

Hierarchical Forest Site Classification According to the Perennial Plant Species in the Alacadağ Nature Reserve District

Kubilay Yatman^{1*}, Serkan Gülsoy¹

(1) Isparta University of Applied Sciences, Faculty of Forestry, Department of Forest Engineering, TR-32260 Isparta, Turkey

Correspondence: e-mail: kblyytmn@gmail.com

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ABSTRACT

In the study, vegetation was classified according to the distribution of perennial plant species in the Alacadağ Natural Reserve (NR) district which has high plant species richness. Classified vegetation groups were modeled by using environmental factors. Using these models, vegetation communities were mapped according to hierarchical classification. A grid network with a cell size of 100 · 100 m was created and 150 sample plots of 20 · 20 m in size were established. Plant species coverage was recorded in field studies according to the Braun-Blanquet scale. Cluster analysis was applied for the classification of vegetation communities based on binary hierarchical classification. Cluster groups were modeled with environmental variables using the classification tree analysis. The accuracy of the vegetation groups as a result of cluster analysis and modeling was tested by chi-square, kappa, and multiple permutation analyses at each distinction stage. Model groups with significant results were generalized and mapped on digital layers by using the prediction values. Indicator species for the vegetation groups were identified by indicator species analysis. As a result of this process, the study area was divided into 4 vegetation groups. The elevation and, correspondingly, climate were the most effective environmental variables in the differentiation of vegetation groups. In addition, ruggedness, hillshade, roughness, and heat index were the other important environmental variables for the vegetation groups in the district. As a result of this study, forest sites were classified for the conservation, sustainability, development, and future planning of the Alacadağ NR region.

Keywords: Alacadağ Natural Reserve; clustering; modeling; classification; vegetation

INTRODUCTION

The presence, growth, development, death, regeneration, and productivity of plants are the most fundamental elements of change and dynamism in forest areas (McDowell et al. 2020). This change and dynamism maintain its continuity under the influence of human activities and natural factors. Within the current dynamism, environmental variables enable the formation of vegetation elements such as trees, shrubs, grasses, etc. in forest areas. The fundamental method for characterizing the spatial distributions, diversities, structural characteristics, and productivity of plant species in forest succession stages is the identification of their relationships with environmental factors (Siddiqui et al. 2013). However, communities within forest ecosystems are highly complex and contain a lot

of uncertain information that needs to be analysed. To reveal the correct information in this complex structure, communities first need to be classified and then ecologically related to environmental variables (Özkan and Negiz 2011). In other words, by associating living individuals or classified biotic communities with information pertaining to environmental variables in ecosystems, the complex interactions within the environment can be elucidated. For this purpose, it is imperative that detailed inventory studies be conducted primarily within ecosystems. During the inventory process, raw data pertaining to biotic and abiotic components are primarily collected from the field, followed by the processing of these data using various analytical techniques. This enables the acquisition of detailed and technical information about individuals and biotic communities.

It is technically possible to divide ecological research in forest sites into two subgroups: studies on autecology and on synecology (also known as community ecology) (Özkan et al. 2021). An important part of the studies completed in the field of community ecology in the literature consists of topics such as vegetation communities, biological diversity, and population behavior of living organisms. Vegetation classifications have an important place in these studies. In these studies, when vegetation-environment relationships are considered, the preferred dependent variables are perennial plant species. In this context, perennial plant species, which are non-motile organisms in their own sites, play a significant role in vegetation classification studies. Due to their longer life cycles, they exhibit greater spatial and temporal stability, making them reliable indicators of environmental gradients (Dengler et al. 2008, Kent 2011). Moreover, perennial species are less affected by short-term disturbances such as seasonal climatic fluctuations or episodic grazing (Kleyer et al. 2008), and they tend to persist even under moderate human or animal pressure. Additionally, compared to ephemeral annuals, perennials are often easier to identify during field surveys, as they are present for longer periods and retain diagnostic features more consistently (Chytrý et al. 2002, Özkan and Negiz 2011).

In vegetation classification studies, firstly, the recording of information on plant species (presence-absence or cover-abundance) is carried out according to the coordinates of the sampling sites through inventory studies in the forest area. To ensure the correct classification of vegetation, the execution of an accurate and successful inventory process is the most basic start (Grossman et al. 1998). In most studies on this subject, Braun-Blanquet (1932) method has been preferred (Chytrý and Otýpková 2003, Willner et al. 2009). Flora inventory data collected from different site conditions—once recorded manually—are now digitized and processed numerically, serving as a crucial input for vegetation classification. While analytical methods such as ordination and cluster analysis have long been used in phytosociology, the advent of computer-assisted multivariate techniques has significantly accelerated the analysis process and enabled the handling of large and complex datasets (De Cáceres and Wiser 2012). Thanks to these techniques, vegetation classification can be conducted hierarchically, while simultaneously identifying the distinctive plant species that are influential at each stage (Özkan et al. 2021). The most basic alternative methods that can be used to create vegetation groups objectively and analytically are association analysis (Williams and Lamberg 1959), cluster analysis (Pritchard and Anderson 1971) and two-way indicator species analysis (Hill 1979). These methods differ from each other by the use of alternative distance measurement formulas and by the detailed information they present in the result dendrograms.

After the classification of vegetation communities, the descriptive environmental variables for the resultant groups are identified. In this process, ordination methods, which commonly provide extensive and visual outputs, are frequently utilized (Fontaine et al. 2007, Özkan et al. 2009). It is possible to elaborate vegetation and environment relationships using various modeling techniques and to convert current model information into habitat or ecosystem classification maps using digital maps (Franklin 1995, Guisan and Zimmermann

2000, Elith and Leathwick 2009). These studies are generally referred to by different definitions, such as model-based ecosystem classification, ecological land classification, or forest site classification (Clare and Ray 2001, Bailey 2009). In the literature, it is also common to find studies where model-based vegetation-environment relationships are simulated and mapped according to climate change scenarios for future projections (Hickler et al. 2012, Hengl et al. 2018, Zhang et al. 2025, Zhao et al. 2025). In Türkiye, the number of studies that classify and map vegetation communities in forest areas is very limited (Özkan and Gülsoy 2010, Özkan and Mert 2011). It is known that a substantial portion of the existing studies do not employ modeling techniques. In other words, forest site classification studies that address model-based relationships for vegetation classification in Türkiye are almost non-existent (Özkan 2014). Although this is the case, the fact that the country's forest areas contain many different plants and living species, high biological diversity, complex land structure and geomorphological formations, as well as have a very high climatic variation, large forest areas and manage these areas sustainably make it obligatory to classify vegetation communities in our forest areas.

Forest site classification plays an important role in ecological planning and the sustainable use of forest resources. Considering the variation of plant species and vegetation communities in forest sites within ecosystems with a large and very heterogeneous geographical structure and variation in environmental factors, such as Türkiye, the results vary. Therefore, there is a growing need for forest site classification studies to be conducted at multiple spatial scales such as regional, local, and watershed levels to support ecologically relevant planning and adaptive forest management. At this stage, protected areas, particularly those with high ecological value or complex management needs, represent important forest units where forest site classification studies can provide significant contributions, both at national and international scales. To support the sustainability of the protected areas and to guide natural restoration efforts when needed, model-based forest site classification represents a valuable approach, particularly in data-driven contexts, even though it can be complemented by other ecological assessment and planning methods. This study, on this basis, was performed to classify, model and map vegetation communities according to perennial woody and herbaceous plant species in Alacadağ Nature Reserve in Finike district of Antalya province. The results from the study are aimed to provide important information regarding planning, protection and management of the area. The potential of this study to serve as a practical guide for places with protected area status on both national and international level is significant.

MATERIALS AND METHODS

Study Area

The study area, Alacadağ Nature Reserve (NR), which was designated as a protected site in 2017, is located between 36° 25' 00" and 36° 18' 43" north latitudes, and 30° 01' 30" and 30° 05' 24" east longitudes. Alacadağ NR is situated in the southwestern part of the Beydağları section, within the boundaries of the Finike and Demre districts in the western

Mediterranean region of Türkiye (Figure 1). Although Alacadağ NR itself covers approximately 425 hectares, the study area was extended to a total of 4,012 hectares, including the surrounding forested zones. This broader scope was chosen to assess how ecologically distinct Alacadağ NR is from its adjacent vegetation, thereby enabling a more robust and meaningful forest site classification.

Most of the mountains seen in a rugged structure in the area are in the form of an extension of the Western Taurus Mountains, and the highest point of the area is the Alacadağ with a height of 2,302 m (Öner and Vardar 2018). According to the Thornthwaite method (1948), the moisture effective index (Im) in the Alacadağ region has been determined to be 24.21. Based on this value, the prevailing climate type and precipitation effectiveness class in the region were characterized as "humid".

The study area contains a large number of tree species, including rare forest tree species, and mostly reflects the characteristics of the Mediterranean floristic region in terms of vegetation diversity. Due to variables such as land surface forms, soil characteristics, and differences in elevation, it is possible to observe a wide variety of vegetation structures within the area. In the forests of the study area, the predominant species are *Cedrus libani* A. Rich var. *libani*, *Juniperus excelsa* M. Bieb subsp. *excelsa*, *Juniperus foetidissima* Willd., *Pinus brutia* Ten., and various deciduous tree species. Apart from forest vegetation, the area is dominated by bush vegetation in the form of maquis, steppe vegetation in high mountainous parts and rock vegetation with steep slopes where forest cover is not dominant. In addition, in some parts of the area, it is possible to come across aquatic vegetation

structure and grassland, pasture or meadow vegetation. All these vegetation differences mentioned in the area enrich the region in terms of habitat diversity, ecological diversity and species diversity.

Land Survey and Data Preparation

Digital elevation model (DEM) was created according to the area boundaries by using the contour curves of the 1/25,000 scale topographic maps (P24-A1-95 and P24-A4-95). In the inventory process, perennial woody and herbaceous plant species were recorded in 150 sample plots (20 · 20 m), distributed according to a stratified sampling design. Strata were defined based on key environmental gradients, including elevation (low, mid, high zones), slope classes (gentle, moderate, steep), and dominant vegetation types (forest, bush/maquis, steppe). The plots were proportionally allocated within each stratum and positioned to maximize coverage while avoiding spatial clustering. The coordinates of all sample plots were recorded as in the UTM WGS84 coordinate system using the Global Position System (GPS). In each of these areas distributed between 374 and 1,866 m, the abundance and cover of perennial plant species were visually assessed and recorded using the semi-quantitative Braun-Blanquet (1932) cover-abundance scale. Then, this data set was converted into binary data (presence-absence) and prepared for statistical analysis.

Following the field studies, the previously created DEM was used in ArcGIS, and elevation, slope, ruggedness, roughness and hillshade index, and topographic position index maps of Alacadağ NR were created, respectively (Jeness 2006). The radiation index and heat index maps were

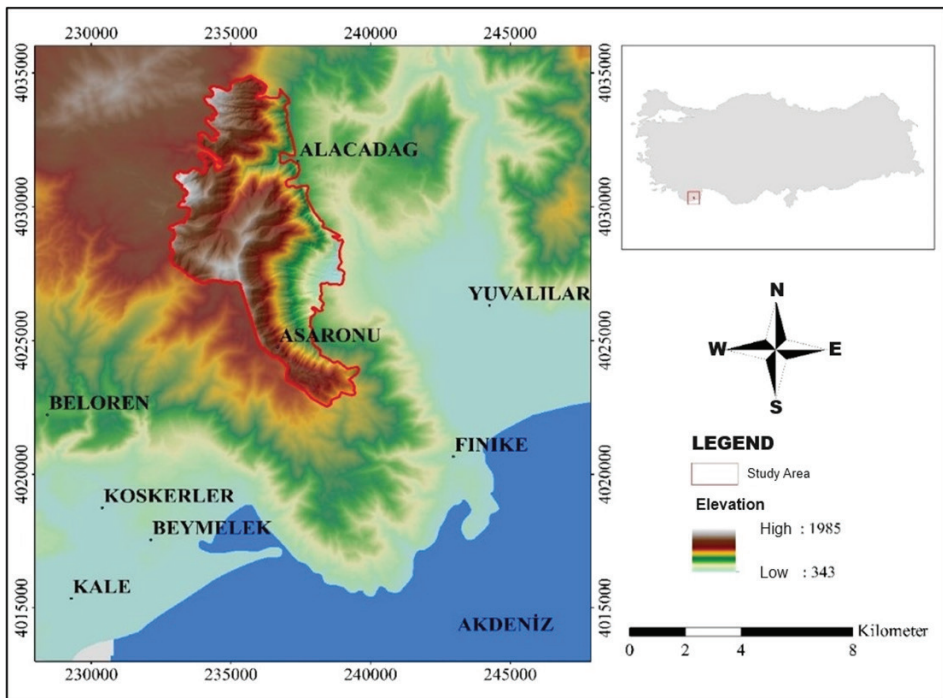


Figure 1. Study area: the Alacadağ NR district map .

created by calculating with the relevant formulas (Moisen and Frescino 2002, Aertsen et al. 2010, Wei et al. 2010, Brown and Ahl 2011). For climate maps 19 different bioclimatic variables (750 m resolution) by Hijmans et al. (2005) were downloaded in ASCII format, cut at the scale of the study area and made ready for use. The coordinates of 150 sample plots were transferred to the digital bases and the data were obtained for all descriptive environmental variables. These variables were given codes and prepared for the statistical analysis (Table 1).

Statistical Evaluation

Within the scope of the research, the vegetation classification approach was applied under the principle of binary analytic hierarchical distinction (Özkan et al. 2013). At this stage, the vegetation data matrix was evaluated by cluster analysis (McCune and Grace 2002). In the cluster analysis, the Jaccard-Ward method was applied in the selection of the combination of distance measurement and group distinction technique. The groups identified through cluster analysis were recorded as class variables and modeled with environmental variables using the classification tree method (De'ath and Fabricius 2000). Receiver Operating Characteristic (ROC) analysis was applied to test the performance of the models (Hanley and McNeil 1982). Bioclimatic variables were examined for multicollinearity using Pearson correlation analysis (Özdamar 2013). Variable pairs with high correlation coefficients ($r \geq 0.80$) were considered redundant, and in such cases, the variable with lower ecological relevance or interpretability was excluded from further analysis. In order to determine the degree of agreement between vegetation groups obtained hierarchically through cluster analysis and model groups, chi-square tests (Cole 1949), Cohen's kappa statistics (Cohen 1960, Viera and Garrett 2005) and Multi-Response Permutation Procedure (MRPP) test

(Zimmerman et al. 1985) were applied at each distinction stage, respectively (Poole 1974, Ozkan 2002). Indicator plant species of vegetation groups with statistically significant results were identified through indicator tests (Dufrene and Legendre 1997, Negiz et al. 2015). Following these analyses, ArcGIS software was utilized to map forest site classes in a hierarchical order. Statistical analyses within the scope of the study were performed in open-source R-Studio using AUC (Ballings and Van den Poel 2013), cluster (Maechler 2013), factoextra (Kassambara and Mundt 2020), dendextend (Galili 2015), caret (Kuhn et al. 2020), chisq. posthoc.test (Ebbert 2019), corrplot (Wei and Simko 2017), ROCR (Sing et al. 2005), and tree (Ripley and Ripley 2016) packages. Additionally, PCOrd software was used to conduct the Multi-Response Permutation Procedure (MRPP) to test the statistical significance of group differentiation, while DTREG software was used to perform indicator species analysis to identify diagnostic species associated with specific forest site types.

RESULTS

As a result of the inventory studies carried out in 150 sample plots, 60 different tree and shrub species and 8 perennial herbaceous species (with distinctive forest site characteristics) were included in the vegetation data matrix in the study. Considering the frequency of these plant species in the sample plots, 37 of the perennial woody species and 4 of the perennial herbaceous species had frequency values greater than 3%. From this point of view, the vegetation data matrix created with a total of 41 plant species was subjected to analytical evaluation for forest site classification in the study (Table 2).

Table 1. The environmental variables included in the study and their abbreviations.

Environmental variable	Abbreviation	Environmental variable	Abbreviation
Elevation (m)	Elvtn	Temperature Annual Range (BIO5-BIO6)	bio7
Slope (°)	Slope	Mean Temperature of Wettest Quarter	bio8
Radiation Index	RadInd	Mean Temperature of Driest Quarter	bio9
Heat Index	HeatInd	Mean Temperature of Warmest Quarter	bio10
Ruggedness	RggedI	Mean Temperature of Coldest Quarter	bio11
Roughness	RoughI	Annual Precipitation	bio12
Topographic Position Index	TPI	Precipitation of Wettest Month	bio13
Hillshade Index	Hillsh	Precipitation of Driest Month	bio14
Annual Mean Temperature (°C)	bio1	Precipitation Seasonality (Coefficient of Variation)	bio15
Mean Diurnal Range (monthly average (max. Temperature - min. Temperature)) (°C)	bio2	Precipitation of Wettest Quarter	bio16
Isothermality (BIO2/BIO7 (-100))	bio3	Precipitation of Driest Quarter	bio17
Temperature Seasonality (standard deviation · 100)	bio4	Precipitation of Warmest Quarter	bio18
Max Temperature of Warmest Month	bio5	Precipitation of Coldest Quarter	bio19
Min Temperature of Coldest Month	bio6		

Table 2. Plants to be statistically evaluated and their abbreviations.

Species	Abbreviation	Species	Abbreviation
<i>Acer hyrcanum</i> subsp. <i>sphaerocaryum</i>	AceHyr	<i>Olea europaea</i> L. subsp. <i>slyvestris</i> (Miller) Lhr.	OleEur
<i>Arbutus andrachne</i> L.	ArbAnd	<i>Origanum onites</i> L.	OriOni
<i>Asparagus acutifolius</i> L.	AspAcu	<i>Ostrya carpinifolia</i> Scop.	OstCar
<i>Calicotome villosa</i> (Poir.) Link	CalVil	<i>Paliurus spina-christi</i> P. Mill.	PalSpi
<i>Capparis spinosa</i> L.	CapSpi	<i>Phillyrea latifolia</i> L.	PhiLat
<i>Cedrus libani</i> A.Rich.	Cedlib	<i>Phlomis grandiflora</i> H.S.Thompson var. <i>Grandiflora</i>	PhlGra
<i>Celtis australis</i> L. sp. <i>australis</i>	CelAus	<i>Phlomis lycia</i> D. Don	PhlLyc
<i>Cercis siliquastrum</i> L.	CerSil	<i>Pinus brutia</i> Ten.	Pinbru
<i>Cistus creticus</i> L.	CisCre	<i>Pistacia terebinthus</i> L. Subsp. <i>terebinthus</i>	Slopes
<i>Cotinus coggygria</i> Purpose.	CotCog	<i>Prunus divaricata</i> Ledeb. var. <i>divaricata</i>	PruDiv
<i>Crataegus monogyna</i> Jacq. var. <i>monogyna</i>	CraMon	<i>Pteridium aquilinum</i> (L.) Kuhn	PteAqu
<i>Cyclamen graecum</i> subsp. <i>anatolicum</i> Letsw.	CycGra	<i>Quercus coccifera</i> L.	QueCoc
<i>Erica manipuliflora</i> Salisb.	EriMan	<i>Quercus infectoria</i> Oliv. subsp. <i>infectoria</i>	QueInf
<i>Euphorbia kotschyana</i> Fenzl.	EupKot	<i>Rosa canina</i> L.	RosCan
<i>Fraxinus ornus</i> L. Subsp. <i>Ornus</i>	FraOrn	<i>Salvia tomentosa</i> Mill.	SalTom
<i>Genista acanthoclada</i> DC.	GenAca	<i>Smilax aspera</i> L.	SmiAsp
<i>Inula heterolepis</i> Boiss.	InuHet	<i>Styrax officinalis</i> L.	StyOff
<i>Juniperus excelsa</i> M.Bieb. subsp. <i>excelsa</i>	JunExc	<i>Thymelaea tartanraira</i> (L.) All.	ThyTar
<i>Juniperus foetidissima</i> Willd.	JunFoe	<i>Verbascum cheiranthifolium</i> Boiss.	VerChe
<i>Juniperus oxycedrus</i> L.	JunOxy	<i>Verbascum sinuatum</i> L.	VerSin
<i>Laurus nobilis</i> L.	LauNob		

In the study, a Pearson correlation analysis was initially conducted to identify descriptive variables with high correlation ($r > 0.85$) that could lead to multicollinearity issues in the models. As a result of the analysis, all climate variables except for bio2 and bio12 were found to be highly correlated with elevation (Elvtn). Therefore, a total of 10 variables were chosen for the modeling processes: 8 topographical (Elvtn, Healnd, Hillsh, RadInd, Roughl, Rggedl, Slope, TPI) and 2 bioclimatic (bio2, bio12).

According to the cluster analysis applied based on the hierarchical vegetation distinction, the vegetation classification of Alacadağ NR was completed in 3 stages. The vegetation groups obtained by cluster analysis were modeled with the classification tree technique with environmental variables as dependent variables at each

distinction stage. The ROC (receiver operating characteristic) values of the training and test data sets at each distinction stage and the descriptive variables in the models are given in Table 3.

Cohen's kappa statistics, chi-square values, and their significance levels ($p < 0.05$) calculated based on the number of sample plots that have deviated and shifted between the vegetation groups obtained from the cluster analysis and the model groups formed as a result of the modeling analysis are presented in Table 4.

As a result of the cluster analysis and classification tree models, the model groups that were significantly ($p < 0.05$) separated from each other were classified into four different forest site classes, coded as MG1, MG2-1, MG3-1, and MG3-2 (Figure 2).

Table 3. Receiver operating characteristic (ROC) values and the descriptive variables as a result of the classification tree.

Stages of forest site classification	Training ROC	Test ROC	Model parameters
1 st	0.91233	0.85133	Elvtn, Rggedl, Hillsh
2 nd	0.82170	0.75138	Rggedl, Elvtn
3 rd	0.84079	0.71266	Roughl, Healnd, Elvtn

Then, a Multi-Response Permutation Procedure (MRPP) test was used to determine intergroup distance (T) and intragroup homogeneity (A) values in these model groups at each distinction stage (Table 5).

According to the results of the MRPP test, the distance of the model groups to each other was the highest at the first distinction stage, while the intra-group homogeneity value was the highest at the second distinction stage. In the next part, the distinctive indicator plant species of these forest site classes at the local scale were determined. Consequently, the hierarchical site classification of forest areas in Alacadağ NR was completed, and a final map containing indicator species for each forest site class was obtained (Figure 3).

In Alacadağ NR, four different forest site classes were obtained at three distinction stages. At the end of the first distinction stage, the variables of elevation, ruggedness index and hillshade index were decisive for the formation of forest site classes. According to the model rules, Alacadağ NR was classified into a separate forest site named Model Group 1 (MG1) based on the following criteria: a) areas with an elevation above 1,538.5 meters and a ruggedness index greater than 0.0428, and b) areas with an elevation between 1,118.5 meters and 1,538.5 meters, with a ruggedness index greater than 0.0428, and a hillshade index greater than 109.5. Correspondingly, Model Group 2 (MG2) was classified based on the following criteria: a) areas with an elevation less than or equal to 1,188.5 meters, b) areas with

Table 4. The numbers and statistical results of sample plots showing deviation between cluster groups and model groups in the forest site classification process.

Stages of forest site Classification	Number of deviated plots		Kappa statistics	Chi-squared value	p
1 st	CG1 » MG1	CG2 » MG2	0.723	172.531	0.000
	10 plots	3 plots			
2 nd	CG1 » XG	CG2 » MG2-1	0.704	57.589	0.000
	6 plots	3 plots			
3 rd	CG1 » MG3-2	CG2 » MG3-1	0.710	54.381	0.000
	12 plots	4 plots			

CG – cluster group 1; MG – model group; XG – the group under continued separation; p – significant at the 0.05 level ($p < 0.05$)

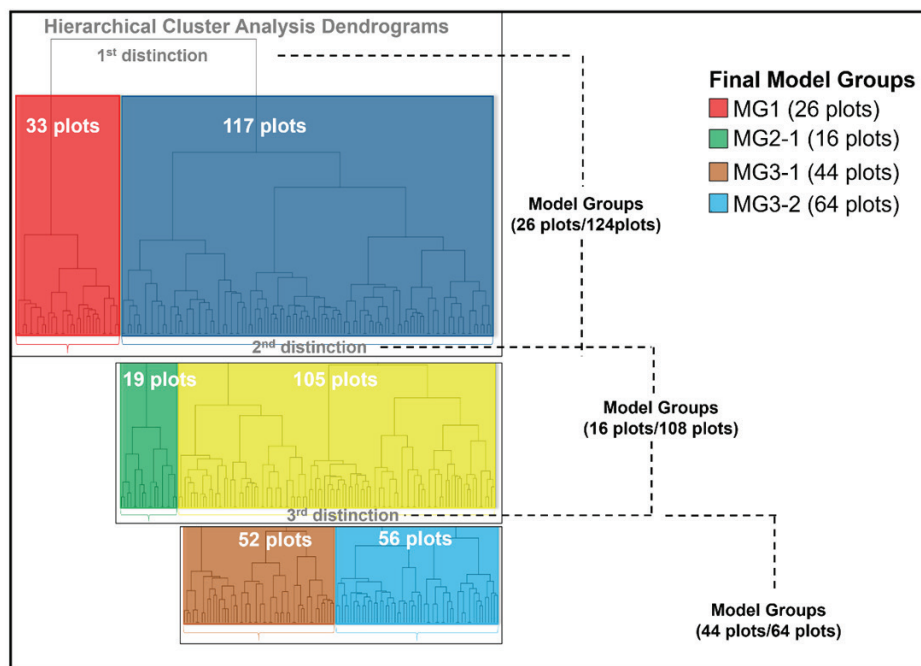


Figure 2. Cluster analysis processes applied to the vegetation data matrix according to Jaccard-Ward's method.

Table 5. Multi-Response Permutation Procedure (MRPP) test results in model groups of each distinction stage for Alacadağ Natural Reserve.

Distinctions	T	A	p
1 st distinction stage	-31.821	0.044	0.000
2 nd distinction stage	-29.403	0.047	0.000
3 rd distinction stage	-15.877	0.028	0.000

T – distance value of the model groups; A – intra-group homogeneity value; p – significant at the 0.05 level ($p < 0.05$)

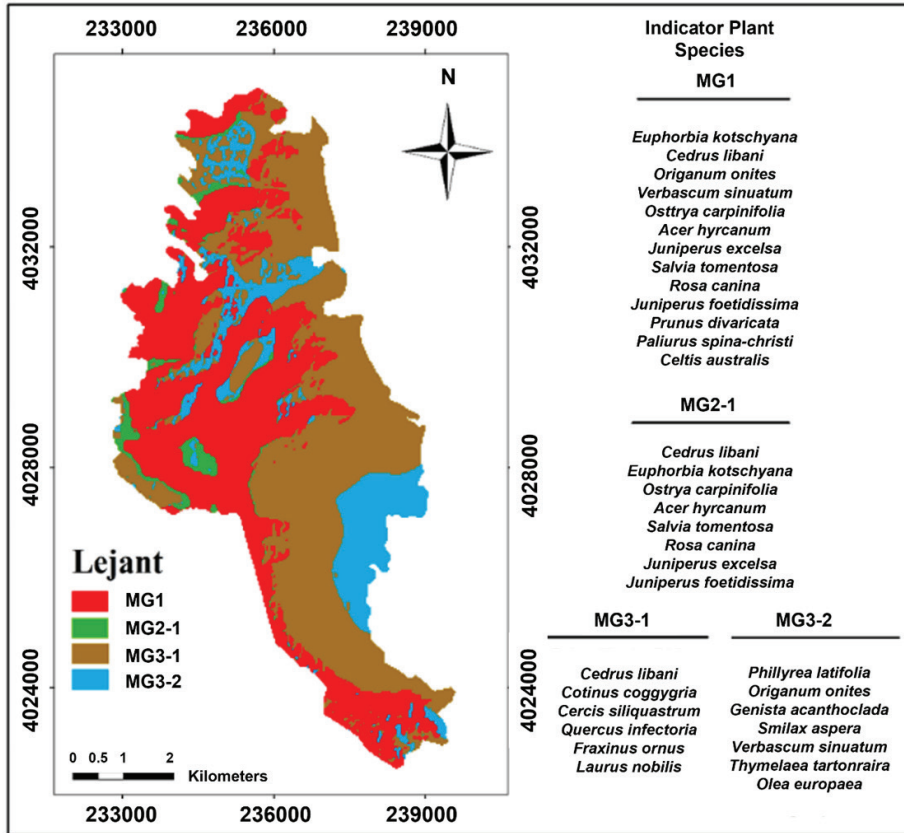


Figure 3. Model-based forest site classes and their associated significant indicator plant species ($p < 0.05$).

an elevation greater than 1,188.5 meters and a ruggedness index less than or equal to 0.0428, and c) areas with an elevation between 1,188.5 meters and 1,538.5 meters, with a ruggedness index greater than 0.0428, and a hillshade index less than or equal to 109.5.

The MG1 represents *Cedrus libani* forests of the district, which are generally between 1,100 and 1,500 m, in shady areas with a lot of ruggedness, and more rugged areas above 1,500 m. In addition, important distinguishing plants in this habitat class were *Acer hyrcanum* subsp. *sphaerocarum*, *Juniperus excelsa*, *Juniperus foetidissima*, and *Ostria carpiniifolia* Scop. MG2, on the contrary, represents general forest sites in lower hilly and less shaded areas between 1,100 and 1,500 m in elevation. These areas generally

correspond to the description of the *Pinus brutia* forest sites in Alacadağ NR, extending from the lowest elevation to the highest elevation limit. In MG2, the most dominant distinguishing species are *Quercus coccifera* L., *Pistacia terebinthus* L., *Arbutus andrachne* L., *Cotinus coggygria* Scop., *Cistus creticus* L., and *Phillyrea latifolia* L., which are typical indicators of the Mediterranean phytogeography. At the end of the first classification stage, MG1 in Alacadağ Nature Reserve was not further subdivided into another class, while MG2 was further divided into two distinct forest site classes coded as MG2-1 and MG2-2.

MG2, as described above, generally represents forest areas below 1,500 m. In MG2, ruggedness index and elevation variables were decisive in the distinction of forest

site classes. According to the model rules at this stage, in Alacadağ NR areas with an elevation greater than 1,530.5 meters and a ruggedness index greater than 0.0365 were classified as a separate forest site class, MG2-1. The indicator plant species of the MG2-1 forest site were found to be quite similar to those of the MG1 forest site, which is classified at a higher level. The most dominant distinguishing species that set MG2-1 apart from MG1 are *Origanum onites* L., *Verbascum sinuatum* L., *Paliurus spina-christi* P. Mill., *Prunus divaricata*, and *Celtis australis*. The model rules defining the MG2-2 forest site class within the MG2 category are as follows: a) areas with an elevation less than or equal to 1,530.5 meters, and b) areas with an elevation greater than 1,530.5 meters where the ruggedness index is less than or equal to 0.0365. The MG2-2 forest site is represented by the association of tree and shrub species including *Pinus brutia*, *Quercus coccifera*, *Pistacia terebinthus*, *Cistus creticus*, *Cotinus coggygria*, *Arbutus andrachne*, and *Genista acanthoclada* DC. In this forest site class, *Genista acanthoclada* is included as a different distinguishing species, while *Phillyrea latifolia*, which is present in the MG2 forest site, is not found here. At the end of the second classification stage, MG2-1 in Alacadağ NR was not further subdivided into another class, while MG2-2 was further divided into two distinct forest site classes coded as MG3-1 and MG3-2.

In the third classification stage, the variables that influenced the determination of forest site classes in Alacadağ Nature Reserve were, in order, ruggedness index, heat index, and elevation. According to the new model rules obtained within MG2-2, the following were classified as a separate forest site class coded as MG3-1: a) areas where the ruggedness index is greater than 11.698, and b) areas where the ruggedness index is less than or equal to 11.698, the heat index is greater than 0.842, and the elevation is greater than 861.5 meters. The dominant distinguishing species of this forest site are *Cedrus libani*, *Cotinus coggygria*, *Cercis siliquastrum* L., *Quercus coccifera*, *Fraxinus ornus*, and *Laurus nobilis* L. Based on this information, it is understood that the rugged terrain structure shaping from the lower elevations to the upper elevation steps of Alacadağ NR is the most defining environmental descriptor for this forest site. According to the other model rules at this stage, a) areas where the ruggedness index is less than or equal to 11.698 and the heat index is less than or equal to 0.842, and b) areas where the ruggedness index is less than or equal to 11.698, the heat index is greater than 0.842, and the elevation is less than or equal to 861.5 meters, were classified as the forest site class coded as MG3-2. For MG3-2, the most prominent distinguishing species are *Origanum onites*, *Smilax aspera* L., *Genista acanthoclada*, *Phillyrea latifolia*, *Verbascum sinuatum*, *Thymelaea tartonraira* (L.) All., and *Olea europaea* L. In the shaping of this forest site, the parts where the heat index is high at the lowest elevation step of the region were decisive.

DISCUSSION

Increasing demands on forest ecosystem services such as timber supply, carbon storage, biodiversity, and recreation driven by continued population growth and land-use change, are placing escalating pressure on forest

areas globally (Dublin et al. 2004, Sloan and Sayer 2015, Curtis et al. 2018, FAO 2022). On the other hand, forests are being destroyed as a consequence of global threats such as climate crisis and environmental pollution, whose effects we can already experience today. Given the widely accepted prediction that the Mediterranean basin is one of the most vulnerable regions to the climate crisis characterized by rising temperatures, prolonged droughts, and increasing wildfire risks, monitoring the status of Türkiye's Forest ecosystems, particularly of the protected areas, has become increasingly important (Cramer et al. 2018, Lionello and Scarascia 2018, Lee et al. 2023). The results of this study demonstrate that vegetation classification based on perennial woody and herbaceous species, combined with environmental modeling, is an effective approach for defining forest site classes within protected areas such as Alacadağ Nature Reserve. By identifying ecologically distinct vegetation communities and mapping their spatial distribution, we have provided a practical foundation for monitoring ecological changes and supporting forest planning efforts under the principles of sustainability (Guisan and Theurillat 2000, Fontaine et al. 2007, Özkan 2009).

The identification of forest site classes that host high species diversity, endemic or relict taxa, and ecologically valuable resources such as medicinal and aromatic plants, plays a crucial role in determining priority areas for conservation and sustainable management. These findings are particularly relevant given the increasing threats to natural forest ecosystems due to climate change, pollution, forest pests, invasive species, fires, and grazing pressure (Başkent et al. 2003, Özkan and Gülsoy 2010, Özkan and Mert 2011). The generated maps can serve as baseline tools for forest managers to track ecosystem dynamics, assess site-specific pressures, and support regionally adaptive decisions.

In a global context where the loss of natural forest areas is accelerating, particularly in biodiversity hotspots like the Mediterranean region, the strategic conservation of intact forest ecosystems has become increasingly important (Brujnzeel 2004, Ticktin 2004). Our study reinforces the notion that protected forest sites serve as crucial gene pools and refugia for endemic and rare species, while simultaneously providing essential ecosystem services such as hydrological regulation, soil protection, bioenergy potential, and carbon sequestration.

Therefore, the integrative approach employed in this study—linking vegetation to environmental gradients and generating model-based site classification maps—contributes valuable insights for modern forestry practices. These outputs support both conservation and utilization objectives, providing actionable data for long-term ecological monitoring and sustainable resource use in Alacadağ NR and similar protected areas.

As a result of all the applied classification and modeling processes, the Alacadağ NR district was divided into four different forest site classes and mapped accordingly. Similar studies have been carried out in Türkiye and abroad for the purpose of the planning of forest ecosystems, the improvement of destroyed forest communities and the conservation of natural resources (Brzeziecki et al. 1993, Zimmermann and Felix 1999, Miller and Franklin 2002, Fontaine et al. 2007, Liu et al. 2009, Özkan and Negiz 2011).

Since plant species characterize the features of their habitats, the obtained model-based vegetation distribution maps are an important ecological information pool. In the case of forest sites they represent and serve as a guide for planners. In other words, the classification of vegetation communities and forest sites is important for the planning of forest ecosystems accurately in the future. On the other hand, with the information from such studies, the future status of species and vegetation communities during a possible climate change can be predicted (Thomas et al. 2004). Therefore, if future climate scenarios are included in such models, it is possible to determine the effects of climate change on vegetation communities or the distribution of species.

In light of the provided information, this study modeled the relationships between the distribution of perennial woody and herbaceous species and environmental variables in a hierarchical manner. Considering all the results, the environmental variables that were effective in the distinction of the forest sites were elevation, hillshade and ruggedness index, heat index and roughness index. In general, the elevation variable was the most effective in the distinction of the groups. In general, elevation was the most influential environmental variable in the classification of forest site types in Alacadağ NR. It can be said that all other climatic factors, primarily temperature and precipitation, which vary with elevation, are also decisive here. This indicates that potential future climate change will have a significant impact on such protected areas. Therefore, to manage the process most accurately in these areas, there is a need for up-to-date and modern conservation action plans. In this context, model-based forest site classification and maps are among the most important guiding resources.

The final forest site classification map obtained in this study has significant advantages compared to maps produced by the classical approach. The first of these advantages is that the proximity of the different forest site units separated on the map can be determined much more clearly. In other words, it is much easier to perceive how close or distant these units are to each other in terms of their ecological characteristics. For example, in this study, the similarity between the MG1 forest site from the first classification stage and the MG2-1 forest site from the second classification stage was determined using this approach. The hillshade index has been particularly decisive in the distinction of these sites. The MG2-2 vegetation group, which has been distinguished within the MG2 forest site, is characterized by typical Red Pine forests (*Pinus brutia*) and warm Mediterranean and maquis elements. The first distinction within this vegetation group, MG3-1, represents areas above approximately 850 meters and extending to the upper limit of *Pinus brutia* in sunny aspects. In the lower elevations of this forest site, species such as *Cotinus coggygria*, *Laurus nobilis*, *Cercis siliquastrum*, and *Quercus infectoria* are identified, while distinguishing species such as *Cedrus libani* and *Fraxinus ornus* are found at higher elevations. The MG3-2 vegetation group has revealed a forest site characterized by warm Mediterranean, maquis, or garrigue communities dominated by distinguishing species such as *Origanum onites*, *Smilax aspera*, *Genista acanthoclada*, *Phillyrea latifolia*, *Verbascum sinuatum*, and *Olea europaea*. These species are generally distributed below approximately 850 meters in Alacadağ NR, in areas with less rugged terrain compared to higher elevations.

In conclusion, this study's results are of great importance in terms of determining the regional limits of seed transfer between similar growing environments or determining strategies to increase the diversity in the area through distinctive species. In this way, appropriate strategies can be determined for more effective conservation of the area under changing environmental conditions. The tangible outcomes obtained from the study can be utilized in the process of taking measures to protect species against factors that may have adverse effects on the ecosystem, such as the climate crisis, fire, insect damage, invasive species, and environmental pollution. All the findings in this study were determined by using analytical methods. With the information obtained from these methods, the boundaries of the forest site types identified in the area can be monitored in the future. In this way, it will be possible to observe the effects of adverse events such as the climate crisis on the natural site in the future. Additionally, this study provides indirect information for important ecosystem functions such as wildlife, erosion prevention, clean water, the conservation of endemic, rare, and relic plant species, and the use of medicinal aromatic plants in the district. In summary, when all the results revealed in the study are taken into consideration, it is concluded that the study can facilitate both scientific and practical applications.

CONCLUSIONS

This study highlights the crucial role of integrating vegetation-based classification with environmental modeling for the sustainable management of forest ecosystems, particularly within sensitive and protected Mediterranean landscapes such as Alacadağ Nature Reserve. The results demonstrate that elevation and topographical heterogeneity are key determinants of forest site differentiation, shaping the distribution of both woody and herbaceous perennial species. By linking floristic composition with environmental gradients, this approach offers a reproducible and scalable framework for ecological monitoring and adaptive forest planning under changing climatic conditions. Moreover, the study underscores the potential of model-based forest site maps as strategic tools to guide restoration, seed transfer, and conservation practices. Such integrative analyses contribute not only to the scientific understanding of forest ecology but also to the formulation of modern, data-driven conservation policies aimed at preserving biodiversity, mitigating climate impacts, and ensuring the long-term resilience of Mediterranean forest ecosystems.

Author Contributions

KY and SG conceived and designed the research, KY carried out the field measurements and data collection, KY performed the statistical analyses and modelling, SG supervised the research, contributed to data interpretation, and reviewed the manuscript, KY prepared the manuscript draft, and SG provided critical revisions, both authors read and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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