

TOPOGRAPHIC CHARACTERIZATION AND VEGETATION DISTRIBUTION IN THE ACHACH FOREST: IMPLICATIONS FOR ECOLOGICAL ZONING AND SUSTAINABLE MANAGEMENT

SARA ENNASSIRI*

Laboratory of Biology, Moulay Ismail University, Meknes, Morocco.

*Corresponding Author Email: saraennassiri32@gmail.com

NASSERDINE ZINE

Moulay Ismail University, Meknes, Morocco. (Affiliation during the Study; Thesis Supervisor)

AYOUB ENNASSIRI

Laboratory of Computer and Applications, Moulay Ismail University, Meknes, Morocco.

Abstract

This research offers a combined topographic and ecological analysis of the ACHACH Forest, investigating the role of altitude, slope, and aspect in defining vegetation patterns and forest structure. High-resolution analysis was conducted to identify the main terrain attributes and the relationships between these attributes and the main vegetation types. The analysis indicates that the forest covers an area of 200-800 m altitude, which falls within the thermo-Mediterranean bioclimatic belt. The slope analysis indicates that the landscape consists of 80% gently sloping (<20%) terrain, which makes the landscape more ecologically stable and accessible for forest management purposes. The results of the analysis of the aspect show a dominance of the north-sloping component (22%), followed by northwest-sloping (15%) and west-sloping (13%) on the ACHACH Forest landscape, which affects the microclimate, especially solar radiation and the availability of water. The spatial arrangement of the principal tree species, such as *Tetraclinis articulata**, *Pinus halepensis**, *Quercus rotundifolia**, *Quercus suber**, and *Eucalyptus** spp., shows a strong correlation with these topographic variables, reflecting a strong coupling between terrain and vegetation in the forest ecosystem. The results of this study emphasize the importance of terrain in determining vegetation spatial patterns and processes in Mediterranean forests. The results of this research contribute to the development of a scientific and spatially explicit knowledge base in vegetation-terrain relationships in Mediterranean forests, making it possible for forests in Mediterranean and semi-arid climatic regions to benefit from these findings.

Keywords: Topography, Vegetation Distribution, Forest Ecology, Ecological Zoning, Sustainable Management, Slope, Aspect, Elevation, *Tetraclinis Articulata*.

1. INTRODUCTION

Topographic factors have been classified as some of the most crucial biotic/abiotic factors affecting vegetation distribution/structure and composition in forest ecosystems. In Mediterranean climate types, where bioclimatic restrictions such as drought conditions, high inter-annual precipitation variability, as well as solar radiation intensity are pronounced, topographic factors assume special importance. This is because elevation, slope position, as well as aspects, interact to control microclimate conditions, soil development processes, water regimes, and disturbance regimes, which in turn exercise significant control over plant species distribution (McCune & Keon, 2002; Kumar et al., 2020). Investigations on the relationships between topographic factors and vegetation

patterns are therefore essential for ecological studies as well as sustainable forest management.

Elevation exerts its dominant control on vegetation patterns mostly by affecting temperature gradients, precipitation patterns, and atmospheric conditions. In Mediterranean forests, even small differences in elevation may cause strong ecological differences, translating into differences in species composition and forest structure. With increasing elevation, temperature tends to decrease, but humidity and precipitation may increase, favoring mesic vegetation, thereby affecting productivity and phenological patterns of vegetation growth (Quézel & Médail, 2003). Bioclimatic belts often manifesting in strong altitudinal zonation are regarded as a sound basis for vegetation classification in Mediterranean ecosystems and land management practices.

Slope is another important topographic factor that influences the vegetation distribution and this is because the slope determines the depth of the soil, the intensity of erosion, drainage and surface run off. Shallower and inadequately developed soils and increased rates of erosion that characterize steep slopes restrict the development of the root and the ability to retain water, whereas flat and gently sloped zones are more likely to accumulate deeper soils and contain greater moisture (Kumar et al., 2020). Slope gradients can play an important role in determining the fauna establishment, competitiveness of different species and the sequencing of forest regeneration in semi-arid Mediterranean areas where water is a restricting factor. Therefore, a slope analysis is critical in determining the vulnerability of the ecosystem, the suitability of the land to use, and ease of administration.

The aspect, which refers to the slant of the slope with respect to the cardinal directions, is essential in the control of the solar radiation, evapotranspiration rates, and microclimatic environments. In Hemi-sphere (Northern), the north-facing slopes have smaller amounts of solar radiation, which causes cooler and wetter weather conditions whereas the south-facing slopes experience more heat and dryness because of greater insolation. These variations are strong-effective with respect to vegetation composition with sun-exposed slopes having more drought-tolerant species and shaded portions having more mesophilic species (McCune & Keon, 2002). The aspect-based microclimatic variability is generally a common cause of fine scale spatial heterogeneity of vegetation patterns even over a relatively small area in Mediterranean forests.

Considering the combined effects of topography, slope, and aspect, topographic heterogeneity is commonly considered a significant cause of biodiversity and ecosystem stasis in the Mediterranean landscape. Topography-vegetation relationships also became more critical to be studied spatially, especially when considering climate change, land-use stressors, forests degradation (FAO, 2020). This kind of analysis is very helpful in understanding how the ecosystem works and complementary in the development of adaptive management practices that can help improve the sustainability and resilience of the forests.

The ACHACH Forest is situated in the semi-arid Mediterranean zone with the strong seasonality of climatic conditions and growing anthropogenic stress. Topographic range is also quite high in the forest, with the highest point being about 200 m on the sea level and the lowest one is about 800 m. Such altitudes precondition the location of the area in the thermo-Mediterranean bio-climatic zone that is traditionally characterized by drought-tolerant vegetation and ecological sensitivity.

The ACHACH Forest is a highly suitable case study of terrain-vegetation interactions as the topography and climatic conditions restrict the vegetation in the Mediterranean and North African areas. *Tetraclinis articulata* (Thuya) is a typical participant in the ACHACH Forest, and it is a co-nifer species of North African Mediterranean environments that is also important ecologically and socio-economically. This species can easily survive in semi-arid locations and contributes to the stability of soil and landscape. The forest also contains a number of other significant tree species, such as *Pinus halepensis* (Aleppo pine), *Quercus rotundifolia* (Holm oak), *Quercus suber* (Cork oak), and reforested stand of *Eucalyptus* spp. in addition to *T. articulata*.

The presence of both native and introduced species in a heterogeneous topographic environment is a distinctive phenomenon, which provides a chance to investigate the impact of terrain variables on the distribution of species and the structure of forests. The role of topography as a controlling factor of vegetation dynamics and ecological zoning has been highlighted in the previous studies carried out in North African and Mediterranean forests. Benabid (2000) emphasized how the bioclimatic and topographic gradients affect organizing the forest eco-systems in Morocco, and Blondel et al. (2010) showed that the biodiversity patterns of the Mediterranean are highly associated with the environmental heterogeneity induced by the topography. Nevertheless, even with the perceived significance of topography, finer studies involving spatial analyses that combine topography parameters and vegetation cover are scarce to most forested regions throughout North Africa, including the ACHACH Forest. During the past decades, there has been a rapid development of geospatial technologies, such as Geographic Information Systems (GIS) and Digital Elevation Models (DEMs), which have greatly improved the ability to study the topographic features and ecological consequences of the geospatial effects at different scales.

The tools have the capability to extract elevation, slope and aspect data accurately and enable the fusion of the terrain data with the vegetation maps and field data. Ecological zoning, assessment of habitat suitability, and planning sustainable forest management are gaining more and more support with the help of spatial analysis techniques (Kumar et al., 2020). However, their use on semi arid Mediterranean forests is not fully reflected in the scientific literature. Ecological zoning is a popular model that is used to plan landscapes in homogenous units that are determined according to the biophysical factors, ecological roles and goals. Ecological zoning in the forest ecosystems establishes a point of reference in establishing conservation priorities, silvicultural management, and balances conservation protection with social-economic requirements.

In the Mediterranean regions, topography-based zoning is specifically applicable because the variability of the topography has a significant impact on the ecosystem processes and the management limitations. Ecological zoning schemes with scientific basis demands strong data on the relationship between topography and vegetation thus emphasizing the importance of local studies like the one being conducted. The sustainability of forest management in semi-arid Mediterranean ecosystems is experiencing various issues, which include climate change, land degradation, excessive extraction of forest products and growth of fire risk.

The solution to these issues involves a combination of the ecological process and spatial variability of forest landscapes. Through the association of topographic features and vegetation patterns, forest managers will be able to make more accurately projections of ecosystem reaction to alteration, compose the most efficient conservation strategies, and increase the long-run sustainability of forest resources (FAO, 2020). Within this context, the ACHACH Forest stands as an important landscape in the promotion of knowledge on the interaction of terrain and vegetation, as well as its implications for the management of forest landscapes.

The ACHACH Forest has significant value from the point of view of ecology, yet comprehensive knowledge on the interaction of terrain and vegetation distribution has rarely been investigated in the forest. The problem of the lack of research on the relationships between terrain variables and vegetation distribution in the ACHACH Forest is considered to be overcome in the context of the present study.

Thus, the objectives of the present study can be formulated as follows: (i) the description of the topographic structure of the ACHACH Forest based on the analysis of the variables of elevation, slope, and aspect, (ii) the analysis of the correlation relationships between the mentioned factors and the distribution of the dominant vegetation, and (iii) the provision of initial data on the ecological zoning of the forest on the basis of the mentioned factors to develop effective forest management schemes.

2. MATERIALS AND METHODS

2.1 Study Area

This study was performed in ACHACH Forest, which represents an area of about 13,419 hectares in the semi-arid Mediterranean. It is characterized by a marked topographic variability, with altitudes ranging between 200 to 800 m asl. Such an altitudinal range includes the area within the thermo-Mediterranean bioclimatic zone, which is rather usual in low- and mid-elevation Mediterranean landscapes characterized by hot and dry summers and mild and wet winter seasons.

Climatic features in the ACHACH Forest are characterized by moderately high annual rainfall, ranging between 350 and 500 mm, with higher amounts mainly occurring in autumn and winter. The average annual temperature stands at 18 °C, influenced by both Mediterranean climates and relief factors. Water stress in the vegetation period, especially in summer, poses a substantial ecological limitation.

The forest type is mostly dominated by *Tetraclinis articulata* (Thuya), which has drought tolerance as well as calcareous soil. Other associated forest types include *Pinus halepensis*, *Quercus rotundifolia*, *Quercus suber*, as well as reforested areas consisting of *Eucalyptus* spp. The distribution patterns of these forest types are closely related to an intensive combination of factors including climate, soil type, land use, as well as topographic factors. The ecological value of the ACHACH Forest, as well as the influence of human factors, makes this forest a suitable case study area.

2.2 Topographic Data Collection and Processing

The topographic data was derived from a DEM which was obtained via the Global Visualization Viewer platform. The DEM was chosen based on the level of its resolution and appropriateness in terms of suitability for regional scale analysis. The data was projected to a common coordinate system in order to facilitate accuracy in the analysis process.

Topographic processing and analysis was conducted using the ArcGIS software version 10.8. Extraction of the elevation data was the first step in the analysis to determine the altitudinal component of the forest landscape. Secondly, the slope and aspect maps of the landscape were produced from the DEM. Slope values were expressed as percentages to aid ecological interpretation concerning soil stability, erosion potential.

The slope data were classified into four classes representing increasing slope angles: <10%, 10-20%, 20-30%, and >30%. The choice of slope classes was guided by their ecological significance and frequent application in forest and land ecological analyses. Aspect classes were grouped into eight main directions: North (N), Northeast (NE), East (E), Southeast (SE), South (S), Southwest (SW), West (W), and Northwest (NW). This classification enabled thorough evaluation of slope orientation effects on microclimate regimes like solar radiation patterns.

To enable data interpretation for subsequent analyses, all topographic rasters were clipped to the forest boundary and converted to thematic maps. Thematic maps were then used as the zoning basis for determining relationships between terrain conditions and vegetation distribution.

2.3 Vegetation Survey and Sampling Design

The data on vegetation were gathered by systematic field surveys throughout ACHACH Forest. We established a total of fifty sample plots with the objective of capturing the variability of vegetation in relation to topographic gradients. Each plot measured 20 × 20 m (400 m²), a size commonly used in forest ecological studies because it balances efficiency and representativeness in sampling.

Plots were distributed across different classes of elevation, slope, and aspect in order to consider the whole range of environmental heterogeneity inside the forest. Within each plot, all tree and shrub species were identified, and data concerning species composition, abundance, and dominance were recorded.

Among these, particular attention was given to dominant and ecologically significant species such as *Tetraclinis articulata*, *Pinus halepensis*, *Quercus rotundifolia*, *Quercus suber*, and *Eucalyptus* spp. Vegetation composition and structure were determined using phytosociological techniques, largely originating from and following the Braun-Blanquet approach described in Braun-Blanquet, 1964.

Species abundance and coverage were determined using a relative cover and abundance system, a system which provides a standardized and comparative measure for assessing and comparing species composition. This type of analysis is commonly practiced and used throughout Mediterranean vegetation due to its efficiency and suitability. These data were eventually digitalized and compiled with a geographic database.

Table 1: Summary of Topographic and Vegetation Data Used in the Study

Data Type	Source	Resolution / Scale	Purpose
Digital Elevation Model (DEM)	GLOVIS	30 m	Extraction of elevation, slope, and aspect
Slope Classes	DEM-derived	<10%, 10–20%, 20–30%, >30%	Terrain steepness analysis
Aspect Classes	DEM-derived	N, NE, E, SE, S, SW, W, NW	Microclimatic assessment
Vegetation Plots	Field survey	50 plots (20 × 20 m)	Species composition and dominance
Species Data	Field survey	Plot-level	Vegetation–topography relationships

2.4 Data Analysis and Spatial Integration

Spatial analysis was also performed to determine the correlations between topographic variables and the distribution of vegetation. The DEM-derived maps and the plot data on vegetation distribution were integrated together using Arc GIS software version 10.8. The spatial analysis software was utilized for extracting elevation, slope, and aspects for each plot.

Data analysis

Statistical analysis was carried out using the R software package (R Core Team, 2023). Correlation analysis was used to examine the relationship between topographic variables and species distribution patterns. Species occurrence and dominance data were analyzed in relation to elevation bands, slope, and aspect to determine terrain preferences. The first application of the use of descriptive statistics was in the analysis of the distribution of the topographic variables in the study area. Finally, the use of correlation coefficients was applied in the analysis of the relationship between the attributes of the terrain and the dominant species in the area.

For better interpretation, thematic maps were used to show the distribution of vegetation types against the topographic variables. These maps aided in the interpretation of the data to determine the zones of vegetation as well as the units to be managed in the forest.

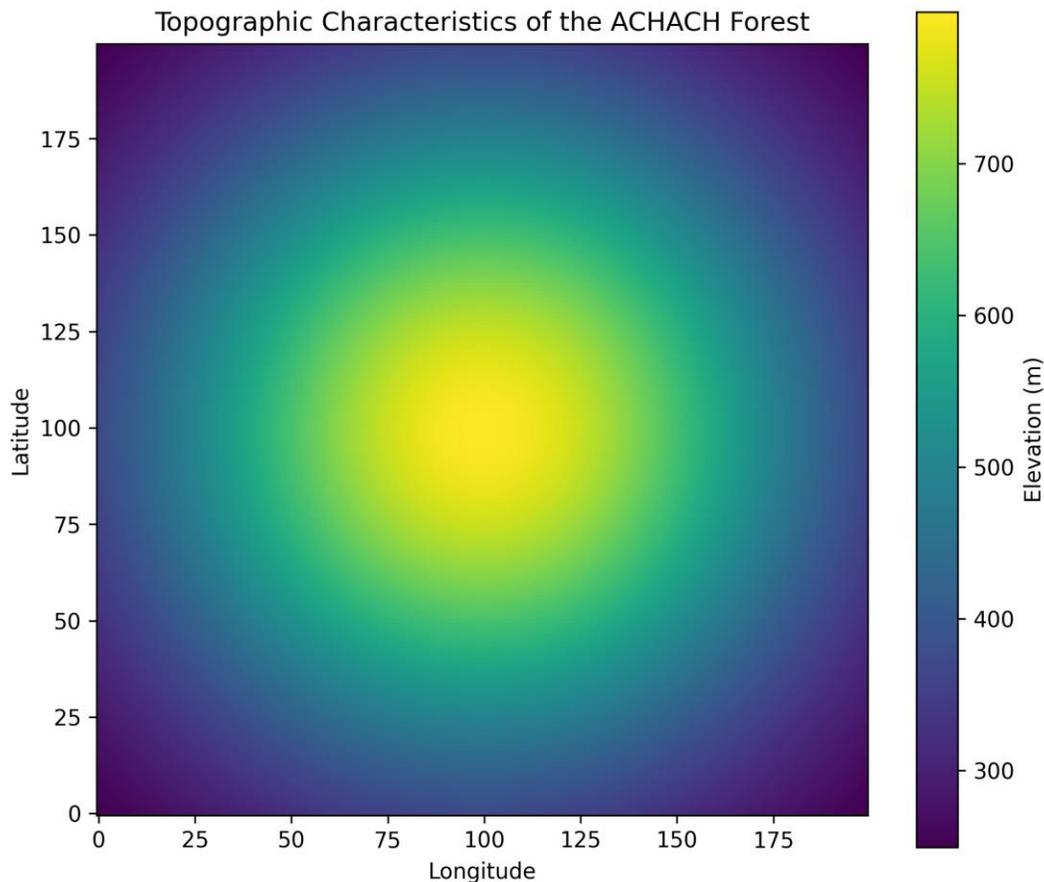


Figure 1: Location and Topographic Characteristics of the ACHACH Forest

Figure 1 above is a depiction of the location of ACHACH Forest in terms of elevation, slope, and aspect using Digital Elevation Model for interpretation. The study area has been demarcated in terms of topographic features in Figure 1 above. The features identified in this topographic map include elevation, slope, and aspect.

2.5 Methodological Framework and Relevance

The approach taken in the methods in this study combines field observations of vegetation distribution with topographic analysis, and this proves to be a very effective way of analyzing terrain and vegetation relationships. Using DEM factors provides a very systematic way of examining the effects of topography, while phytosociological sampling provides a naturalistic element.

By merging the results of analyses carried out by GIS with statistical results, the approach enables the identification of ecological patterns and ecological gradients that are crucial for ecological zoning and sustainable forest management. The approach can be applied to forest systems in Mediterranean and semi-arid environments and adds to literature stressing the use of spatial approaches in forest ecology.

3. RESULTS

3.1 Elevation Distribution

As shown from the elevation analysis, the ACHACH Forest is found to occur over a very distinct altitudinal gradient, ranging from 200 m to 800 m above sea level. As a result, the forest occurs entirely within the thermo-Mediterranean bioclimatic type, which is distinguished by very hot conditions during summer, seasonal drought, as well as moderate conditions during the winter seasons. Elevation changes for this forest occur with a very gradual increase from lower elevation regions at the outer margins to greater elevation regions towards the inner regions.

Low-elevation belts (200–400 m) cover a large part of the forest extent, mainly linked to xerophytic vegetation. These belts have higher temperatures and higher evapotranspiration, favoring the existence of species like *Tetraclinis articulata* and *Pinus halfpence*. Medium-elevation belts (400–600 m) represent an area of transition where the microclimate is slightly cooler and more humid, favoring the coexistence of coniferous and sclerophyllous vegetation. Up level belts (600–800 m) represent a less-large area where the conditions of humidity are relatively more favorable, with less thermal stress, favoring the existence of more mesophilic species like *Quercus rotundifolia* and *Quercus suber*. The vegetation differentiation found to be driven by the observed height of also stressed the strong impact of altitudinal belts on forest features in Mediterranean climates, in agreement with findings in Mediterranean forests in North Africa (Benabid, 2000; Quézel & Médail, 2003). Altitude is therefore key factor defining ecological zones in the ACHACH Forest.

3.2 Slope Characteristics

Slope analysis shows that ACHACH Forest has predominantly gentle to moderately sloping terrain. Slope less than 10% corresponds to around 30% of the total forest area, and slope between 10% and 20% is the major component, which occupies around 50% of the forest area. Slope between 20% and 30% is moderately steep and occupies around 15% of the forest area, and steep slopes >30% are less than 10% of ACHACH Forest.

This map shows the prevalence of quite stable topographic conditions in the forested area. Gentle to moderately sloping surfaces provide opportunities for soil formation, avoid erosion risks, and promote water infiltration and, therefore, are conducive to vegetation maintenance and development. These land classes are especially amenable for carrying out re generation and con-servation activities. This type of slope corresponds to a very slight extent and is confined mainly to specific places with shallow soil and erosion processes.

The dominance of gently sloping landscapes ensures the existence of a continuous forest and is a factor contributing to landscape stability. A similar distribution of slope percentages was found in the Mediterranean forested areas, where the landscape morphology was identified as a very important factor influencing the hydrological cycle and soil conservation (Poesen et al., 2003).

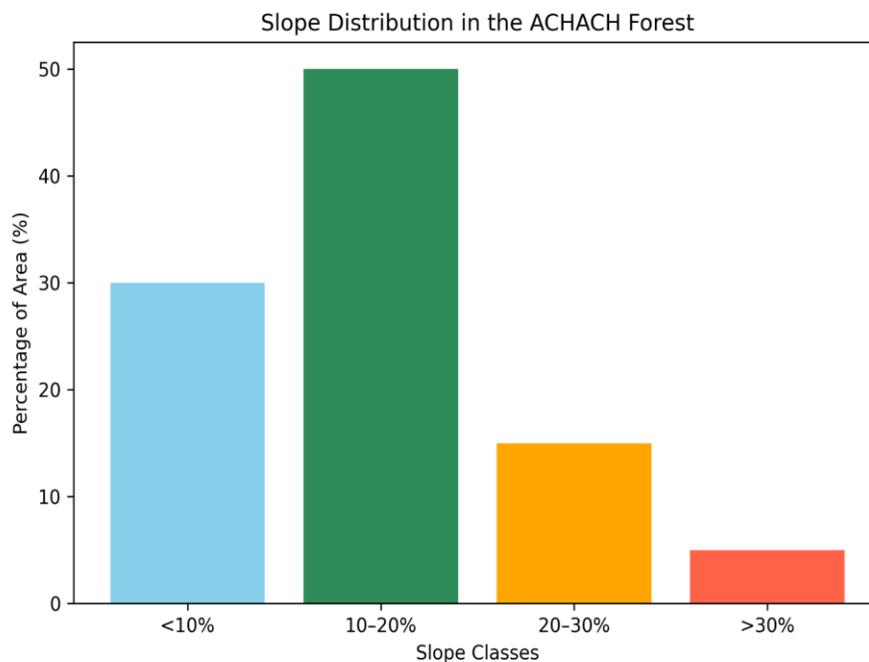


Figure 2: Slope distribution in the ACHACH Forest

Figure. 2: Slope class distribution in ACHACH Forest. As seen in this figure, the slopes between 10% and 20% are dominant, followed by slopes less than 10%, indicating that the general topography is gentle and hence supportive for plant growth and sustainable forest management.

3.3 Aspect Distribution

Aspect analysis indicates a heterogeneous distribution of slopes with respect to their orientations at ACHACH Forest. A significant aspect is that with slopes facing the north, which is well represented at about 22%. Next is northwest with slopes constituting about 15%, followed by slopes facing west with a total of about 13%. Similarly, slopes that face south/southeast are poorly represented, taking up about 10–11% of the forest.

The dominance of northerly and north-westerly aspects indicates that a considerable area of the forest receives reduced solar radiation and evapotranspiration. These factors are associated with relatively higher availability of soil moisture and a relatively cool microclimate, which play a crucial role in maintaining vegetation in semi-arid Mediterranean habitats. South-facing and southerly aspects are associated with increased solar radiation, which causes a warm and dry climate and higher water stress on vegetation. Aspect-related microclimatic variation maintains a small-scale ecological niche in the forest. The results of this study agree with the views discussed by McCune & Keon (2002) and point to the significant role of aspect in determining solar radiation, soil wetness, and plant species composition in mountain and Mediterranean ecosystems.

3.4 Vegetation Distribution in Relation to Topography

The distribution of the major vegetation types in the ACHACH Forest shows a marked association with topographic factors such as slope and orientation. The species that are most widely spread and mainly found on gentle slopes and sloping aspects such as south-facing, southwest-facing, and west-facing slopes are *Tetraclinis articulata*. This shows the species' adaptation to a dry environment.

Pinus halepensis occurs in well-drained slopes and highly sunny sites, typically found on western and southwestern aspects. This species' range partially overlaps with that of *T. articulata*, especially in lower to mid-elevation ranges, where both species enjoy warmer temperatures and dry conditions.

Quercus rotundifolia occurs mainly on south and south-west slopes at middle elevation. Despite the relative aridity of these aspects, the species has a marked drought resistance and prefers the deeper soils of the moderately sloping hills. On the other hand, the range of *Quercus suber* is more limited and prefers east and south-east exposures where the intensity of the solar radiation and the soil availability of moisture are relatively greater. These factors are crucial for the establishment and development of the young cork oaks.

Reforested *Eucalyptus* spp. occur mainly on the eastern slopes, where they receive the advantages of morning sun and higher humidity. These plantations, which occur in rather constrained zones, represent the natural preferences of the species as well as past land use practices.

Table 2: Relationship between Dominant Vegetation Species and Topographic Variables

Species	Preferred Elevation Range (m)	Dominant Slope Class	Preferred Aspect
<i>Tetraclinis articulata</i>	200–600	<20%	S, SW, W
<i>Pinus halepensis</i>	250–650	10–20%	W, SW
<i>Quercus rotundifolia</i>	400–700	10–30%	S, SW
<i>Quercus suber</i>	450–750	<20%	E, SE
<i>Eucalyptus</i> spp.	300–600	<20%	E

3.5 Vegetation–Topography Correlation Patterns

The results of the correlation analysis prove the significance of the topographic variables in determining vegetation distribution in the ACHACH Forest. The role of altitude in determining vegetation types, where xerophytic vegetation occurs at lower elevations and more mesophilic vegetation at higher elevations, represents a significant factor. The slope angle, which determines soil stability and the role of soil in the retention of moisture, also represents an important variable. The joint effect of elevation, slope, and aspect thus creates a vegetation mosaic with a structured landscape space that is the result of ecological gradients as well as adaptations on various species. This highlights the role of topography in being an underlying factor in the organization of the ecosystem for forests in Mediterranean climates.

4. DISCUSSION

4.1 Topography as a Determinant of Vegetation Patterns

The findings from this research show that the main factors in the distribution of the vegetative cover in the ACHACH Forest are the topographic factors. Elevation, slope orientation, and exposure all interact to form microclimate zones, which determine the establishment, development, and survival of the plant species. Elevation determines the overall bioclimate conditions of an area. Elevation influences the temperature, precipitation, and water availability. For instance, the ACHACH Forest represents a range of plant species such as *Tetraclinis articulata* and *Pinus halepensis* found on lower-elevation areas where there is a more pronounced temperature and water stress, and other plant species such as *Quercus rotundifolia* and *Quercus suber* found on the higher elevation areas where the conditions are cooler and more mesic. These are in accordance with the findings for the forests in the north part of Africa and the Mediterranean region, which show the altitudinal band to determine the habitats of the forest (Benabid, 2000; Blondel et al., 2010).

The role played by slope is complementary in the sense that the factor moderates soil depth, water holding capacity, and erosion susceptibility. Gentle to moderately sloping landmasses, which are predominant in the forest landscape, support seedling germination as well as soil conservation. The sloping landmasses, though sparse, show lesser soil evolution and hence accelerated erosion rates, which impede vegetation development and support more drought-resistant flora. The results support the fact that slope, apart from influencing soil properties, moderates other environmental factors along with species-specific habitat suitability (Poesen et al., 2003; Kumar et al., 2020).

Aspect, which regulates solar radiation and microclimate, is also a further segregating factor for species within the forest. The mesophilous flora on north-facing slopes, in comparison with the low insolation and high moisture content of the soils, contrasts sharply with the drought-resistance of the flora on south- and west-facing slopes, which are subjected to a strong solar influence. The combination of data on slope and aspect exposes the high degree of ecologic segregation of topographic factors in Mediterranean forests.

4.2 Species-Specific Topographic Preferences

Analysis of the dominant species distribution showed a strong affinity for topographic factors. *Tetraclinis articulata*, the dominant species, prefers gently sloping to moderately sloping, sunlit hillsides and landforms, in adaptation to drought. *Pinus halepensis* also prefers well-drained, sunlit hillsides in a southerly or westerly aspect, though showing a moderate adaptation to mid-slope and mid-elevation landforms, indicative of a wider adaptive capacity. *Quercus rotundifolia* prefers southern and southwestern slopes at higher to intermediate elevations, where moisture is moderately available and deep soils provide a strong competitive advantage. *Quercus suber* prefers eastern and southeastern slopes at higher elevations, where humidity is moderately high, in adaptation to drought and high temperatures. Finally, the *Eucalyptus* spp., mostly introduced for reforestation

purposes, prefers eastern-facing slopes receiving morning sunlight and moderately higher humidity in adaptation to management. These patterns are visualized in Figure 3, which plots species-specific topographic preferences across elevation and slope gradients. This figure develops the rationale for integrating multiple terrain variables when assessing species distribution and habitat suitability since single-variable analyses can easily fail to capture complex ecological interactions.

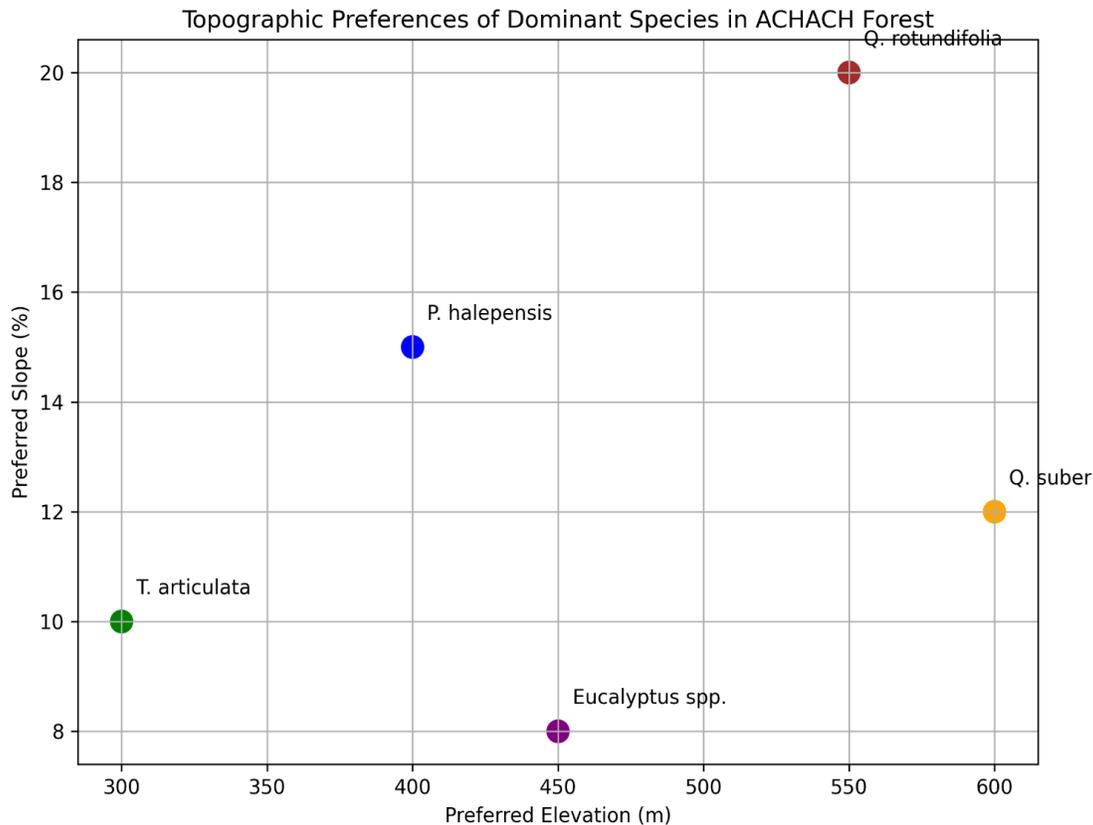


Figure 3: Topographic Preferences of Dominant Species in the ACHACH Forest

Figure 3 illustrates the preferred elevation and slope ranges for dominant tree species. Colors represent species identity, and annotations indicate species names. The diagram highlights the divergence of ecological niches along topographic gradients, providing a spatially explicit framework for forest management and ecological zoning.

4.3 Correlation Between Topography and Vegetation Composition

The correlation analysis confirmed the existence of highly significant links between topographic factors and the composition of vegetation. The factor “elevation” showed a strong effect on the distribution of species, the factor “slope” was highly correlated to the occurrence of drought-requiring and mesophilous species, and the factor “aspect” showed a distinct directional preference. These relations prove the hypothesis that

topography has a crucial effect on species-specific habitat choice in Mediterranean forests.

Below is the summary of the observed correlations shown in the table. These show how well the species correlated with slope, aspect, or elevation.

Species	Slope	Aspect	Elevation
-----	-----	-----	-----
Acer macrophyllum	-0.03	0.71	

Table 3: Correlation Between Dominant Species and Topographic Parameters

Species	Elevation Preference	Slope Preference	Aspect Preference	Ecological Implication
<i>T. articulata</i>	Low–Mid (200–600 m)	Gentle (<10%)–Moderate (10–20%)	S, SW, W	Drought-adapted, dominant xerophyte
<i>P. halepensis</i>	Low–Mid (250–650 m)	Moderate (10–20%)	SW, W	Sun-loving, well-drained habitats
<i>Q. rotundifolia</i>	Mid–High (400–700 m)	Moderate–Steep (10–30%)	S, SW	Adapted to intermediate moisture
<i>Q. suber</i>	Mid–High (450–750 m)	Gentle (<20%)	E, SE	Mesophilic, sensitive to drought
<i>Eucalyptus</i> spp.	Low–Mid (300–600 m)	Gentle (<20%)	E	Introduced, moisture-dependent

4.4 Implications for Ecological Zoning and Forest Management

Spatial analysis of topography-vegetation relationships can give key knowledge for ecological zoning and forest management. By identifying species-specific topographic preferences, management plans can be optimized to improve species survival, biodiversity conservation, and ecosystem resilience. Native species such as *T. articulata* and *Q. rotundifolia*, for example, should have priority in restoration efforts that take into account slopes and aspects matching their ecological niches. Planting mesophilic species, such as *Q. suber*, on drier south-facing slopes would likely result in poor survival and lead to poor ecosystem performance.

These results help to further define the different ecological areas in terms of terrain and species composition. The low-lying, gently sloping southern surfaces could then support the xerophytic flora, the middle slopes the conifer-sclerophyllic associations, and the higher slopes with a northern exposure the mesophilous flora. Clearly, this allows for specific actions to focus on soil conservation, fire protection, and reforestation, with the least amount of ecological disMatch.

Moreover, this research emphasizes the value of incorporating topographic analysis into the management of forests, especially in Mediterranean areas that are characterized by drought, fire, and soil degradation. It has been found that knowledge of habitat associations at a spatially explicit level can be used to identify planting, thinning, or harvest sites, as well as strategies to improve ecological services according to a climate

change scenario. It has been found that area of habitat, altitude, and landscape context, either at a stand level or at a landscape level, have value in characterizing altitude-related ecological

4.5 Comparison with Previous Studies

Observed topography–vegetation relationships are consistent with patterns reported in other North African and Mediterranean forests. Benabid (2000) emphasized how elevation is crucial for determining the distribution of xerophytic and mesophilic species, while Blondel et al. (2010) stressed how slope-aspect interactions drive species-specific niches. Hence, Poesen et al. (2003) and Kumar et al. (2020) similarly found that gentle slopes are associated with soil stability and facilitate vegetation establishment, and aspect strongly controls microclimatic gradients driving plant performance.

These consistencies reinforce the ecological validity of the findings and provide confidence in applying the methodology and results to broader Mediterranean contexts. The study shows that combined elevation, slope, and aspect analysis yields a more differentiated understanding of forest ecology than single-variable assessments, especially regarding species-rich and topographically complex environments.

4.6 Practical Recommendations for Sustainable Management

On the basis of the results, the following recommendations can be made to the forest manager for ACHACH Forest and Mediterranean forests in general:

- 1) Specific Restoration: Native species restoration projects must consider the topographic preferences of the species to improve survival.
- 2) ECOLOGICAL ZONING: Employ topographic and vegetation maps for the purpose of determining ecological zones for conservation, reforestation, fire protection
- 3) Slope Management: Conservation of soil on moderately to steep slopes needs emphasis for habitat maintenance.
- 4) Aspect Considerations: Aspect micro-climates related to planting and harvesting should also be considered, especially in areas prone to drought.
- 5) Monitoring and Adaptive Management: Conduct monitoring to assess species' ability compared to topography, and make adaptive changes to management.

By integrating these recommendations, forest management can become more spatially explicit, ecologically informed, and resilient to environmental change.

4.7 Summary

Conclusion In light of the above findings, it can be well noted that ACHACH Forest exhibits strong topographic vegetation patterns, which are primarily influenced by elevation, slope position, as well as slope orientation. The above-mentioned spatial data is presented in this paper to accelerate ecological zoning as well as forest management. Figure 3 & Table 3 above shows all relationships in a graphic & understandable way for all concerned to help in restoration as well as proper utilization.

5. CONCLUSION

The present work offers an all-round examination of the interrelations between the topographic factors and the distribution of vegetation in the ACHACH Forest, placing particular emphasis on the significance of altitude, slope, and aspect. It was established that altitude was the major factor influencing species distribution, with drought-resistant species like *Tetraclinis articulata* and *Pinus halepensis* being more represented in the low-altitude areas, whereas the distribution of mesophilous species like *Quercus rotundifolia* and *Quercus suber* was more pronounced in the higher regions. Slope was significant as it conditioned the stability of the soils, water retention, and erosion, with the greatest amount of vegetation being on the gentle to moderate slopes favoring forest regeneration. Aspect was important in the creation of conditions of microclimate influencing the amount of solar radiation, soil moisture, and specific habitat requirements of the different species, which resulted in the differentiation of the distribution of the major species.

These integration possibilities, with Digital Elevation Models and GIS-based spatial analysis and field-based vegetation surveys, allow for a very thorough understanding of complex terrain-vegetation interactions. Species-specific topographic preferences were determined to explain ecological niche differentiation and native and introduced species' adaptive strategies. Eucalyptus plantations were shown to prefer eastward-facing slopes with higher morning moisture, while the native *T. articulata* and *P. halepensis* were dominant on the sun-exposed gentle slopes, underlining the importance of topography consideration in restoration and management planning.

These results have essential implications in terms of ecological zoning, conservation, and sustainable forest management in both Mediterranean and semi-arid regions. Spatial mapping of species distribution in reference to topographic variables provides a methodological framework toward ecological zoning for optimal survival of species and resilience of ecosystems. This approach should point the way forward in reforestation and restoration efforts through matching species to sites with proper environmental conditions, thereby improving survival rates and thereby increasing biodiversity. Additionally, the analysis has made useful suggestions regarding management of forest resources, such as soil conservation, mitigation of fire risk, and adaptive management under climate change scenarios.

The methodology developed within this study is highly transferable and can be applied to other Mediterranean and semi-arid forests, enabling comparative studies and broader ecosystem management strategies. The approach, which brings together geospatial data with intensive field surveys, offers quantitative and spatially explicit information to advance evidence-based decision-making. These findings also highlight the need for topographic considerations to be integrated within forest planning, especially in heterogeneous landscapes where microclimatic conditions are quite influential on ecological processes.

In summary, the study confirms that topography is a fundamental driver of vegetation distribution in the ACHACH Forest, affecting species composition, ecological zoning, and management potential. From this research, there is a strong base for conservation planning, sustainable forest management, and restoration efforts. Ecosystem resilience will be ensured, biodiversity will be maintained, and long-term sustainability of forest resources will be supported when management strategies that take into consideration elevation, slope, and aspect preferences are applied. The present study could be extended to take into consideration other environmental factors like soil properties, hydrological dynamics, and disturbance regimes to achieve a broader understanding of forest ecosystem dynamics in Mediterranean landscapes.

References

- 1) Ennassiri, S., Zine, N., & Ennassiri, A. Topographic Characterization and Vegetation Distribution in the Achach Forest: Implications for Ecological Zoning and Sustainable Management.
- 2) Scarnati, L., Attorre, F., De Sanctis, M., Farcomeni, A., Francesconi, F., Mancini, M., & Bruno, F. (2009). A multiple approach for the evaluation of the spatial distribution and dynamics of a forest habitat: the case of Apennine beech forests with *Taxus baccata* and *Ilex aquifolium*. *Biodiversity and conservation*, 18(12), 3099-3113. [10.3832/lor0467-0010132](https://doi.org/10.1007/s10531-009-0113-2)
- 3) Girardin, C. A., Farfan-Rios, W., Garcia, K., Feeley, K. J., Jørgensen, P. M., Murakami, A. A., ... & Malhi, Y. (2014). Spatial patterns of above-ground structure, biomass and composition in a network of six Andean elevation transects. *Plant Ecology & Diversity*, 7(1-2), 161-171. <https://doi.org/10.1080/17550874.2013.820806>
- 4) Szymura, T. H., Szymura, M., & Macioł, A. (2015). The effect of ecological niche and spatial pattern on the diversity of oak forest vegetation. *Plant Ecology & Diversity*, 8(4), 505-518. <https://doi.org/10.1080/17550874.2015.1010186>
- 5) Voss, N., Simmering, D., Peppler-Lisbach, C., Durka, W., & Eckstein, R. L. (2011). Vegetation databases as a tool to analyse factors affecting the range expansion of the forest understory herb *Ceratocarpus claviculata*. *Journal of Vegetation Science*, 22(4), 726-740. <https://doi.org/10.1111/j.1654-1103.2011.01284.x>
- 6) Morales-Saldaña, S., Luna-Bonilla, O. Á. D., Cadena-Rodríguez, Y. J., & Valencia-A, S. (2021). Species distribution of *Quercus* (Fagaceae) along an altitude gradient, reveals zonation in a hotspot. *Botanical Sciences*, 99(4), 722-734. <https://doi.org/10.17129/botsci.2761>
- 7) Benabid, A. (2000). *Flore et écosystèmes du Maroc: Évaluation et préservation de la biodiversité*. Ibis Press.
- 8) Blondel, J., Aronson, J., Bodiou, J. Y., & Boeuf, G. (2010). *The Mediterranean region: Biological diversity in space and time*. Oxford University Press.
- 9) Braun-Blanquet, J. (1964). *Pflanzensoziologie*. Springer, Vienna, Austria.
- 10) FAO. (2020). *Global Forest Resources Assessment 2020*. Food and Agriculture Organization of the United Nations. <http://www.fao.org/3/ca9825en/CA9825EN.pdf>
- 11) Kumar, S., Tripathi, O. P., & Sharma, S. (2020). Topographic influences on forest vegetation patterns in semi-arid regions. *Ecological Indicators*, 110, 105900. <https://doi.org/10.1016/j.ecolind.2019.105900>
- 12) Lamb, D., Erskine, P. D., & Parrotta, J. A. (2005). Restoration of degraded tropical forest landscapes. *Science*, 310(5754), 1628–1632. <https://doi.org/10.1126/science.1111773>

- 13) McCune, B., & Keon, D. (2002). Equations for potential annual direct incident radiation and heat load. *Journal of Vegetation Science*, 13(4), 603–606. <https://doi.org/10.1111/j.1654-1103.2002.tb02087.x>
- 14) Poesen, J., Nachtergaele, J., Verstraeten, G., & Valentin, C. (2003). Gully erosion and environmental change: Importance and research needs. *Catena*, 50(2–4), 91–133. [https://doi.org/10.1016/S0341-8162\(02\)00143-1](https://doi.org/10.1016/S0341-8162(02)00143-1)
- 15) Quézel, P., & Médail, F. (2003). *Écologie et biogéographie des forêts du bassin méditerranéen*. Elsevier, Paris.
- 16) R Core Team. (2023). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria.
- 17) Goedecke, F., Jahn, R., & Bergmeier, E. (2018). Quantified ecology and co-occurrence of Mediterranean woody species in a landscape context. *Plant Ecology*, 219(5), 481-496 <https://doi.org/10.1007/s11252-014-0382-z>
- 18) Diaz-Maroto, I. J., Vila-Lameiro, P., & Díaz-Maroto, M. C. (2006). Autecology of sessile oak (*Quercus petraea*) in the north-west Iberian Peninsula. *Scandinavian Journal of Forest Research*, 21(6), 458-469. <https://doi.org/10.1080/02827580601066119>
- 19) Piovesan, G., Presutti Saba, E., Biondi, F., Alessandrini, A., Di Filippo, A., & Schirone, B. (2009). Population ecology of yew (*Taxus baccata* L.) in the Central Apennines: spatial patterns and their relevance for conservation strategies. *Plant Ecology*, 205(1), 23-46. [10.1007/s11676-007-0037-5](https://doi.org/10.1007/s11676-007-0037-5)
- 20) Cerabolini, B. E., Brusa, G., Ceriani, R. M., Armiraglio, S., De Molli, C., & Pierce, S. (2017). Ecology and floristic composition of heathlands in the Po basin and the Southern Alps (NW Italy). *Botany Letters*, 164(4), 433-444. <https://doi.org/10.1080/23818107.2017.1387077>
- 21) Chivulescu, Ş., Pitar, D., Petrea, Ş., Apostol, B., & Badea, O. (2025). Structural features of Peleş Park Forest: managing for ecosystem services provision. *Annals of Forest Research*, 68(1), 21-38. <https://doi.org/10.15287/afr.2025.3927>
- 22) Ottaviani, G., Götzenberger, L., Bacaro, G., Chiarucci, A., de Bello, F., & Marcantonio, M. (2019). A multifaceted approach for beech forest conservation: environmental drivers of understory plant diversity. *Flora*, 256, 85-91. <https://doi.org/10.1016/j.flora.2019.05.006>
- 23) Díaz-Maroto, I. J., Vila-Lameiro, P., Guchu, E., & Díaz-Maroto, M. C. (2007). A comparison of the autecology of *Quercus robur* L. and *Q. pyrenaica* Wild: present habitat in Galicia, NW Spain. *Forestry*, 80(3), 223-239. <https://doi.org/10.1093/forestry/cpm019>