

Assessing the Impact of Canopy Plant Area Index (PAI) and Soil Moisture on Forest Fire Susceptibility: A Remote Sensing Approach from the SENTHYMED/MEDOAK Experiment

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Abstract

This study explores the potential of Canopy Plant Area Index (PAI) and soil moisture measurements, derived from the SENTHYMED/MEDOAK experiment, to assess the susceptibility of Mediterranean forests to wildfires. Through rigorous analysis of in-situ measurements and utilizing Python for statistical analysis, this study performs descriptive statistics, temporal trend analysis, rolling mean calculations, and correlation analysis between PAI and soil moisture to unveil their predictive potential for forest fire risk. Through these methods, the study tries to establish a correlative framework that enhances the predictive accuracy of forest fire risk models. The key findings reveal a pronounced seasonal variation in soil moisture and PAI, with implications for identifying periods of increased wildfire susceptibility. These insights aim to contribute an understanding of forest vulnerability and resilience to climate-induced stressors, offering a foundation for enhancing forest fire risk assessment models.

Keywords

Forest Fires, Remote Sensing, Soil Moisture, Canopy Plant Area Index, Mediterranean Forests, SENTHYMED/MEDOAK.

1. Introduction

Forest fires pose a major ecological and socio-economic threat, which has led to an increasing interest in developing more accurate fire risk assessment models. Traditional methods, often reliant on historical data and physical models, may not adequately capture the dynamic interactions within forest ecosystems. Recent advancements in remote sensing technologies have revolutionized our ability to monitor these dynamics in real-time. Our study builds upon these innovations, particularly the findings from the SENTHYMED/MEDOAK experiment (Adeline et al., 2024), to explore how Canopy Plant Area Index (PAI) and soil moisture measurements might enhance models of fire susceptibility in Mediterranean forests, a region increasingly affected by climate change and anthropogenic pressures.

The field of forest fire research has benefited greatly from interdisciplinary approaches and the integration of cutting-edge remote sensing technologies. For example, the utilization of machine learning algorithms for mapping fire susceptibility and the advanced sensor comparisons for early detection have demonstrated significant improvements in predictive capabilities (Hendel & Ross, 2020; Seddouki et al., 2023). Additionally, studies by Gale et al. (2021) and Schroeder et al. (2008) have demonstrated how remote sensing facilitates detailed insights into fire behavior and fuel types, even under challenging conditions like cloud coverage. The capabilities of hyperspectral imaging and Unmanned Aerial Vehicle (UAV)-based sensing systems have also been crucial in mapping burned areas and assessing fire severity, as seen in the work of Moreno Ruiz et al. (2012) and Veraverbeke et al. (2018). Moreover, some studies have also utilized remote sensing to monitor forest dynamics and assess fire risk, like the study explored by Laneve et al. (2020), which utilizes these infrastructures to aid in forest management. Similarly, the study by Adeline et al. (2024) focuses on the SENTHYMED/MEDOAK experiment, which provides a comprehensive dataset encompassing Canopy Plant Area Index (PAI) and soil moisture measurements and aims to evaluate their potential in enhancing forest fire susceptibility models. These technological enhancements enable not only the assessment of burn severity but also contribute to the refinement of forest management practices, essential for mitigating the impacts of climate change and anthropogenic influences on vulnerable Mediterranean ecosystems.

For this study, the focus is centered on the Mediterranean oak forests in the Northern Montpellier region of France, which are increasingly subjected to climate change variability and anthropogenic pressures that is affecting their structure and ecosystem. Three objectives were searched and obtained: First, to assess the relationship between PAI and soil moisture and their combined effect on fire risk. Second, to evaluate the seasonal variability of these factors and their implications for fire susceptibility. And third, to develop a predictive framework that integrates these ecological indicators, enhancing the accuracy and timeliness of fire risk assessment. The SENTHYMED/MEDOAK experiment, conducted in 2021, was chosen as the basis for this study since the experiment aimed to closely monitor Mediterranean oak forests through advanced remote sensing techniques, and it provided an invaluable dataset for understanding the interplay between vegetation structure and moisture content in the context of fire risk. By integrating remote sensing and ground-based observations, the purpose of our study is to refine the predictive capabilities of existing forest fire risk models, emphasizing the importance of precise, multi-temporal ecological data.

2. Materials and Methods

The methodology of this study leverages recent advancements in remote sensing technologies to analyze ecological indicators critical to assessing forest fire susceptibility. This study utilized comprehensive datasets from the SENTHYMED/MEDOAK experiment conducted in 2021, which provided extensive measurements of soil moisture and Canopy Plant Area Index (PAI) (Adeline et al., 2024). These datasets are crucial as they provide direct assessments of vegetation

structure and soil conditions and are pivotal for the study's analysis as they are significantly correlated with forest health and fire risk in the Mediterranean region.

The SENTHYMED/MEDOAK experiment supplied comprehensive datasets, including soil moisture measurements and PAI data, from Mediterranean oak forests in Montpellier, France. This study's approach involved merging spatial data from shapefiles with corresponding measurements, facilitating a detailed examination of environmental variables across different forest plots. This application was inspired by the work of Veraverbeke et al. (2018), who emphasized the transformative role of remote sensing in enhancing our understanding of forest ecology and fire dynamics, which this study applied on advanced analytical methods to assess how these ecological indicators influence forest fire susceptibility. This included spatial analysis to determine the distribution of vegetation and moisture content, and temporal analysis to track their fluctuations over time.

Data analysis was conducted using Python 3.7, with extensive use of libraries such Pandas (v2.2) for data manipulation, Matplotlib (v3.8.4) for data visualization, and SciPy (v1.13) for statistical analysis. Soil moisture was analyzed using Python scripts to calculate descriptive statistics and identify significant temporal patterns. Similarly, PAI data underwent processing to ascertain mean values and temporal trends. The rolling mean was calculated using the Pandas library's `rolling()` (v1.3.0) function, with a window size of 7 days, to smooth out PAI and soil moisture data for trend analysis. The choice of a 7-day window for the rolling mean calculation was determined based on preliminary analyses indicating this period effectively captures the cyclical nature of PAI and soil moisture variations while smoothing out day-to-day variability. This approach allowed us to explore the spatial and temporal dynamics of PAI and soil moisture comprehensively.

2.1 Study Area

The SENTHYMED/MEDOAK experimental sites, located in the north of Montpellier, France, consist of two primary forest areas, the Puechabon and Pic Saint-Loup national forests, which are characterized by a diverse range of flora including *Quercus ilex* and *Quercus pubescens* genus of oak trees, and the *Juniperus oxycedrus*, *Pistacia terebinthus* and *Bruxus sempervirens* genus of bush, which are predominant in the area. These sites represent diverse Mediterranean forest ecosystems with varying canopy cover and phenological dynamics.

2.2 Data Collection

The study utilizes Canopy Plant Area Index (PAI) and soil moisture data collected from April to October 2021. Soil moisture was measured using Time Domain Reflectometry (TDR) probes, while PAI values were obtained using LI-COR-LAI-2000 Plant Canopy Analyzers.

2.3 Data Analysis

Data processing involved merging geospatial shapefiles with corresponding textual data records, followed by a comprehensive statistical analysis. This integration facilitated a comprehensive analysis of environmental variables. Descriptive statistics, temporal trend analysis, and rolling mean calculations were performed to examine the variations in PAI and soil moisture over time. These methods allowed this study to assess the predictive capabilities of PAI and soil moisture for forest fire susceptibility, which incorporated insights from Hendel & Ross (2020) on the efficacy of remote sensing in early fire detection.

2.3.1 Canopy Plant Area Index (PAI) Measurements:

PAI is the total area of plant leaves, stems, and other photosynthetically active components per unit ground surface area, as measured above the ground. This index is derived from the ratio of transmitted light below the canopy to the incident light above the canopy, reflecting the canopy's density and its ability to intercept light. PAI is an extension of the Leaf Area Index (LAI) and includes other plant parts in addition to leaves, providing a more comprehensive measure of canopy structure.

The effective Plant Area Index (PAI) was calculated using measurements from LI-COR plant canopy analyzers (either LAI-2000 or LAI-2200) based on the two-sensors mode to perform the measurements, with one sensor measuring clear sky in the open and the second sensor measuring below the canopy. The merging of the data from the two optical sensors and the effective PAI computation would involve formulas provided by the FV2200 software, which computes PAI based on the gap fraction values for different zenithal orientations.

The equations for calculating the Plant Area Index (PAI) from the LAI-2000 or LAI-2200 plant canopy analyzers are based on two main applications that follow the methodology suggested by Saitoh et al. (2012). The first one, the gap fraction method, is a technique that typically involves the calculation of the light transmittance through the forest canopy, which can be determined by comparing the light levels detected by the sensors under the canopy to those in open area:

$$\text{Gap Fraction} = \frac{\text{Light Through Gaps}}{\text{Total Light}}$$

The second approach to calculating PAI applies Beer's Law, which describes the attenuation of light as it penetrates through a canopy made up of leaves and branches. The law is formulated to account for the area of foliage and its effect on light transmission. By using the gap fraction method, it estimates a measurement of the amount of light passing through the canopy (hence the negative logarithmic):

$$PAI = \frac{-\ln(\text{gap fraction})}{k}$$

Where k is an extinction coefficient that depends on the leaf angle distribution. Which ranges from 0 to 1, where 0.5 means a randomly oriented diffusion of light among the canopy and can vary depending on specific canopy and light conditions.

2.3.2 Soil Moisture Measurements:

Soil moisture content measurements in the SENTHYMED/MEDOAK study utilized Time Domain Reflectometry (TDR) or similar probes for in-situ measurements, as mentioned with the use of Campbell CS616 probes and IMKO probes in PUE and PSL, respectively. The volumetric soil moisture percentage is a direct output of these measurements, often requiring no further calculation beyond calibration adjustments specific to each instrument's protocol.

In this study, soil moisture analysis focused heavily on data aggregation, where the daily averages of soil moisture data were calculated and grouped. This data was merged by date to ensure synchronization between environments. Daily average was calculated as:

$$\text{Daily Average} = \frac{\Sigma \text{of daily values}}{\text{number of values in each day}}$$

2.3.3 Descriptive Statistics:

This study utilized basic descriptive statistics for both PAI and soil moisture, which indicate the central tendency and dispersion of the datasets, were done through Python using Python libraries. These calculations are:

$$\text{Mean: } \bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$

$$\text{Standard Deviation: } s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}$$

In addition to the above, percentile analytics were used, and the values below which a certain percentage of observations fall were chosen. These are typically calculated using interpolation between the observed values. This study focuses on the minimum, 25th percentile, median, 75th percentile and maximum.

2.3.4 Rolling Mean Calculation:

Rolling mean or moving average was used to analyze temporal trends over time for soil moisture and PAI. This technique smooths out short-term fluctuations and highlights longer-term trends or cycles, which helps provided a clearer view of the overall trend by minimizing the effect of daily fluctuations thus helping identify longer-term changes in the canopy and soil moisture that are relevant for assessing fire risk. The rolling mean is calculated as the average of the current and the preceding values over a specified period (7 days) to produce a series of averages. These calculations were done though

Python using Python libraries such as `pandas.rolling()` which is based on the rolling mean formula for a time series:

$$MA_t = \frac{1}{k} \sum_{i=t-k+1}^t x_i$$

Where k is the window size (7 days for this study).

2.3.5 Relationship Analysis Between PAI and Soil Moisture:

This analysis aimed to quantify the degree of association between the two variables which are crucial indicators of vegetation health and fire risk susceptibility. To quantitatively assess the relationship between Canopy Plant Area Index (PAI) and soil moisture within the Mediterranean oak forests, data aggregation was conducted through Python using Python libraries such as Pandas to conduct this data manipulation. This was applied to the daily mean values of PAI and volumetric soil moisture, which provided a statistical measure of how closely PAI and soil moisture variations are linearly related across the study period from April to October 2021. A time series visualization was employed to provide a visual trend on how these variables change over time.

2.3.6 Fire Risk Assessment:

To establish scientifically sound thresholds for the fire risk assessment, this study draws on the research conducted by MacDonald and Huffman on post-fire soil water repellency (MacDonald & Huffman, 2004). Their findings provided a framework for the analysis of PAI and soil moisture data to derive thresholds indicative of heightened fire risk, which utilizes real-time data to evaluate forest conditions. The methods employed involve the aggregation of daily mean PAI and soil moisture values, and the establishment of their relationship with potential fire occurrence. To identify these thresholds, the study uses statistical techniques to analyze the data distribution and define specific PAI and soil moisture ranges that correlate with increased fire risk. These thresholds were:

$$\text{High Risk PAI Threshold} = PAI_{75\%}$$

$$\text{High Risk Soil Moisture Threshold} = \text{Soil Moisture}_{25\%}$$

These thresholds include assessing the 75th percentile values, where higher PAI in combination with lower soil moisture levels may signal greater susceptibility to wildfires. These data-driven thresholds are essential for developing predictive models that can be used to alert forest management to emerging high-risk conditions, particularly for regions prone to seasonal dryness and wildfire outbreaks. Ultimately, this segment of the study aims to contribute towards improving the accuracy and timeliness of forest fire risk assessments, which is of paramount importance in the proactive management and conservation of Mediterranean oak forests.

3. Results

The study's findings reveal pronounced seasonal variation in soil moisture and PAI, similar to patterns observed in studies by Schroeder et al. (2008) and Hendel & Ross (2020), where remote sensing technologies were crucial in identifying and understanding these fluctuations. The correlations observed between PAI and soil moisture align with predictive models discussed by Seddouki et al. (2023), further validating the study's methodology and supporting the utility of these measures in fire risk assessment.

3.1 Soil Moisture Observations

3.1.1 Volumetric Soil Moisture by Location

This study's analysis revealed significant variations in volumetric soil moisture across different site plots within the Mediterranean oak forests, ranging from 0% to 35%. Notably, plots PUE_CP1 and PUE_CP2 displayed the widest range of soil moisture values, indicating diverse hydrological conditions within these areas. Conversely, plots PSL_22, PSL_10, PSL_5, and PSL_7 exhibited lower volumetric soil moisture percentages, positioning them at the more arid spectrum of the studied sites. This disparity underscores the spatial heterogeneity of soil moisture within the forest, suggesting that certain areas may be more susceptible to drought stress compared to others (Figure 1).

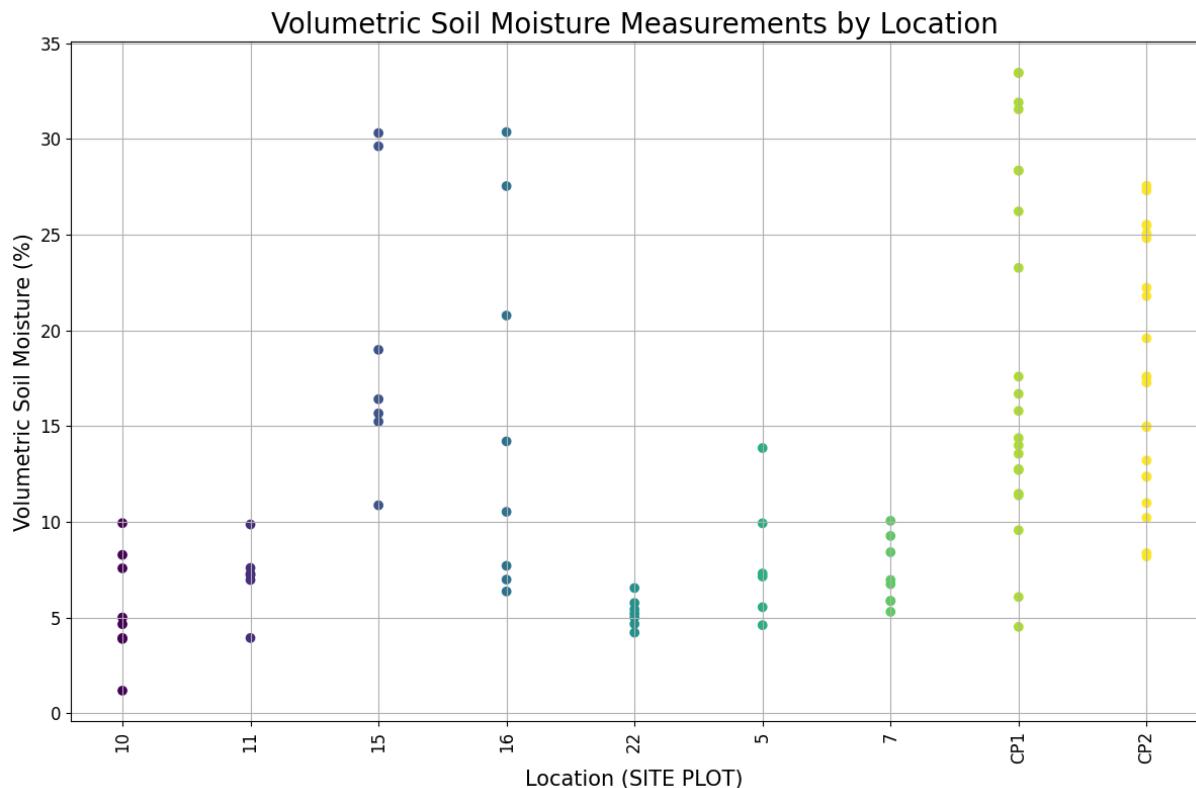


Figure 1: Volumetric soil moisture measurements from the forest plot locations found in the Montpellier region.

3.1.2 Spatial Distribution of Soil Moisture

The spatial analysis of soil moisture measurements, based on longitudes (15.575 to 15.800) and latitudes (43.74 to 43.80), indicated pronounced clustering of data points at the extremities of our study area. Intermediate longitudinal and latitudinal ranges appeared devoid of significant moisture measurements, illustrating a pronounced spatial variability in soil moisture distribution. This pattern could reflect topographical influences or variations in forest canopy cover, which merit further investigation (Figure 2).

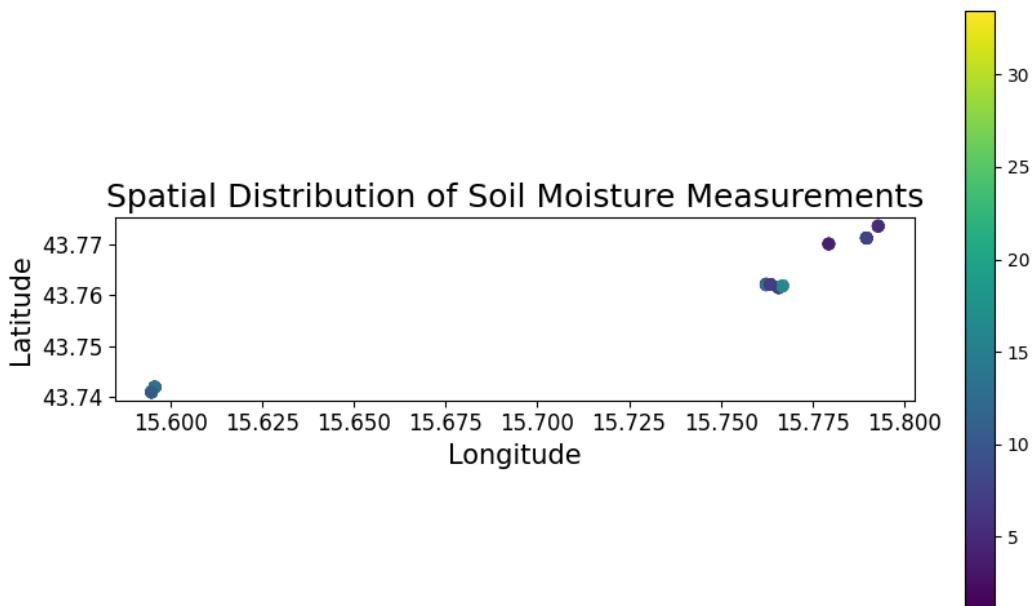


Figure 2: The spatial distribution of soil moisture based on the latitude and longitude of the region.

3.1.3 Temporal Patterns of Soil Moisture

Temporal examination of soil moisture over a 250-day period revealed episodic measurement intensities, with day 66 exhibiting the highest data point concentration, focusing mostly on the lower end of soil moisture. This suggests sporadic rainfall or irrigation events, leading to fluctuating soil moisture levels across the study plots. The scatter plot visualization of these measurements by forest plot indicates that soil moisture variability is not only spatial but also temporal, emphasizing the dynamic nature of hydrological processes in these forests (Figure 3).

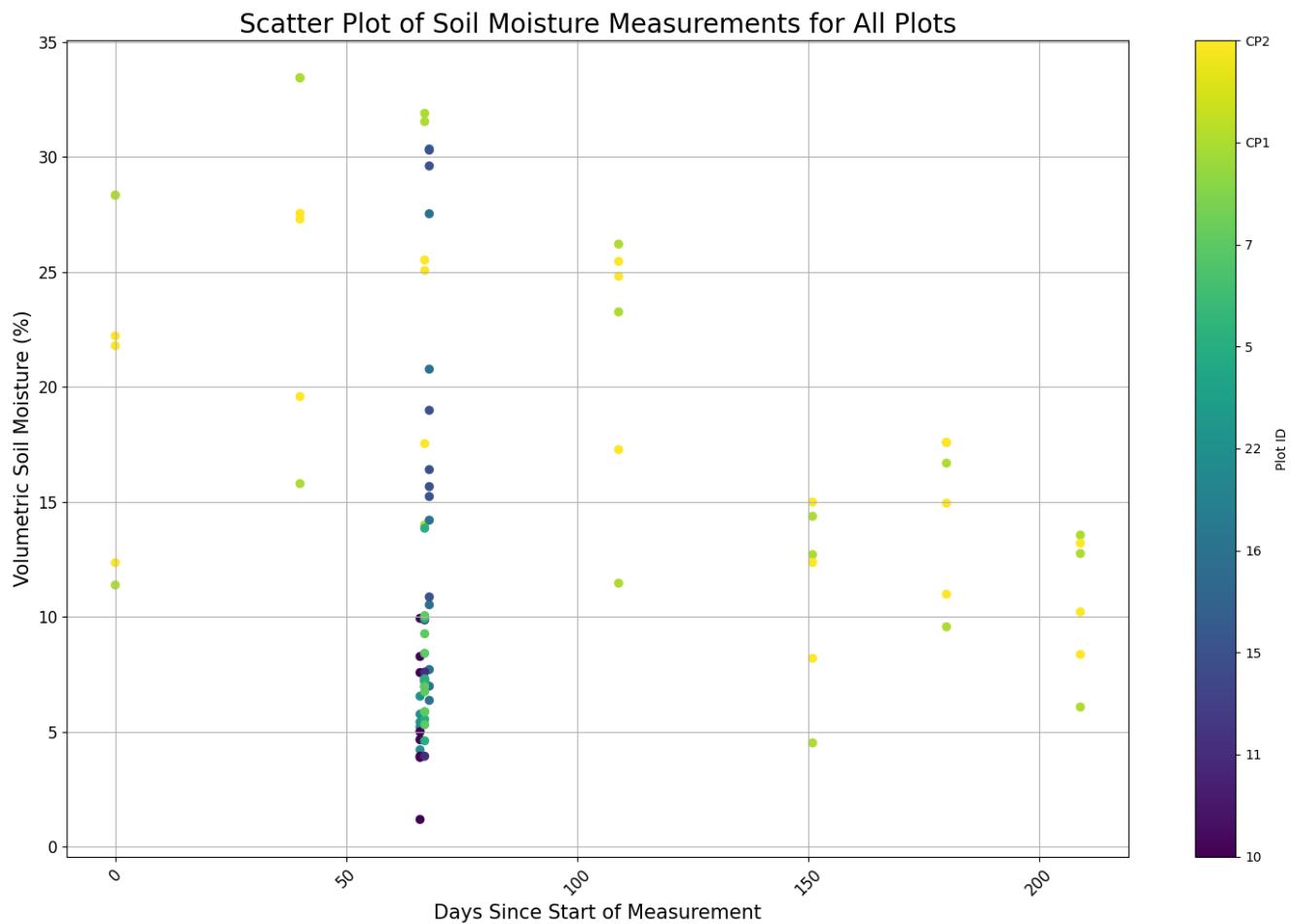


Figure 3: Temporal patterns of soil moisture measurements in a period of 250 days.

3.1.4 Correlation Between Soil Moisture and Temperature

The study also explored the interplay between soil moisture and temperature, observing a reverse trend between these two critical environmental variables. As soil temperature peaked mid-study period, soil moisture exhibited a sharp decline, followed by fluctuating recovery. This inverse relationship suggests that elevated temperatures may exacerbate moisture loss, potentially heightening wildfire risks during peak temperature periods. The dynamic fluctuations in soil moisture, juxtaposed with soil temperature trends, highlight the intricate balance between these variables in mediating forest health and fire susceptibility (Figure 4).

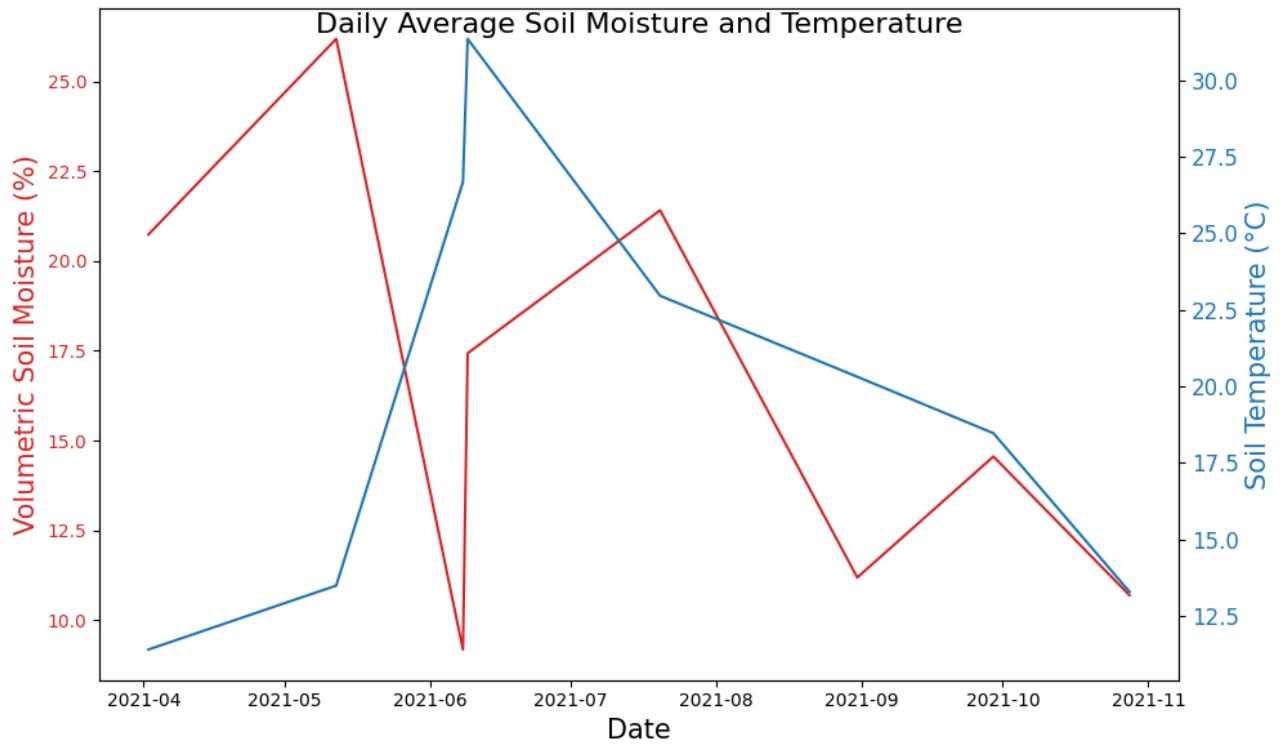


Figure 4: Correlation between average soil moisture and temperature.

3.1.5 Descriptive Statistics of Soil Moisture

Our analysis encompassed ninety-two soil moisture measurements, revealing an average volumetric soil moisture of 13.77% with a standard deviation of 8.59%. The moisture content ranged from a minimum of 1.18% to a maximum of 33.45%, highlighting the broad variability within the study area. The lower quartile (25%) of measurements was at 6.96%, and the upper quartile (75%) reached 17.94%, indicating a significant spread of moisture values across the Mediterranean oak forests (Table 1).

Descriptive Statistics for Soil Moisture	
Count	92.0000
Mean	13.7654
Standard deviation	8.5924
Minimum	1.1800
25%	6.9600
50%	11.1800
75%	17.9375
Maximum	33.4500

Table 1: Statistics of soil moisture measurements

3.1.6 Temporal Analysis of Soil Moisture

A focused examination of soil moisture over selected days illustrates the fluctuating nature of this critical environmental variable. On day zero, the mean soil moisture was observed at 20.74%, which peaked at 26.19% by day 40, indicative of a wet period in the early phase of the study. A sharp decline to 5.41% on day sixty-six, the lowest observed value, suggests a rapid onset of dry conditions, which slightly recovered in the subsequent days. By day 109, moisture levels again increased to 21.41%, followed by gradual decreases and increases, reflecting the dynamic interplay between precipitation, evaporation, and transpiration processes within the forest ecosystem (Table 2).

Temporal Analysis of Soil Moisture	
Days Since Start	Mean Soil Moisture by Day
0	20.74 %
40	26.19 %
66	5.41 %
67	11.35 %
68	17.43 %
109	21.41 %
151	11.19 %
180	14.56 %
209	10.69 %

Table 2: Mean soil moisture percentage by day

3.1.7 Spatial Highlights of Soil Moisture Variability

Identifying areas of high and low moisture content is crucial for understanding forest vulnerability to stressors such as drought and fire. Plots PUE_CP1, PUE_CP2, PSL_16, and PSL_15 emerged as regions with the highest moisture levels, placing them in the top 10% of the measurements. These areas could potentially represent microhabitats with favorable conditions for moisture retention or access to deeper water sources. Conversely, areas like plots PSL_22, PSL_10, PSL_11, and PSL_5 were among the bottom 10%, indicating significantly lower soil moisture levels. This distribution underscores the spatially heterogeneous nature of moisture availability, which could influence species composition, forest health, and fire susceptibility (Table 3).

Moisture Content Distribution for Area Plots				
Areas with High Moisture Content (Top 10%)	PUE_CP1	PUE_CP2	PSL_16	PSL_15
Areas with Low Moisture Content (Bottom 10%)	PSL_22	PSL_10	PSL_11	PSL_5

Table 3: Areas with high or low moisture content

3.1.8 Rolling mean analysis for Soil Moisture Over Time

The analysis of "Soil Moisture Over Time" reveals the variability in volumetric soil moisture throughout the observation period. The raw data exhibits significant fluctuation, reflective of the diverse moisture conditions within the Mediterranean oak forest ecosystem. The application of a 7-day rolling mean (plotted as a red line) provides a smoothed trend that navigates through the daily variability, highlighting key periods of moisture increase and depletion. This rolling mean trend, starting from, approximately, 20-25% volumetric soil moisture and experiencing peaks and troughs corresponding to specific dates, underscores the dynamic nature of soil moisture in response to climatic conditions and potential evapotranspiration rates within the forest (Figure 5). The high initial moisture level that peaked around May could possibly be attributed to spring precipitation. The sharp decline of soil moisture is consistent as the data collection moves into the drier summer months, reaching its lowest between July and August, which is consistent with typical Mediterranean climate patterns. This pattern could be critical for fire risk management, as the prolonged period of low soil moisture could increase fire susceptibility.

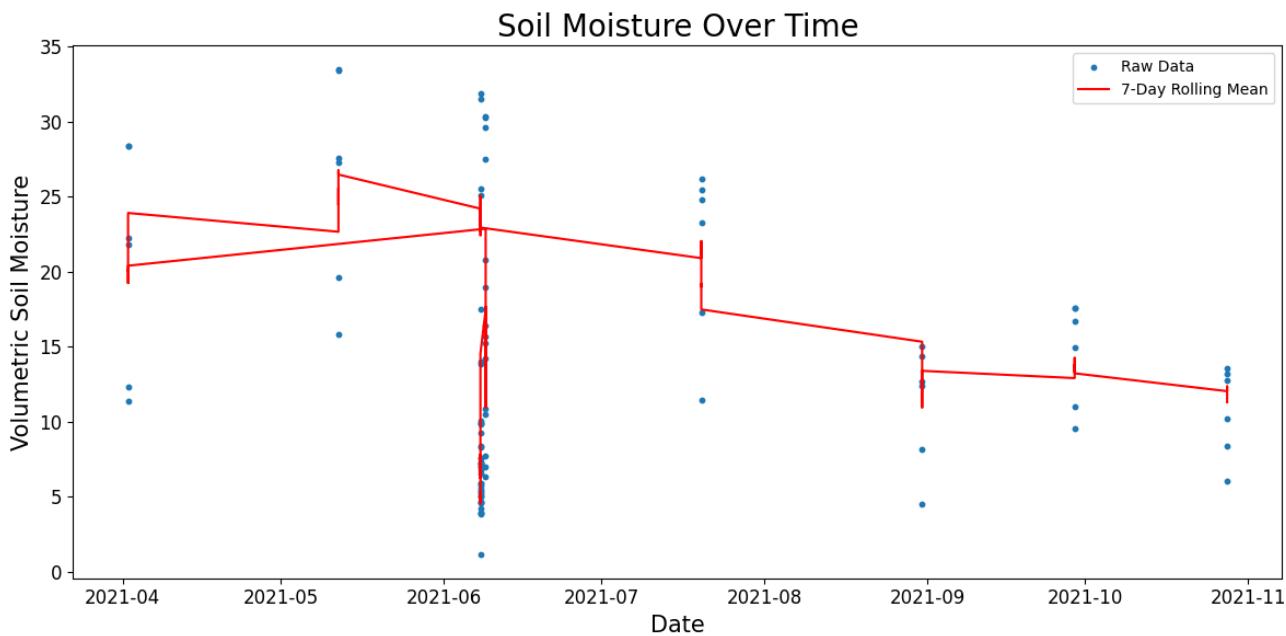


Figure 5: Seven day rolling mean of soil moisture over time.

3.2 PAI Observations

3.2.1 PAI Temporal Dynamics

The "Mean Plot Effective PAI over 2021" plot revealed distinct temporal patterns in PAI among the thirteen study plots. Plots PUE_CP1 and PUE_CP2 demonstrated a stable PAI throughout the year, suggesting consistent canopy coverage or minimal phenological changes. Conversely, plots PSL_8, PSL_5, and PSL_4 exhibited a notable increase in PAI, peaking in July before a steady decline, indicating significant seasonal canopy growth and subsequent reduction. Plot PSL_7 showed a sharp increase from May to June, stabilizing through July, then gradually diminishing, reflecting a distinct

growth phase followed by stabilization and reduction. Plot PSL_6 remained stable between June and July, indicating a period of minimal canopy change, followed by a steady decrease in PAI, suggesting seasonal canopy reduction (Figure 6).

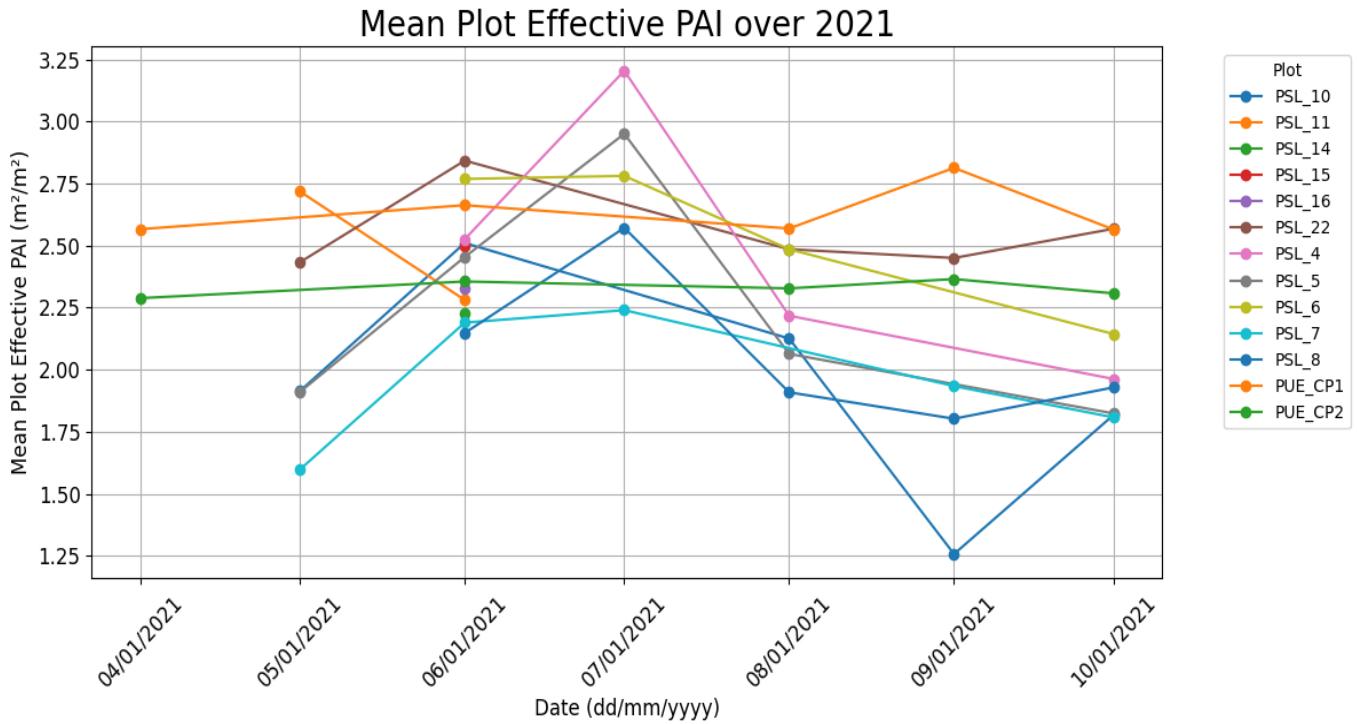


Figure 6: PAI temporal dynamics showing the mean of effective PAI over 2021

3.2.2 PAI Distribution Analysis

The "Monthly PAI Distribution by Plot" scatter plot, covering data from April to November, highlighted the variability of PAI values across the thirteen plots. Each plot's data points, color-coded for differentiation, underscored the seasonal dynamics and heterogeneity of canopy density and coverage within the study area. This distribution provides insights into the site-specific vegetation responses to environmental conditions and management practices (Figure 7).

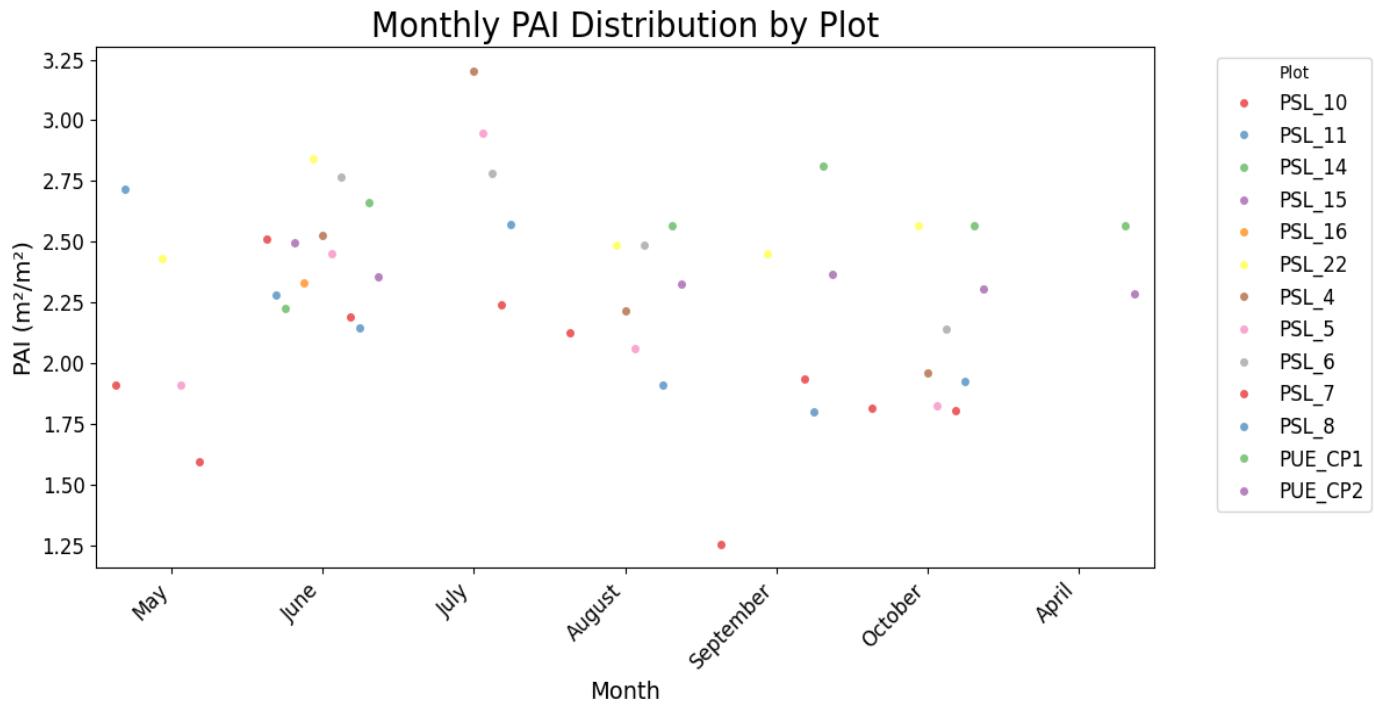


Figure 7: Monthly PAI distribution.

3.2.3 PAI Descriptive and Comparative Statistics

Analysis of PAI measurements ($n=678$) across all plots yielded an average PAI of $2.33 \text{ m}^2/\text{m}^2$, with variability indicated by a standard deviation of 0.76. The range of PAI values spanned from 0.23 to $4.40 \text{ m}^2/\text{m}^2$, delineating the extremes of canopy density encountered. The interquartile range, from 1.85 (25th percentile) to 2.85 (75th percentile), highlighted the middle 50% of PAI values, further illustrating the distribution's spread. (Table 4).

A descending order ranking of average PAI by plot revealed that PUE_CP1, PSL_22, and PSL_6 were the top three plots with the highest mean PAI values, indicating denser canopy cover compared to other study areas. In contrast, PSL_10, PSL_7, and PSL_8 exhibited the lowest mean PAI, suggesting sparser canopy or different forest structure and composition (Table 5).

Summary Statistics of PAI Values	
Count	678.0000
Mean	2.3254
Standard Deviation	0.7618
Minimum	0.2316
25%	1.8490
50%	2.3944
75%	2.8480
Maximum	4.3966

Table 4: Statistics of PAI values.

Average PAI by Plot (Descending Order)	
Plot	PAI
PUE_CP1	2.6349
PSL_22	2.5553
PSL_6	2.5443
PSL_11	2.4993
PSL_15	2.4970
PSL_4	2.4773
PSL_16	2.3295
PUE_CP2	2.3286
PSL_5	2.2402
PSL_14	2.2264
PSL_8	2.0718
PSL_7	1.9534
PSL_10	1.9249

Table 5: Average PAI by forest plot.

3.2.4 Rolling Mean Analysis for PAI Over Time

The "PAI Over Time" plot extends our understanding of the temporal dynamics of the Plant Area Index within the study area. Similar to soil moisture, PAI data also show considerable daily variation. The 7-day rolling mean for PAI delineates a more consistent pattern across the observation period, ranging from lower values of around 1 m²/m² to higher values up to 3 m²/m². This analysis interprets the growth phases of the forest canopy, marked by periods of increase in PAI, which is an indicative of new leaf growth or canopy densification, and subsequent declines, which may signal leaf shedding or other factors that may contribute to reducing canopy cover. The peaks in the rolling mean may correlate with periods of rapid growth or phenological changes such as leaf expansion, which can increase fuel availability and potentially affect fire risk. The rolling mean thus offers a refined visualization of canopy dynamics, critical for understanding the forest's susceptibility to fire under varying canopy densities (Figure 8).

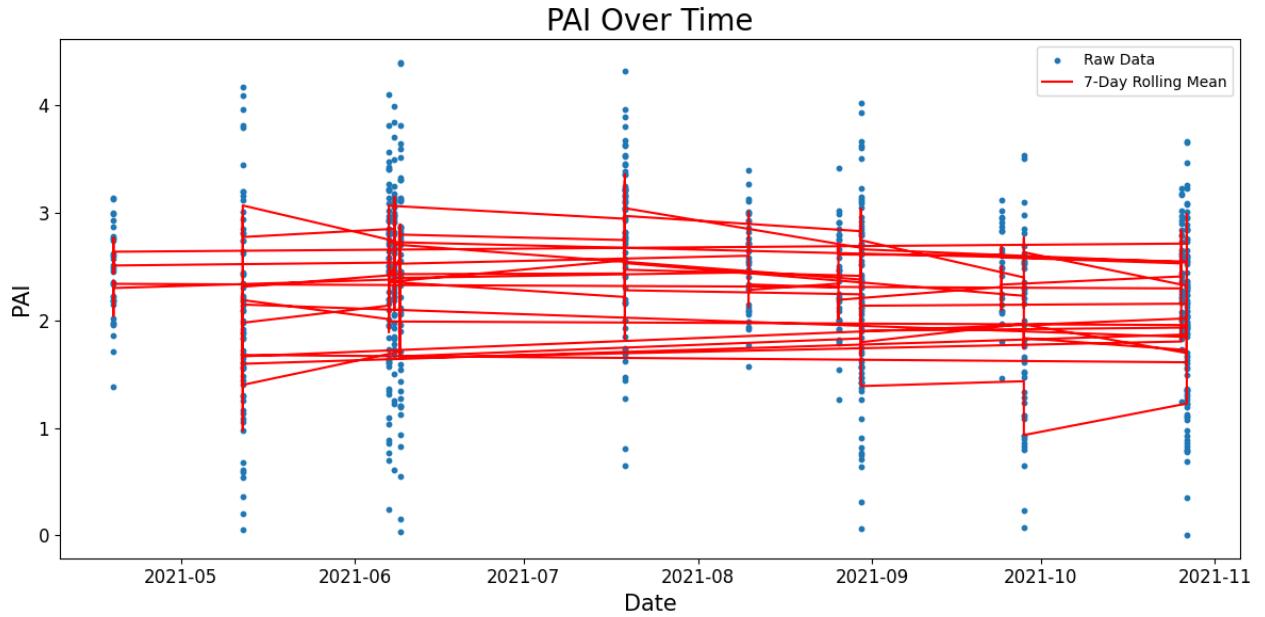


Figure 8: Seven day rolling mean of PAI over time.

3.3 Soil Moisture and PAI Observations

The analysis revealed a clear seasonal pattern in soil moisture and PAI, with significant variations observed across the study period. Soil moisture showed a decreasing trend during the dry months, while PAI values exhibited fluctuations corresponding to phenological changes in the forest canopy.

3.3.1 Relationship between Volumetric Soil Moisture and PAI

The "Relationship between Volumetric Soil Moisture and PAI" plot indicated a complex interaction between these two key variables across the study period. A notable observation was the pronounced peak in both PAI and volumetric soil moisture in July, suggesting a potential period of heightened vegetation growth coinciding with optimal soil moisture conditions. Conversely, the lowest values observed in October reflect a period of decreased vegetation density alongside reduced soil moisture, potentially signifying an increased vulnerability to forest fires due to drier conditions (Figure 9).

Relationship Between Volumetric Soil Moisture and PAI

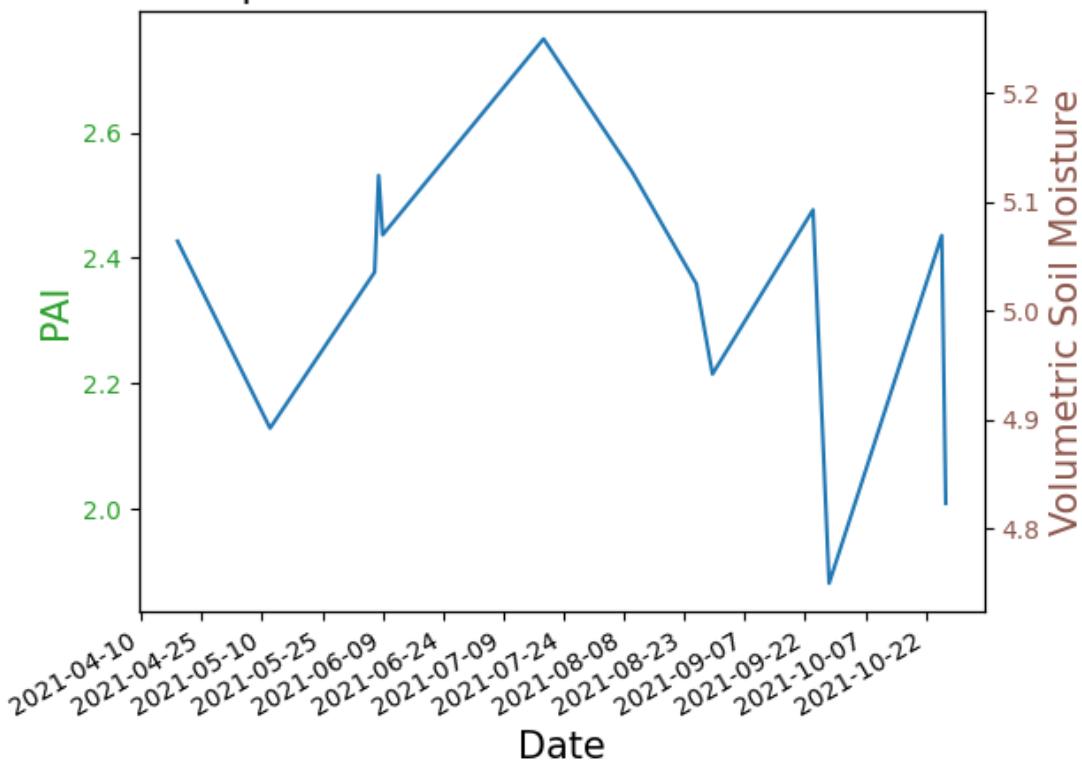


Figure 9: Relationship between volumetric soil moisture and PAI.

3.4 Fire Risk Assessment

By integrating soil moisture and PAI data, the study identifies thresholds indicative of increased fire risk. Spatial analysis further highlighted specific plots with elevated susceptibility to forest fires, underscoring the importance of targeted monitoring and management efforts.

3.4.1 PAI Distribution by Fire Risk Level

The "Distribution of PAI by Risk Level" bar plot interprets the frequency distribution of PAI values within designated fire risk categories. Low-risk areas predominantly fell within the lower PAI range ($0\text{-}2 \text{ m}^2/\text{m}^2$), suggesting that regions with sparser vegetation cover may pose a lower fire risk under the current assessment model. Conversely, high-risk areas were characterized by higher PAI values ($2.8\text{-}4.5 \text{ m}^2/\text{m}^2$), indicating that denser canopy areas are considered more susceptible to fire, especially when PAI values are between 2.8 and $3 \text{ m}^2/\text{m}^2$. This distribution highlights the critical threshold of vegetation density beyond which fire risk significantly increases (Figure 10).

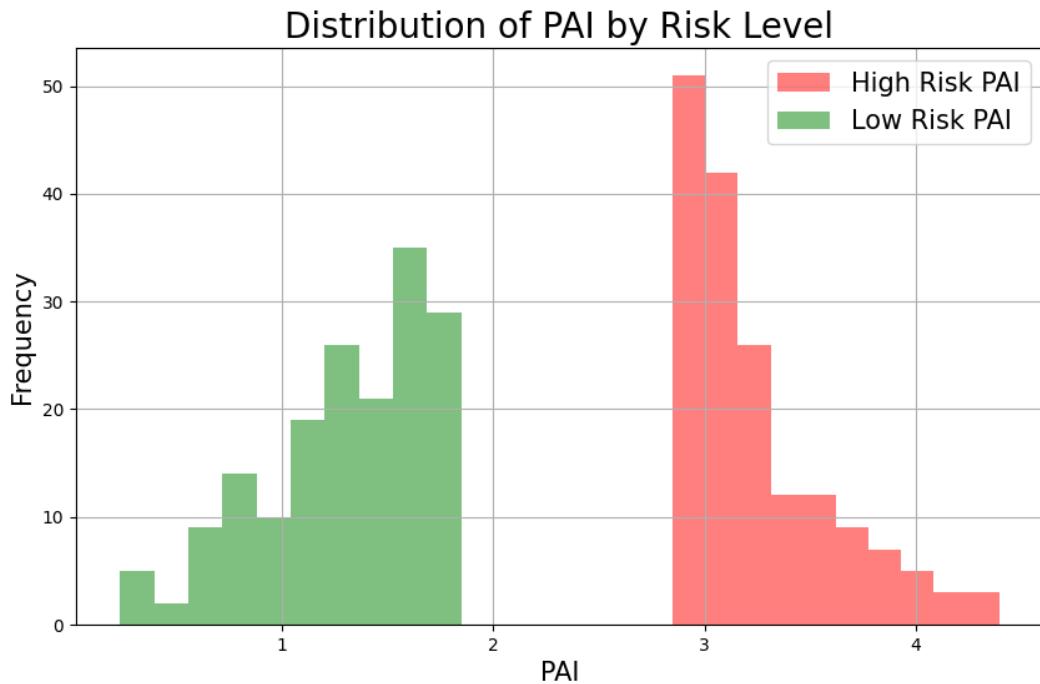


Figure 10: Distribution of PAI by fire risk level.

3.4.2 Fire Risk Assessment Based on PAI and Soil Moisture

The "Fire Risk Levels Based on PAI and Average Soil Moisture" bar plot (Figure 11) and associated statistical data further substantiate the relationship between PAI, soil moisture, and forest fire risk. With 74.93% of the study area classified under moderate risk and 25.07% under high risk, it's evident that a significant portion of the forest landscape could be vulnerable to fire under certain conditions (Table 6). The distinction between moderate and high-risk levels underscores the importance of continuous monitoring and management strategies to mitigate potential fire threats.

To demonstrate a clearer assessment, the findings from PAI rolling mean implementation with soil moisture indicate how these variables might interact to influence fire risk. For instance, if high PAI coincides with low soil moisture, it might signal a heightened fire risk period while the periods of decrease in the rolling mean could correspond to reduced canopy density or health, potentially lowering fire risk temporarily.

Distribution of Fire Risk Levels (%)	
Moderate Risk	74.93
High Risk	25.07

Table 6: Distribution of fire risk levels

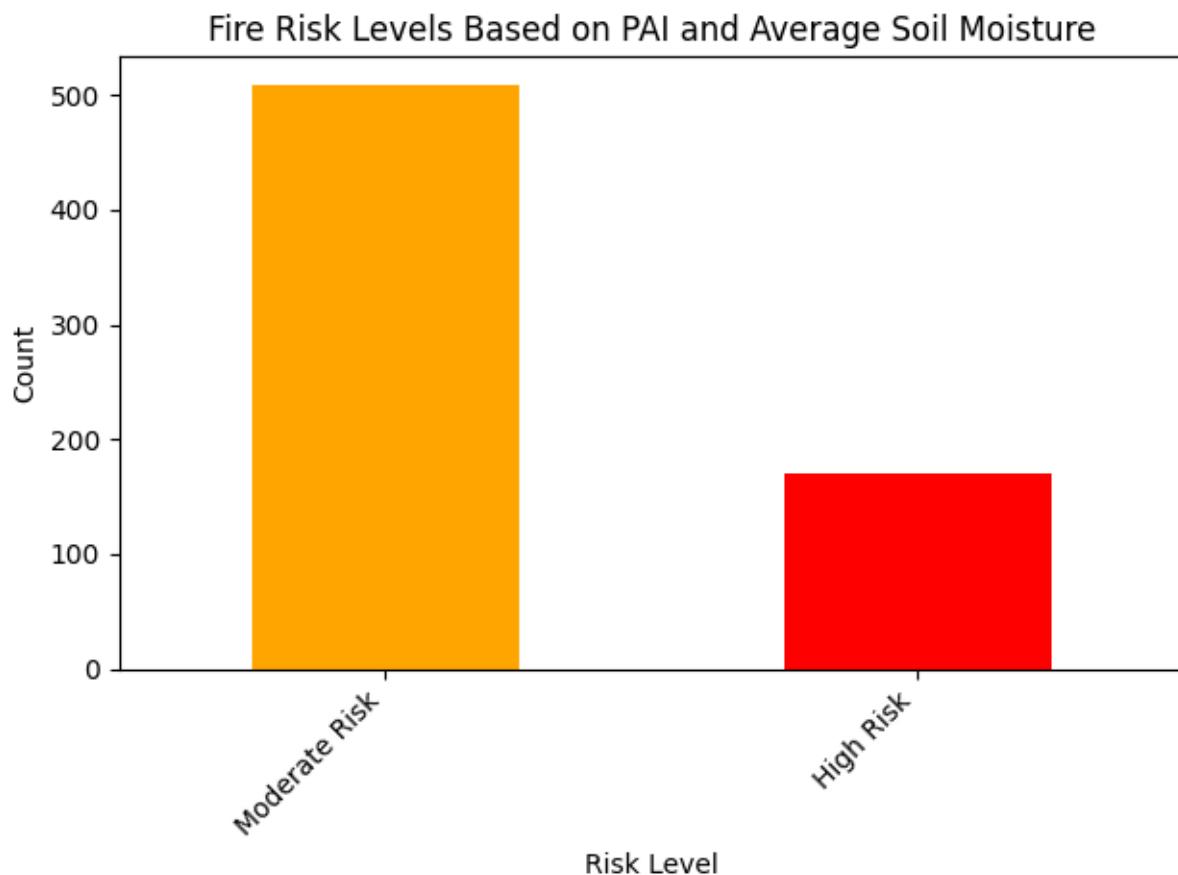


Figure 11: Fire risk level based on PAI and average soil moisture.

4. Discussion

This study's integration of PAI and soil moisture measurements for assessing fire susceptibility not only corroborates the findings by Laneve et al. (2020) regarding the efficacy of remote sensing in forest management but also extends them by applying these techniques to the Mediterranean oak forests. The variations in PAI and soil moisture noted in the study's results are consistent with the ecological ramifications discussed by Gale et al. (2021) who reviewed the biotic determinants of fire behavior through remote sensing, further underscoring the critical interplay of ecological factors in fire dynamics. In brief, this study identified a critical threshold of PAI and soil moisture that correlates with increased fire risk, which can be used in tandem with real-time forest monitoring systems, and identified seasonal variations in PAI and soil moisture that revealed distinct patterns that align with known fire risk periods, which could be used to anticipate and mitigate fire occurrences more effectively. By linking these ecological indicators with fire risk, this research supports the growing body of evidence that real-time remote sensing can offer more dynamic accurate assessment compared

to traditional methods, thus bridging computational intelligence with ecological modeling to enhance the robustness of fire risk models.

To describe these findings in more detail, the variability in soil moisture, which is highlighted through the descriptive statistics and temporal analysis, indicates a noteworthy influence of microclimatic and edaphic factors on water availability in Mediterranean oak forests. By integrating quantitative data with spatial and temporal analyses, this study offers nuanced insights into the hydrological dynamics of Mediterranean oak forests, contributing to a more informed approach to forest management and conservation. This insight is further aided by the identification of plots with consistently high or low moisture levels that provide a basis for targeted research and management interventions, particularly in the context of climate change and increasing fire risks. Additionally, the dynamic changes observed in soil moisture over the study period underscore the necessity for continuous and comprehensive monitoring. Understanding these patterns is essential for developing effective strategies to mitigate the impacts of drought and ensure the resilience of these ecologically valuable ecosystems.

In addition, the detailed analysis of PAI through both temporal and spatial lenses highlights the intricate dynamics of canopy development and decline within Mediterranean oak forests. The observed seasonal fluctuations in PAI underscore the forests' phenological responses to climatic variables, potentially influencing the ecosystem biodiversity support. Furthermore, the variability in PAI across forest plots underscores the impact of site-specific factors, including soil type, moisture availability, and forest management practices, on canopy structure and function. Moreover, these findings emphasize the importance of continuous monitoring of PAI as a key indicator of forest health and productivity. By identifying plots with consistently high or low PAI values, forest managers can tailor conservation and management strategies to enhance forest resilience and mitigate the impacts of stressors such as drought and pests.

Equally important, the rolling mean analyses for both soil moisture and PAI significantly enhance our comprehension of the temporal patterns and their implications for forest fire risk. The smoothed trends provided by the rolling mean allow for a clearer interpretation of how these key ecological variables evolve over the season, thereby offering a predictive insight into periods of increased fire risk. Notably, the correlation between periods of low soil moisture and decreased PAI, which signifies low rolling mean values, signal higher fire risk that supports the assumption that drier conditions are more favorable for the spread of wildfires due to their dominant presence during the peak summer months. Furthermore, the rolling mean approach mitigates the impact of outlier readings and short-term anomalies, presenting a more reliable basis for long-term forest management and fire prevention strategies. This methodological refinement underscores the potential of advanced data analysis techniques in improving the accuracy and applicability of remote sensing data for environmental monitoring and risk assessment.

Nevertheless, this study was not without limitations. First, the study restricted to a single growing season, which may not fully capture inter-annual variability in PAI and soil moisture dynamics. Second, while the dataset provided a comprehensive coverage of the region, its findings may not be universally applicable to other Mediterranean forest environments without additional localized calibration. Finally, the reliance on specific remote sensing tools and methods may limit the generalizability of the findings to regions where such technology is not readily available or feasible to deploy.

In summation, the integration of remote sensing data, including PAI and soil moisture measurements, offers a nuanced approach to predicting forest fire risk. As observed from the findings, the peak in PAI and soil moisture during July, followed by a decrease leading into the drier months, underscores the seasonal vulnerability of these ecosystems to fire. Moreover, the categorization of fire risk based on PAI distribution reveals the critical role of canopy density in fire susceptibility assessments. By identifying thresholds of vegetation density and moisture content that correlate with increased fire risk, forest managers can prioritize areas for monitoring and intervention. Additionally, this study highlights the potential for developing dynamic fire risk models that account for temporal and spatial variations in key ecological indicators.

5. Conclusion

This study addressed the objectives outlined at the onset by demonstrating the utility of integrating remote sensing data, specifically Canopy Plant Area Index (PAI) and soil moisture measurements, in enhancing predictions of forest fire susceptibility. This approach provides a valuable tool for forest management authorities to implement preemptive measures and mitigate the impact of wildfires in Mediterranean ecosystems. The study's findings suggest targeted monitoring of areas with low soil moisture and high PAI values as critical hotspots for fire risk, advocating for adaptive management practices to reduce wildfire susceptibility.

Moreover, this analysis, which utilizes the SENTHYMED/MEDOAK dataset, illuminates the intricate dynamics between soil moisture, PAI, and forest fire risk in Mediterranean oak forests. This study established a correlation between canopy density (PAI) and soil moisture that enhances the predictive accuracy of fire risk models while also identifying seasonal patterns and thresholds that are critical for fire risk assessment in Mediterranean forests. This analytical perspective contributes to the development of more effective forest management and fire prevention strategies, emphasizing the critical role of continuous ecological monitoring in mitigating the impacts of climate change on forested landscapes. Therefore, by contributing to the refinement of fire risk assessment models, this research advocates for informed, data-driven forest management practices aimed at preserving Mediterranean oak forests amidst escalating climate variability.

In conclusion, the integration of remote sensing data on PAI and soil moisture from the SENTHYMED/MEDOAK dataset has significantly enhanced our ability to predict forest fire susceptibility in Mediterranean oak forests. This study confirms the pivotal role of these ecological indicators, as suggested by the extensive literature on remote sensing applications in forest fire management. Moving forward, incorporating next-generation hyperspectral sensors and full-waveform LiDAR, as discussed by Veraverbeke et al. (2018), could further refine these predictions, offering more precise tools for forest management authorities to mitigate the impact of wildfires.

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