness.

The model's performance, as assessed by the ROC curve, yielded an AUC of 0.90, indicating that the environmental model was highly effective (Fig. 5).

While shrub cover may not directly enhance seedling emergence rates, it significantly improves overall regeneration by reducing mortality during the first summer (Keyes & Maguire 2005). This pattern is consistent with many woody species in Mediterranean environments, where seedlings often survive and grow under shrub canopies, away from mature trees (Gómez-Aparicio et al. 2004).

The quality and quantity of forest litter vary with forest structure and composition, as well as with gradients in light, water, and temperature. These factors interact to influence litter decomposition rates and nutrient accumulation in the soil, which in turn affect species regeneration, seedling survival and growth, and the spatial distribution of forest species (Puerta-Piñero et al. 2006). Miina & Saksa (2006) suggest that litter thickness should be reduced to less than 3 cm to improve seedling establishment.

The spatial distribution of *C. libani* seedlings is shaped by a complex interplay of environmental factors, including light availability, litter characteristics, soil moisture, and canopy structure. Canopy cover influences microclimatic conditions and resource availability, thereby affecting seedling distribution through facilitation and competition (Holmgren et al. 1997).

Optimal forest cover density is considered a key factor in promoting seedling emergence and survival in Mediterranean forests. By modifying abiotic conditions, such as reducing evaporation and enabling deeper root access to soil moisture, appropriate canopy density enhances seedling resistance to summer drought (Sánchez-Gómez et al. 2006).

Conclusion

This study demonstrated that several environmental factors positively influence the presence of *Cedrus libani* seedlings in the Jawbat Burghal forest. These include low elevations, steep slopes (20-30°), greater distance from broadleaved trees, proximity to forest roads, open areas, increased shrub coverage, the presence of coniferous and broadleaved litter, and higher stone coverage. In contrast, factors such as dense cedar tree cover, coniferous shrubs (excluding cedar), broadleaved shrubs (excluding oaks), and excessive litter thickness negatively affect seedling emergence.

Given the harsh environmental conditions in Jawbat Burghal, particularly water stress and soil erosion, effective canopy management is essential. Regulating understory shrub density and reducing litter thickness can enhance seedling survival and establishment.

The environmental models developed in this study offer valuable insights into the ecological drivers of *C. libani* regeneration. These models provide a scientific basis for prioritizing forest management interventions to promote natural regeneration. Despite the limited distribution of *C. libani* forests in Syria, their ecological and floristic significance highlights the urgency of conservation efforts. Sustaining population dynamics and regeneration should be a central focus for conservation managers, and the predictive models presented here can serve as practical tools to guide strategic decision-making.

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Supplementary Material

Tab. S1 - Results of the spatial and forest structure variables model.

Tab. S2 - Results of the topographic variables model.

Tab. S3 - Results of spectral variables model.

Tab. S4 - Results of the environmental variables model.

Fig. S1 - Spectral indices maps of Jawbat Burghal forest.

Fig. S2 - Spectral indices maps of Jawbat Burghal forest.

Fig. S3 - Topographic maps of Jawbat Burghal forest.

Fig. S4 - Distribution of sample plots and environmental gradients in Jawbat Burghal.

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