GEOGRAPHICAL ANALYSIS

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Forest Cover Canopy Type Effect on the Northwest Syria Forest's Resilience to Climate Fluctuations

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Abstract

This study investigates the response of various forest canopy types in northwestern Syria to climatic drought using geospatial and statistical methods. By analyzing the Leaf Area Index (LAI) derived from NDVI and its correlation with the Standardized Precipitation Index (SPI) across nine dominant forest types over a 23-year period (2001–2022), the research quantifies the sensitivity of different vegetation communities to precipitation variability. The study reveals that forest types, with deciduous broadleaf species such as Quercus pseudo cerris and Castanea sativa exhibit wider LAI ranges and high correlation with SPI, indicating high responsiveness to drought conditions. Conversely, evergreen oaks (Quercus calliprinos) and Abies cilicica show more stability in canopy development with moderate to low correlations, reflecting greater resilience. Correlation coefficients (r) between LAI and SPI ranged from 0.29 to 0.67, highlighting notable differences in drought sensitivity across forest types. The methodology employed georeferenced sampling, statistical correlation, and LAI modeling based on NDVI, allowing a reliable long-term evaluation of forest canopy dynamics in relation to climatic stress. Findings underline the importance of considering canopy structure, species-specific traits, and site conditions in drought resilience assessments. The results suggest that native and well-adapted species may offer more stable ecosystem functioning under drought, while introduced or less adapted types might be more vulnerable. These insights provide valuable implications for developing forest management strategies aimed at promoting ecological stability, drought resilience, and the preservation of forest functions in climate-sensitive Mediterranean regions.

Keywords: Climate Change, Forest Cover Type, Leaf area Index LAI, Standardized Precipitation Index SPI, Syria Forests

1 Introduction

Forest ecosystems in the Mediterranean region are facing growing vulnerability due to intensifying impacts of climate change, especially the increasing frequency, duration, and severity of droughts[1-3]. These climatic stresses have resulted in widespread forest dieback and reduced productivity across various Mediterranean landscapes[4-6]. Numerous remote sensing-based studies have documented the drought-induced decline in forest vitality using vegetation indices like NDVI, EVI, and LAI, which reflect canopy greenness and physiological status[7-9]. These indices often decline sharply during drought events and recover gradually, mirroring alterations in leaf area and photosynthetic activity, making them reliable remote-sensing indicators of forest stress. As an example, many of remote sensing studies mentioned the drought effect on forests[10-12] with different vegetation behavior[13, 14], The Eastern Mediterranean, including

Northwestern Syria, is currently experiencing a warming trend that exceeds the global average[15-18]. This region is ecologically significant due to its rich forested zones, which are among the most densely vegetated in the country and support a wide range of biodiversity and ecosystem services. Northwestern Syria in particular contains the largest concentration of natural forests in the country, including coniferous, broadleaf, and mixed-species stands. These forests play critical roles in water regulation, microclimate stabilization, carbon storage, erosion control, and offering socio-cultural and recreational benefits to local communities. increasing forest resilience to drought takes big importance under its fragile and sensitivity situation[19]. Given this ecological value and the ongoing climate stressors, strengthening the resilience of forests in this region is a key research priority. Resilience, in the context of forest ecosystems, refers to the capacity of vegetation to absorb climatic disturbances such as drought and to recover to its original state. A growing body of literature has investigated factors influencing forest resilience, such as species composition, canopy structure, stand age, and topographic conditions[20, 21]. However, a notable research gap exists: most prior studies have analyzed forest response to climate change at a general land cover level, without explicitly examining the role of different tree canopy types. Moreover, few studies have leveraged satellite-derived Leaf Area Index (LAI) datasets, despite LAI being a direct and physically meaningful indicator of canopy structure, leaf biomass, and photosynthetic activity[22]. Favoring mixed-species forests, reducing tree density, removing species with high water demands, and introducing robust species are some of the strategies for coping with climate change that have been utilized and suggested[23].

Improving drought resistance requires an understanding of how different forest types differ in their resilience[24-26]. Earth observation satellites gather data on the greenness of pixels, which is related to the canopy cover type, the leaf biomass, and the photosynthetic activity of the forest site[27-32]. Time series of remotely sensed imagery have been used to define forest health response and mortality[33, 34], evaluated the effects of four drought events on 11 different tree species based on satellite-derived canopy greenness (normalized difference vegetation index [NDVI]) With dendrochronology-derived stem growth. The study discovered that recovery-to-sensitivity ratios among the species differed significantly[35, 36].

LAI captures the total one-sided green leaf area per unit ground surface and provides a more detailed picture of canopy condition than greenness indices alone. It enables the monitoring of both the magnitude and temporal variability of vegetation productivity and has been shown to be more sensitive in detecting drought impacts and early warning signals in some forest systems[37, 38]. Thus, using LAI in conjunction with climate drought indicators such as the Standardized Precipitation Index (SPI) can provide a robust framework to quantify forest response and potential resilience thresholds.

In this study, we use remote sensing data to explore the interaction between canopy type and resilience to drought conditions in the forested landscapes of Northwestern Syria. Our methodology integrates Landsat -derived LAI with SPI datasets to examine vegetation dynamics under water stress to assess the extent to which coniferous, broadleaf, and mixed forest types differ in their ecological resilience to drought stress.

Due to the aridity increases described above during the previous ten years and the evidence of forest die-back, we expect to see forest degradation in regions that have recently experienced aridity. Parallel to this, we anticipated that historically wetter areas would be more susceptible to drought than places where dominant species are found.

This study fills an important gap in the literature by focusing on canopy-specific forest dynamics using LAI as a central indicator. The outcomes can inform adaptive forest management and conservation strategies in Syria and similar Mediterranean environments under climate stress.

2 Materials and Methods

2.1 Study area

The area is considered the main habitat of the natural and forested vegetation cover in Syria, where natural forests are spread, and many artificial afforestation sites are located in mountainous areas, plateaus and valleys. The study area is located in the western part of Syria to the east of the Mediterranean Sea, within the administrative boundaries of Lattakia, Tartous and Hama governorates [Fig. 1].

The forest, in its actual geographical concept, appears in the far north of the study area, in Al-Bayr and Al-Basit, where the density is high and the trees are tall of deciduous broad leaf. However, it is becoming thinner, its trees are spreading apart, and the vacant areas are becoming wider towards the south, where the forest trees are transformed

into Mediterranean forest types rich in thorns and small leaves (Maquis).

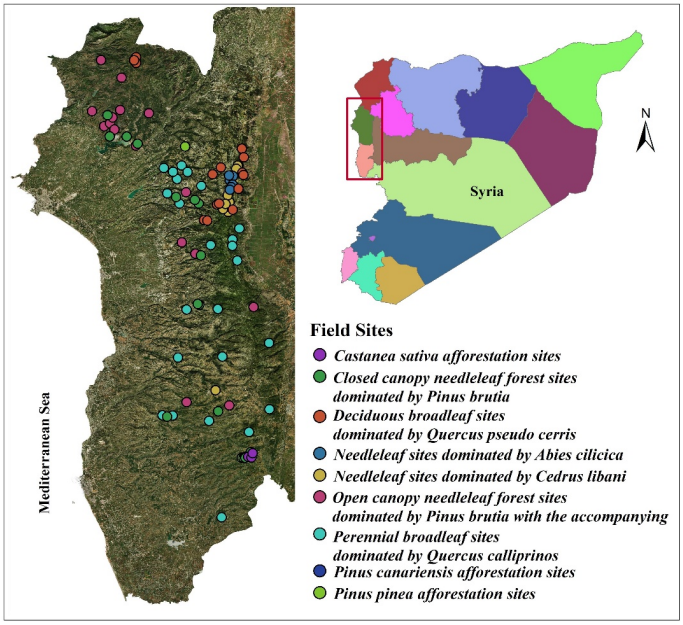


Fig. 1: Study area location

Table 1: Forest cover types of selected sites for the research

Forest cover type	Sites
Perennial broadleaf sites dominated by *Quercus calliprinos*	12
Deciduous broadleaf sites dominated by *Quercus pseudo cerris*	8
Castanea sativa afforestation sites	3
Needleleaf sites dominated by *Cedrus libani*	5
Pinus canariensis afforestation sites	2
Pinus pinea afforestation sites	4
Closed canopy needleleaf forest sites dominated by *Pinus brutia*	6
Needleleaf sites dominated by *Abies cilicica*	2
Open canopy needleleaf forest sites dominated by *Pinus brutia* with the accompanying species of broad leaf	12

Forests of the area are distributed according to the nature of the forest cover type that forms them into:

1. Coniferous forests: They constitute 27% of the total forests, and include mainly pine, in addition to cedar, fir and other types of pine entered into artificial reforestation sites.

2. Broad leaf forests: Oaks constitute the main component of them, and they account for 58% of the natural forests.

3. Mixed forests: which contain conifers and broad leaf.

4. Afforestation sites.

A field survey was conducted on 96 sites covering different types of forest cover from the forests of the study area. A composite sample consisting of three sub-samples was adopted in which the site specifications and the dominant plant species were determined, and their averages represented the site data ([Table. 1], [**Annex 1**]).

2.2 Methodology

This study assessed the response of different types of forest canopy to drought conditions in northwestern Syria. The methodological framework included satellite-based vegetation indices and climate-derived drought indicators over a 23-year period (2000–2022), by processing satellite images from Landsat (7 and 8) and CHRS data portal within the ERDAS Imagine and ArcGIS software environments.

Image Data analysis:

a) Leaf Area Index (LAI)

To monitor long-term forest canopy dynamics, Landsat imagery was used to extract vegetation indices, with a specific focus on the Leaf Area Index (LAI) as a vegetation cover characteristic was adopted in the research to access the climate change effect on the forest canopy. One cloud-free image from July (representing the end of the growing season) was selected annually for each year of the study period. This timeframe reflects peak canopy development, providing a consistent temporal reference across years.

The LAI, an essential eco-physiological parameter quantitative guide that describes the vegetative canopy, quantifies the ratio of total leaf surface area to ground area and serves as an indicator of vegetation health, productivity, and moisture content that is important for understanding the relationship between climate and vegetation. It was computed using the following equation derived from NDVI[19]:

$$LAI=0.57\times e^{(2.33\times NDVI)}$$

Where NDVI is the Normalized Difference Vegetation Index derived from surface reflectance bands. This approach provides a robust approximation of leaf biomass and canopy photosynthetic capacity, making it suitable for large-scale and long-term analyses.

The use of NDVI to estimate LAI is grounded in the strong empirical relationship between canopy greenness and leaf area. NDVI effectively captures the contrast between red and near-infrared reflectance, which correlates with photosynthetically active biomass. Numerous studies have demonstrated that exponential models linking NDVI to LAI provide reliable proxies for canopy structure, especially in forested ecosystems where direct LAI measurements are impractical on large spatial scales. Compared to other vegetation indices such as enhanced vegetation index EVI, NDVI remains more stable under moderate canopy densities and is less sensitive to soil background in forest environments, making it suitable for retrospective time-series analysis. This approach enhances the accuracy of LAI estimations and allows for consistent monitoring of vegetation dynamics across years[39, 40].

Importantly, the relationship between NDVI and LAI is not strictly linear, particularly in dense forest canopies. At lower NDVI levels, small changes in NDVI can correspond to significant differences in LAI. However, beyond a certain NDVI threshold, increases in LAI become less pronounced. Therefore, an exponential model better captures this non-linear behavior, improving the reliability of LAI estimation across varying vegetation densities[41, 42].

The spatial resolution and radiometric quality of Landsat data ensured accurate detection of vegetation patterns at a detailed scale, allowing for the distinction between forest types such as broadleaf deciduous, evergreen, and coniferous species.

b) Standardized Precipitation Index (SPI)

Drought was adopted as a phenomenon of climate change by studying the Standardized Precipitation Index (SPI) values for a time scale of 9 months.

precipitation data acquired from Center for Hydrometeorology and Remote Sensing (CHRS) data portal were prepared (using GIS functions), for the accumulative amount of an entire growing season, from September to May of the following year, for a 23-year time series from 2000-2022,

SPI calculated using the formula[43, 44]:

$SPI = (Xij - Xim)/\delta$

Xij: Accumulative precipitation for a given year

Xim: mean precipitation for the season

δ: Standard deviation of precipitation for the season

The SPI values were classified [Table. 2][44], to detect drought intensity over time, enabling to detect the moisture stress in forest ecosystems.

Table 2: SPI drought classes

Drought class	SPI Value
No Drought	> 0
Mild drought	0.0 – -1.0
Moderate Drought	-1.0 – -1.5
Severe Drought	-1.5 – -2.0
Extreme drought	< -2.0

Correlation Analysis Between LAI and SPI:

To evaluate the sensitivity of forest canopy dynamics to climatic drought conditions, a statistical correlation analysis was conducted between the Leaf Area Index (LAI) and the Standardized Precipitation Index (SPI). The Pearson correlation coefficient (r) was employed to quantify the strength and direction of the linear relationship between LAI and SPI over the 22-year period (2000–2022).

Pearson correlation coefficient was selected for this analysis due to its effectiveness in measuring the linear association between two continuous variables. Unlike non-parametric methods such as Spearman's rank correlation, which are more suitable for ordinal or non-linear data, Pearson correlation provides a direct measure of covariance normalized by standard deviation. This makes it especially appropriate for time-series data like LAI and SPI, where a linear relationship is hypothesized based on ecological and climatic interactions.

Moreover, Pearson correlation is sensitive to changes in both the magnitude and direction of the variables across years, thus offering a robust method to detect consistent patterns of co-variation in long-term environmental studies[42, 45].

3 Result and Discussion

3.1 Temporal Variation in LAI and SPI by Forest Type

An analysis of the annual LAI and SPI trends from 2000 to 2022 revealed clear differences in vegetation response to

drought conditions across the studied forest types in northwestern Syria. Each canopy formation exhibited a distinct range of variability, reflecting its unique structural and ecological characteristics [Fig. 2].

1. **Closed canopy needleleaf forest sites dominated by *Pinus brutia*:** the observed annual LAI values ranged from 0.96 to 1.79, while SPI fluctuated between –1.96 and 2.44 ([Fig. 2]**a**), indicating a relatively moderate sensitivity to interannual precipitation variability. This dynamic suggests that the species responds to fluctuations in rainfall but maintains a certain degree of canopy stability. According to Christopoulou *et al.* (2021)[46], Pinus brutia forests in Mediterranean climates show size-dependent responses to drought, with reduced growth and increased mortality under prolonged precipitation deficits, supporting the interpretation of moderate climate sensitivity in these formations.

2. **Open canopy needleleaf forest sites dominated by Pinus brutia with the accompanying species of broadleaf**: LAI values varied modestly from 0.7 to 1.2, whereas SPI spanned a much broader range from –1.74 to 2.43 ([Fig. 2]**b**). This discrepancy suggests that, despite sustained fluctuations in precipitation, the canopy structure remained relatively stable—indicating a buffering capacity inherent in the species' physiology and mixed-forest configuration. Similar patterns have been reported in Mediterranean mixed pine ecosystems, where P. brutia exhibits little change in leaf area indices but retains pronounced radial growth sensitivity to drought[47]. Such dynamics point to morphological adaptations and community structuring (e.g., facilitative shade by accompanying broadleaf trees) that help mitigate water stress while maintaining canopy cover.

3. **Perennial broadleaf sites dominated by Quercus calliprinos:** the observed Leaf Area Index (LAI) ranged from 0.5 to 0.9, while SPI values spanned from –1.57 to 2.54 ([Fig. 2]**c**), indicating that this species displays resilience under moderate drought stress. These findings align with evidence from Mediterranean evergreen oaks such as Quercus ilex where physiological traits like deep rooting systems and sustained water-use efficiency enable persistent canopy function even during dry spells[48, 49]. Moderate declines in photosynthesis during drought, coupled with substantial recovery upon re-watering, further substantiate the species' capacity to maintain greenness and biomass despite moisture stress[49].

4. **Deciduous broadleaf sites dominated by *Quercus pseudo cerris*:** LAI values ranged from 0.98 to 2.6, while SPI values varied between –1.47 and 2.33 ([Fig. 2]**d**), indicating a pronounced response to interannual climatic fluctuations. The broad range of both indices reflects this species' high sensitivity to drought and moisture availability, likely driven by its deciduous leaf habit and seasonal canopy dynamics, which increase the interannual variability in leaf area. This interpretation aligns with findings on related species such as *Quercus cerris*, which share similar eco-physiological traits. A recent study by[50] demonstrated that *Quercus cerris* exhibits greater adaptability to climatic stress than co-occurring species.

5. ***Castanea sativa* afforestation sites:** LAI values ranged from 1.4 to 2.7, while SPI fluctuated between –1.96 and 2.44 ([Fig. 2]**e**). These results suggest that, although ***Castanea sativa*** demonstrates a notable capacity to sustain leaf production under drought conditions through adaptive physiological mechanisms—such as temporary stomatal closure and compensatory photosynthetic recovery upon rehydration—exceptional or prolonged drought events often lead to a decline in Leaf Area Index (LAI). This reduction is primarily attributed to a decline in vegetative performance, manifested through suppressed leaf development as a means of conserving vital resources.

6. **Needleleaf sites dominated by *Cedrus libani*:** LAI range of 1.1 to 1.9, while SPI values varied from –1.57 to 2.51 ([Fig. 2]**f**), indicating a relatively stable canopy structure that appears less prone to short-term climate variability. This finding aligns with dendroecological research demonstrating *C. libani*'s resilience to summer drought[51] found that radial growth in *C. libani* responded positively to increased moisture in late winter and spring and showcased the highest drought resistance, recovery, and resilience among studied conifers. Further supporting this,[52] reported that *C. libani* recovered faster from water deficits than co-occurring *Juniperus excelsa* in the Taurus Mountains, maintaining higher radial increment rates despite summer stress. These studies

reinforce the interpretation that *Cedrus libani* maintains canopy stability and exhibits robust drought tolerance in line with the limited LAI variability observed in our analysis.

7. ***Pinus canariensis* afforestation sites**: LAI values ranged narrowly from 1 to 1.5, while SPI values spanned –1.42 to 2.33 ([Fig. 2]**g**). Despite moderate interannual variability in precipitation (SPI), the limited LAI range (0.4) suggests a relatively stable canopy structure, indicative of the species' intrinsic drought-buffering capacity. This interpretation is supported by[53], who found that canopy transpiration of *P. canariensis* remained stable in dry summer conditions, thanks to deep tap roots that access deep soil water and stomatal regulation under topsoil drought. Over extended aridity, stem growth declined but did not result in drastic canopy loss, indicating resilience under moisture stress[54].

8. ***Pinus pinea* afforestation sites:** LAI values varied moderately from 0.8 to 1.5, while SPI spanned a much broader range from –1.96 to 2.44 ([Fig. 2]**h**). The relatively limited LAI range compared to SPI suggests a stable canopy structure that buffers seasonal precipitation extremes, indicating a degree of drought tolerance. This finding aligns with current ecological research: P. pinea exhibits functional drought resilience and anatomical plasticity, particularly through xylem adjustments and moderate stomatal control that helps mitigate water stress[55].

9. **Needleleaf sites dominated by *Abies cilicica*:** SPI values ranged from –1.48 to 2.46, while LAI variation remained modest, between 0.55 and 0.8 ([Fig. 2]**i**). This narrow LAI range, despite considerable precipitation variability, suggests a stable canopy structure with limited sensitivity to short-term climate fluctuations. Such stability aligns with documented drought resilience characteristics of Mediterranean *Abies*. Comparative dendroecological analyses indicate that *A. cilicica* demonstrates greater resistance to drought than other *Abies* species exhibiting faster recovery and higher resistance indices even though it remains sensitive under extreme aridity[56].

3.2 Consistency of LAI and SPI Temporal Patterns

In the majority of forest canopy types studied, the annual progression of LAI and SPI did not consistently mirror each other particularly, SPI graphs displayed peaks and troughs that did not always coincide with those of LAI. This decoupling suggests that vegetation greenness (as indicated by LAI) may not immediately or fully track short-term precipitation anomalies represented by SPI. However, in the cases of *Quercus pseudo cerris* and *Castanea sativa* ([Fig. 2]**d,e**), the trajectories of LAI and SPI were closely aligned, indicating a synchrony in how leaf area and moisture availability fluctuate together across seasons.



Fig. 2: LAI and SPI values for each forest cover type: a) *Pinus brutia* (Closed canopy), *b) Pinus brutia* (Open canopy), c) *Quercus calliprinos, d) Quercus pseudo cerris, e) Castanea sativa, f) Cedrus libani, g) Pinus canariensis, h) Pinus pinea*, i) *Abies cilicica*

From a broader ecological perspective, such mismatches between LAI and SPI can be logically explained by

ecological processes inherent to natural systems in mediterranean ecosystems: SPI often responds to precipitation variability on multiple timescales, while LAI reflects the vegetation's eco-physiological threshold and recovery capacity. As highlighted in a broad-scale study of drought sensitivity across Mediterranean forests, multi-scalar drought indices such as SPI and SPEI showed stronger correlation with vegetation growth indicators like NDVI during specific seasons in dry coniferous forests, whereas responses in LAI can lag or flatten during sharp precipitation changes[57, 58].

Similarly, research in the Damqu Basin found that vegetation responses (NDVI or LAI) can lag behind meteorological signals like SPI by several weeks to months especially during drought onset resulting in graph misalignment between precipitation indices and canopy greenness[59].

Thus, the findings are consistent with Mediterranean observations where *Q. pseudocerris* and *C. sativa*, with their pronounced seasonality and rapid leaf-area dynamics, tend to align more closely with precipitation trends. In contrast, species with slower canopy turnover or deeper-rooted hydraulic traits (e.g., conifers) exhibit buffered or lagged responses, leading to the decoupled LAI–SPI shapes observed in mixed forest types.

3.3 Correlation Between LAI and SPI

To assess forest resilience to drought, a correlation analysis was performed between annual LAI and corresponding SPI values for georeferenced points representing dominant forest types. This analysis aimed to quantify the sensitivity of canopy development to precipitation variability at the level of an entire rainy season of 9 months, enabling us to assess the sustainability of these ecosystems under climate change.

The results indicated a significant positive correlation in the all-forest type's locations, the LAI–SPI correlation coefficients (r) [Table. 3] ranged from 0.67 (high sensitivity) in *Castanea sativa* down to 0.29 (low sensitivity) in *Abies cilicica*.

High correlations in *Castanea sativa* (r = 0.67), *Cedrus libani* (r = 0.64), *Quercus pseudo cerris* (r = 0.63), and *Pinus brutia* (Closed canopy) (r = 0.62) indicate that canopy greenness strongly reflects interannual precipitation changes, characteristic of species or formations that rapidly adjust leaf area with water availability.

Moderate correlations observed in Pinus pinea (r = 0.48) and *Pinus canariensis* (r = 0.46) suggest seasonal or managed leaf area changes—responsive yet buffered by phenological timing or silvicultural stability. Conversely, lower correlations in *Pinus brutia* (Open canopy) (r = 0.36) and *Abies cilicica* (r = 0.29) imply that these species exhibit hydraulic or structural traits that decouple canopy greenness from short-term rainfall variations.

Analysis of the relationship between LAI and SPI demonstrates the importance of this integration between climatic and vegetation factors in revealing the ecological resilience of forest species. A higher correlation indicates a species' high sensitivity to rainfall changes, and thus, its relative resilience. A lower correlation may indicate a structural or physiological adaptation that allows trees to maintain stable vegetation cover despite fluctuating hydrological conditions. From this perspective, the results of this analysis can be used as a guide for forest management and reforestation efforts by selecting species with greater drought tolerance in areas most vulnerable to climate change.

Table 3: Correlation coefficients (r) between LAI and SPI by forest cover type

Forest cover type	r
Castanea sativa afforestation sites	0.67
Needleleaf sites dominated by *Cedrus libani*	0.64
Deciduous broadleaf sites dominated by *Quercus pseudo cerris*	0.63
Closed canopy needleleaf forest sites dominated by *Pinus brutia*	0.62
Perennial broadleaf sites dominated by *Quercus calliprinos*	0.50
Pinus pinea afforestation sites	0.48
Pinus canariensis afforestation sites	0.46
Open canopy needleleaf forest sites dominated by *Pinus brutia* with the accompanying species of broad leaf.	0.36
Needleleaf sites dominated by *Abies cilicica*	0.29

It was also observed that forest cover types exhibiting correlation coefficients of 0.5 or higher tended to show a broader range of LAI values throughout the study period, indicating a more variable canopy development response to precipitation fluctuations [Fig. 3].

The widest range was recorded in *Quercus pseudo-cerris* sites (range = 1.62), followed by *Castanea sativa* plantations (range = 1.3). In contrast, the broadleaf evergreen forest types dominated by oaks (*Quercus calliprinos*) exhibited one of the narrowest ranges in LAI (range = 0.4), indicating a relatively stable canopy response

to interannual precipitation changes, despite their broad spatial coverage.

Even more stable were the *Abies cilicica* sites (range = 0.25), likely due to the ecological specificity of their habitats, limited distribution, and particular environmental requirements.

In general, needleleaf species including *Pinus brutia*, *Pinus canariensis*, *Pinus pinea*, and *Cedrus libani* occupied an intermediate position in terms of resilience to precipitation variability, as reflected in their moderate LAI fluctuations.

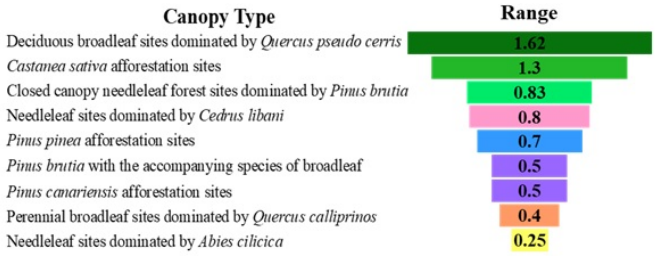


Fig. 3: LAI value range through studied time series in each canopy type

4 Conclusion

The findings of this study highlight the varied responses of different forest cover types to seasonal drought conditions, as revealed through the correlation between canopy development (LAI) and precipitation variability (SPI). These insights are critical for informing sustainable forest management practices, particularly in drought-prone Mediterranean ecosystems such as those of north western Syria.

In light of these results, forest types exhibiting stronger canopy sensitivity to precipitation (*Quercus pseudo cerris* and *Castanea sativa*) should be prioritized for adaptive management strategies that enhance their resilience, such as selective thinning, assisted regeneration, and improved water retention practices.

Furthermore, these findings hold significant value in supporting proactive interventions within strategies aimed at restoring natural ecosystems, particularly in ecologically fragile areas highly exposed to the impacts of climate change. Selecting drought-tolerant plant species is not merely a precautionary measure, but a data-driven approach that enhances the efficacy of reforestation and vegetation rehabilitation programs. Species that one of the narrowest ranges in LAI - such as *Quercus calliprinos* - Open canopy needleleaf forest sites dominated by *Pinus brutia* with the accompanying species of broadleaf are ideal candidates for re-establishment in regions experiencing pronounced precipitation variability, given their capacity to rapidly adjust leaf area in response to water availability. This trait contributes to stabilizing vegetation cover and sustaining ecosystem services including carbon sequestration, local climate regulation, and erosion control, In view of the extensive spatial range and the ecological significance of native species within the region.

Conversely, species with lower correlation values, which display delayed or buffered responses to rainfall fluctuations, may be suitable for scenarios requiring long-term structural stability in canopy cover. However, they might be more susceptible to increased climatic pressures. Therefore, this analysis provides an opportunity to design climate-smart ecological maps that classify species according to their climate resilience, thereby informing more precise and effective forest management plans and reinforcing the adaptive capacity of ecosystems to withstand and recover from accelerating climatic changes.

This approach not only improves the sustainability of forest landscapes but also strengthens their role in climate adaptation and land degradation neutrality under current and future environmental stressors.

These recommendations align directly with global sustainable development objectives, particularly SDG 13 (Climate Action) and SDG 15 (Life on Land). Promoting climate-resilient forest types and integrating ecological monitoring tools like LAI and SPI into policy frameworks can enhance both biodiversity conservation and ecosystem service provision.

Future studies need to combine remote sensing with field analyses to determine physiological tolerances and follow-up retreat processes to better understand how the region's forests will respond to the rapid climate change expected in this region. The results also call for focusing on management systems to increase the resilience of forests in the face of climatic changes and working to intervene in possible locations and push the plant structure towards more resilient systems.

Annex (1): Field sites coordination

Easting	Northing	Field Site
34° 57' 2	34° 57' 2	
34° 57' 2	34° 57' 2	*Castanea sativa* afforestation sites
34° 57' 5	34° 57' 5	
35° 17' 5	35° 17' 5	
35° 39' 2	35° 39' 2	
35° 31' 2	35° 31' 2	
35° 17' 5	35° 17' 5	
35° 24' 3	35° 24' 3	
35° 40' 2	35° 40' 2	
35° 40' 2	35° 40' 2	Closed canopy needleleaf forest sites dominated by *Pinus brutia*
35° 31' 5	35° 31' 5	
35° 32' 2	35° 32' 2	
35° 43' 1	35° 43' 1	
34° 58' 5	34° 58' 5	
34° 57' 1	34° 57' 1	
35° 3' 33	35° 3' 33	
35° 2' 50	35° 2' 50	
35° 51' 6	35° 51' 6	
35° 29' 1	35° 29' 1	
35° 29' 1	35° 29' 1	
35° 31' 2	35° 31' 2	
35° 35' 2	35° 35' 2	
35° 36' 1	35° 36' 1	
35° 29' 1	35° 29' 1	
35° 31' 2	35° 31' 2	
35° 38' 5	35° 38' 5	Deciduous broadleaf sites dominated by *Quercus pseudo cerris*
35° 37' 4	35° 37' 4	
35° 35' 3	35° 35' 3	
35° 35' 1	35° 35' 1	
35° 33' 2	35° 33' 2	
35° 30' 3	35° 30' 3	
35° 50' 2	35° 50' 2	
35° 50' 4	35° 50' 4	
35° 34' 3	35° 34' 3	
35° 35' 9	35° 35' 9	
35° 35' 1	35° 35' 1	Needleleaf sites dominated by *Abies cilicica*
35° 34' 0	35° 34' 0	
35° 33' 4	35° 33' 4	
35° 33' 1	35° 33' 1	
35° 36' 3	35° 36' 3	Needleleaf sites dominated by *Cedrus libani*
35° 35' 1	35° 35' 1	
35° 36' 3	35° 36' 3	
35° 36' 7	35° 36' 7	
35° 30' 2	35° 30' 2	
35° 30' 4	35° 30' 4	

Easting	Northing	Field Site
35° 31' 3	35° 31' 3	
35° 32' 3	35° 32' 3	
35° 31' 2	35° 31' 2	
34° 57' 2	34° 57' 2	
35° 6' 23	35° 6' 23	
35° 4' 47	35° 4' 47	
35° 48' 2	35° 48' 2	
35° 43' 3	35° 43' 3	
35° 44' 1	35° 44' 1	
35° 50' 4	35° 50' 4	
35° 17' 3	35° 17' 3	
35° 26' 1	35° 26' 1	
35° 41' 4	35° 41' 4	Open canopy needleleaf forest sites dominated by *Pinus brutia* with the accompanying species of broad leaf
35° 32' 5	35° 32' 5	
35° 24' 4	35° 24' 4	
35° 39' 1	35° 39' 1	
35° 42' 1	35° 42' 1	
35° 41' 2	35° 41' 2	
35° 43' 1	35° 43' 1	
35° 43' 5	35° 43' 5	
35° 4' 21	35° 4' 21	
34° 49' 1	34° 49' 1	
35° 10' 4	35° 10' 4	
35° 34' 4	35° 34' 4	
35° 33' 4	35° 33' 4	
35° 25' 5	35° 25' 5	
35° 2' 16	35° 2' 16	
35° 12' 4	35° 12' 4	
35° 3' 49	35° 3' 49	
35° 28' 7	35° 28' 7	
35° 23' 4	35° 23' 4	
35° 10' 5	35° 10' 5	
35° 35' 4	35° 35' 4	
35° 31' 2	35° 31' 2	Perennial broadleaf sites dominated by *Quercus calliprinos*
35° 17' 1	35° 17' 1	
35° 17' 1	35° 17' 1	
35° 36' 3	35° 36' 3	
35° 35' 4	35° 35' 4	
35° 32' 4	35° 32' 4	
35° 0' 46	35° 0' 46	
35° 2' 58	35° 2' 58	
35° 3' 1.	35° 3' 1.	
35° 36' 1	35° 36' 1	
35° 26' 3	35° 26' 3	
35° 25' 4	35° 25' 4	
35° 23' 4	35° 23' 4	
35° 36' 2	35° 36' 2	*Pinus canariensis* afforestation sites

Easting	Northing	Field Site
35° 39' 7	35° 39' 7	*Pinus pinea* afforestation sites
35° 39' 7	35° 39' 7	
34° 57' 1	34° 57' 1	
34° 57' 1	34° 57' 1	

Declarations

Ethical Responsibilities of Authors:

All author has read, understood, and has complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

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