Insights into the Effects of Climate Variability and Agricultural Practices on Olive Orchards in Messenia, Greece: A Field Experiment Study

Christos Pantazis [1,2,3], Stavros Solomos [2], Panagiotis Nastos [1,2], Giorgos Maneas [3,4], Orestis Kairis [5], Mauro Centrito [6], Giovanni Marino [6], Pier Paolo Roggero [7], Joanna Mihail [8], Ilias Fountoulakis [2], John Kapsomenakis [2], Vasilis Gkisakis [8], Nektarios Kourgialas [9], Georgios S. Kalantzakis [9], Anastasia G. Papamanolioudaki [9], Chrysi K. Sergentani [9], Christos S. Zerefos [2,3,10,11]

[1]*Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, 15784, Athens, Greece*
[2]*Research Centre of Atmospheric Physics and Climatology, Academy of Athens, 10680, Athens, Greece*
[3]*Navarino Environmental Observatory (N.E.O.), 24001 Messenia, Greece*
[4]*Department of Physical Geography and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden*
[5]*Department of Natural Resources Management & Agricultural Engineering Agricultural University of Athens, 11855, Athens, Greece*
[6]*Institute for Plant Protection, National Research Council, Via Madonna del Piano 10, 50019 Sesto Fiorentino, FI, Italy*
[7]*Department of Agricultural Sciences, University of Sassari, Sassari, Italy*
[8]*Institute of Olive Tree, Subtropical Crops and Viticulture, Hellenic Agricultural Organization-DEMETER, 24100 Kalamata, Greece*
[9]*Institute of Olive Tree, Subtropical Crops and Viticulture, Hellenic Agricultural Organization-DEMETER, 73134 Crete, Greece*
[10]*Biomedical Research Foundation of the Academy of Athens, 11527 Athens, Greece*
[11]*Mariolopoulos-Kanaginis Foundation for the Environmental Sciences, Athens, Greece*

*Corresponding author.
Email address: *chpad@geol.uoa.gr (Christos Pantazis)

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Abstract

Agriculture in the Mediterranean region faces increasing challenges from climate change, including drought, soil erosion, and water scarcity. This study examines the sustainability of intensive olive farming practices, focusing on their effects on soil health, water management, and olive oil quality. Field experiments were conducted in the Messenia region of Greece, renowned for its high-quality olive oil production, to evaluate the impacts of different agricultural techniques on soil erosion and olive oil standards. Two experiments were designed: one addressing irrigation practices (rainfed, localized, and phenology-based irrigation) and the other investigating soil management strategies (herbicide use, mowing natural vegetation, and planting cover crops) on hilly terrain. In the first year, all olive oil samples met the European Commission's standards for extra virgin olive oil. Rainfed plots produced oil with lower acidity but higher peroxide values compared to irrigated plots, indicating differences in freshness and oxidation. Soil erosion data revealed significantly higher soil loss in herbicide-treated plots compared to those with cover crops or natural vegetation. These findings underscore the importance of sustainable farming practices in mitigating soil erosion and enhancing olive oil quality. Adopting such strategies is crucial for maintaining agricultural productivity and ecosystem health in the Mediterranean, especially under the pressures of climate change.

1. Introduction

Agriculture in the Mediterranean region is highly vulnerable to the impacts of climate change (Abd-Elmabod et al., 2020; Perez-Lucas et al., 2024), necessitating a deeper understanding of how meteorological variability and human activities interact to influence natural resources. Key factors, such as rising temperatures, reduced precipitation, and the increasing frequency of extreme weather events—droughts, floods, and soil erosion—disrupt the balance of water and soil nutrients in ecosystems (Furtak & Wolinska, 2023). Under a worst-case climate scenario, the Mediterranean Basin is expected to experience significant warming and drying trends, posing serious risks to the agricultural sector (Tanasijevic et al., 2014). Notably, nearly half of the regions where staple crops, such as olives, are grown will face heightened exposure to droughts, heatwaves, and diminishing agricultural viability due to reduced climate resilience (Zagaria et al., 2023). In the near future (2021–2050), the western Peloponnese is projected to experience an increase in air temperature of 1.4°C to 1.8°C, a 12% decrease in precipitation, and an 8% to 13% rise in potential evapotranspiration (Nastos et al., 2013). These changes will result in increased irrigation needs for olive cultivation, heightened risks of heat stress during critical phenological stages, and greater susceptibility to olive fly infestations (Cramer et al., 2018).

Addressing these challenges, requires an integrated approach that combines new technologies and Nature-based solutions (NbS) to ensure adaptation, resilience, and sustainability (Calliari et al., 2022). Such strategies are critical for aligning agricultural practices with the United Nations Sustainable Development Goals (SDGs) and fostering a resilient, equitable, and sustainable food system by 2030 (European Environment Agency, 2021). The intensification of farming practices has raised significant concerns about their long-term sustainability and the harmful effects on ecosystem health, highlighting the need for advance, modern agricultural techniques (e.g., (Muhie, 2022)). While conventional agriculture has increased production, it has come at a cost to soil health, resulting in issues such as erosion, compaction, nutrient depletion, and salinity (Pierrette et al., 2021). Moreover, monoculture farming exacerbates soil degradation by reducing plant diversity, leading to problems like habitat fragmentation, increased pest susceptibility, and the decline of pollinators (Maurer, 2023). Agriculture has been identified as the most water-intensive sector, posing the greatest risks to water scarcity, once it is responsible for approximately 70% of global freshwater use (Ingrao et al., 2023).

These challenges highlight the need for adaptation measures that enhance the resilience of agricultural systems. Organic farming, based on agroecological principles, promotes environmental sustainability by avoiding synthetic pesticides and fertilizers (Lampkin et al., 2016). It improves soil health through practices like crop rotation and composting (Bhattacharya et al., 2024), while supports biodiversity and helps conserve water by enhancing soil structure, which increases water retention and reduces runoff (Zuazo et al., 2020). While there is broad agreement on the need for sustainable food systems that protect the environment and support farmers' livelihoods, significant changes are required in agriculture practices. These include a transformative shift toward agroecological organic farming, alongside gradual improvements in conventional agricultural (Gamage et al., 2023). Enhancing conventional agriculture through gradual but meaningful improvements can further support this transformation. By integrating organic farming practices with advanced technologies and NbS, we can create a more sustainable, resilient, and adaptive food system that ensures food security and environmental health for future generations. The transition to sustainable agriculture must include a fundamental change towards agroecological organic farming, which emphasizes biodiversity, ecological balance, and reduced reliance on chemical inputs.

The topics studied in this work have emerged through a bottom-up approach, developed in collaboration with local stakeholders. As (Aare & Hansen, 2024) highlight, integrating diverse perspectives and expertise is crucial for addressing complex challenges. Collaborative efforts among researchers, stakeholders, and practitioners often lead to more effective and sustainable solutions. Using the framework of a Living Lab, we engage with stakeholders in the olive oil industry to identify and understand the primary challenges in olive trees cultivation. Our Living Lab, named "ΑΓΟΡΑ," facilitates the co-design, testing, validation, and implementation of advanced technologies and management strategies (Ceseracciu et al., 2023) following the five characteristics identified by (European Network on Living Labs, 2020): multi-method approach, multi-stakeholder participation; active user engagement; real-life setting; co-creation. This is achieved through an inclusive social learning process that integrates traditional and scientific knowledge.

This study aims to address the sustainability of agricultural land under intensive farming practices and their effects on ecosystems, with a focus on developing NbSs to combat environmental degradation, water scarcity and soil loss. Furthermore, it investigates an integrated olive orchard agroecosystem management in Messenia regional unit, northwest

Peloponnese, known for its rich agricultural heritage and olive oil production. The region has a history of olive cultivation and use dating back to the 13th century BCE (Thanopoulos et al., 2024). Based on input from local stakeholders, the primary focus has been placed on water and soil management. Consequently, two field experiments have been developed: one in a hilly orchard to test different soil treatments (herbicides, natural vegetation mowing, and cover crops) with respect, to surface runoff and soil erosion and another in a flat terrain orchard to test three irrigation practices (rainfed, local practices, and phenological stage-based irrigation) assessing their impact on olive oil quality. Environmental data on agrometeorological conditions are collected using ground-based instrumentation and airborne remote sensing.

To underscore the significance of this study, our work provides a holistic, region-specific approach to addressing the pressing challenges of sustainable agriculture in the Mediterranean, with a special focus on olive cultivation. Unlike previous research that often examines isolated factors such as water management (e.g., (Arampatzis et al., 2018; Fraga et al., 2020; Siakou et al., 2021)) or soil conservation (e.g., (Madejon et al., 2009; Oliveira et al., 2024; Panettieri et al., 2020)), this study integrates multiple dimensions—meteorological variability, soil and water management, biodiversity, and socio-economic perspectives—within a single framework. By combining advanced technologies, NbSs, and stakeholder collaboration through the Living Lab “ΑΓΟΡΑ,” our approach ensures practical applicability and scalability. The unique focus on co-creation with local stakeholders, alongside rigorous field experimentation tailored to diverse terrains, positions our work as a comprehensive, adaptable model for enhancing climate resilience and sustainability in Mediterranean agroecosystems.

2. Methodology

2.1. Study area

The present study was implemented in the Pylos-Nestor area, which is part of Messenia regional unit and is located in the southwest Peloponnese (Greece). Messenia has a Mediterranean climate, characterized by hot, dry summers and mild, wet winters, with a unique topography combining coastal plains and mountain area (Kakkavou et al., 2024). The intense landscape diversity influences weather conditions, leading to the formation of multiple microclimates (Kalabokidis et al., 2015). These microclimates necessitate diverse farming practices and significantly affect the phenology, growth stages, and overall productivity of olive trees. The "Koroneiki" variety, renowned for its resilience to drought and adaptability to various soil conditions, is the primary olive cultivar grown in the area. Olive oil production serves as the main economic activity for the local population, making it a critical driver of the region's financial stability and cultural heritage.

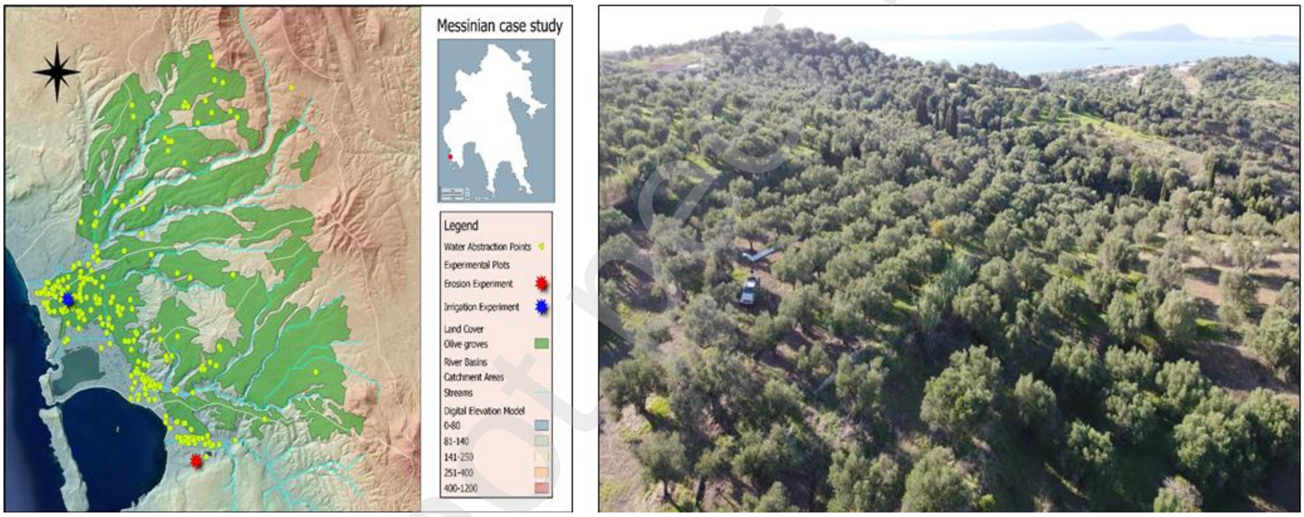


Figure 1: a) Geomorphology of the study area, olive orchards land cover and location of the two experimental plots. b) View of a typical olive orchard in the study area, located in hilly terrain.

This area is predominantly coastal, with extensive olive orchards extending to the seaside and further inland. The coastal setting not only shapes the local climate but also introduces significant environmental challenges, such as the overexploitation of water resources leading to seawater intrusion into groundwater aquifers. This intrusion compromises the quality of available irrigation water, posing a threat to the long-term sustainability of agricultural practices in the region (Kopsiaftis et al., 2009).

However, the coastal nature of the area is associated with increasing touristic development, particularly during the summer months. This period coincides with a peak in water demand for irrigation, as olive trees require sufficient water to sustain critical physiological processes during the dry season. The escalating tourism pressure exacerbates water resource challenges, as the heightened demand for potable water and amenities further strains the already limited supplies. Additionally, the intensification of farming practices to support olive oil production can have unintended consequences on groundwater quality. The widespread use of nitrogen-based fertilizers, commonly applied to enhance olive yields, can lead to nitrate contamination of groundwater. Fertilizers, combined with irrigation practices, promote the leaching of nitrates into aquifers, which poses a significant risk to both the environment and human health.

The following geospatial maps (Figure 2) illustrate two critical aspects of groundwater quality in the Pylos-Nestor area: chloride concentrations, indicative of seawater intrusion, and nitrate concentrations, a marker of agricultural pollution. Both maps use a color-coded contour system to visualize the data, with lighter shades representing higher concentrations and the locations of monitoring wells are illustrated as white dots. The results were generated after taking water samples and conducting chemical analysis in the lab in September of 2018.

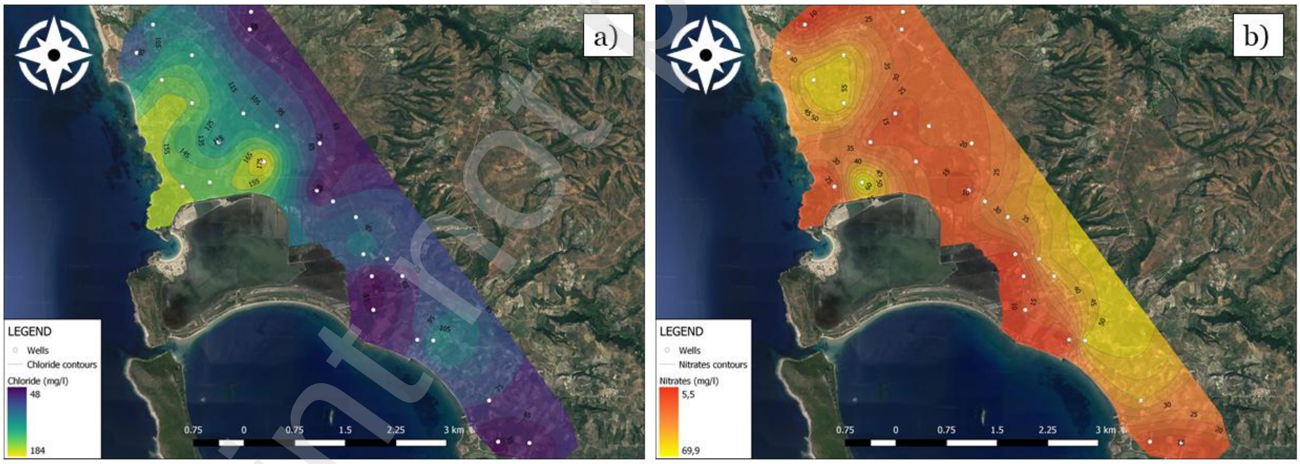


Figure 2: a) Geospatial map showing the distribution of chloride concentrations across the area. b) Geospatial map showing the distribution of nitrate concentrations across the area.

The maps reveal a dual threat to groundwater resources in the study area: seawater intrusion driven by over-extraction near coastal zones and agricultural pollution caused by nitrate leaching inland. These processes result in environmental degradation with significant consequences. Seawater intrusion reduces the availability of fresh groundwater for irrigation and domestic use, which is already under stress from the combined pressures of tourism and agriculture. This situation can disrupt the delicate balance required to sustain olive cultivation, the cornerstone of the local economy. Nitrate contamination further exacerbates water quality issues, particularly in inland areas dominated by intensive farming. Prolonged exposure to high nitrate levels can harm ecosystems, such as wetlands, and contribute to eutrophication in nearby water bodies. Addressing these challenges will require an integrated management approach, combining sustainable irrigation practices, reduced reliance on chemical fertilizers, and improved water resource governance to protect the region's fragile hydrological balance and ensure the continued viability of its agricultural and tourism-based economy.

2.2. Irrigation Experiment

In the study area, the majority of olive orchards are rainfed. However, due to the increasing impacts of climate change, such as higher temperatures and altered precipitation patterns, the availability of natural rainfall may become less reliable. As a result, there is an anticipated shift towards increased irrigation practices to ensure optimal water supply for the olive trees. Nevertheless, some farmers irrigate their plots by extracting water from private boreholes or wells. Groundwater is the primary source of water supply in the area, serving not only for drinking and domestic purposes but also for irrigation. While existing legislation offers recommendations for managing groundwater resources, there is currently no effective system in place to monitor or regulate the amount of water used for irrigation. This lack of oversight raises concerns about the sustainability of groundwater resources, particularly as irrigation demands increase in response to climate change. The increased demand of water, combined with low precipitation and higher temperatures throughout a year, could lead to major future impacts, such as seawater intrusion, especially since the study area is located near the coastline (BinMakhashen & Benaafi, 2024).

In this experiment, we test two irrigation practices and compare the results with a rainfed orchard to assess the impact of water use on olive oil quality and olive tree growth. In collaboration with a local farmer, we are using his orchards, including both the rainfed and the irrigated ones. The irrigated orchard is divided into two parts: one irrigated based on the farmer's experience and the other irrigated according to phenology. All the trees, belonging to Olea europaea, are approximately forty years old and of the Koroneiki variety. Each subplot covers an area of 0.3ha, consists of thirty-three olive trees and the sampled trees are five in each treatment (those which are in the middle row).

Figure 3: Experimental set up of the irrigation monitoring network (left) and a soil moisture sensor (right).

To better understand the impact of different irrigation practices on olive trees, we are closely monitoring several key parameters in the orchard through the installation of sensors and fieldwork campaigns involving in situ measurements. The primary measurements include soil chemical and physical properties, soil moisture (with nine sensors installed at 30 cm depth, 2 meters from the tree trunks), and agrometeorological parameters such as temperature, evapotranspiration, and precipitation (via an agrometeorological station).

By the end of September 2023, eco-physiological measurements were carried out directly on the plants. This involved analyzing leaf gas exchange and using optical analyzers to detect chlorophyll content, pigments, and photosynthetic efficiency. UAV surveys were also conducted to explore the potential for remote, large-scale monitoring of the water and physiological conditions of the olive trees. During these surveys, we used RGB, thermal, multispectral, and hyperspectral sensors. The remote sensing data are being validated by comparing them with the in-situ measurements taken directly from the plants.

Additionally, olive oil analysis is being carried out in the laboratory to assess key physicochemical characteristics such as acidity, polyphenols, peroxides, and oil content. Olive oil samples for analysis were collected from three trees in each treatment group due to the high costs of lab analysis. The olive oil extraction and analysis were performed at the Institute of Olive Tree, Subtropical Crops and Viticulture, Hellenic Agricultural Organization-DEMETER in Crete, in compliance with the International Standard EN ISO/IEC 17025:2005.

2.2. Soil Erosion Experiment

Inappropriate agricultural practices, such as plowing and herbicide application, coupled with extreme drought events and intense rainfall, are significantly exacerbating water erosion. This leads to critical consequences, including soil degradation, diminished agricultural productivity, and heightened flood risks (Firoozi & Firoozi, 2024).

Collaborating with local stakeholder we got access to a representative olive orchard situated on hilly terrain with an average slope of 16%. The orchard's landscape is uniformly distributed, making it an excellent site for examining soil erosion dynamics. For this study, we employed a Randomized Block Design (RBD) to implement three treatments across nine experimental plots, with three replicates per treatment (Figure 4). Each plot contains four olive trees and spans an area of 100 m². The primary aim is to assess the water erosion risk in olive orchards on sloped terrains under three distinct agricultural practices: herbicide application, mowing natural vegetation, and seeding cover crops. Due to the high cost of experimental installation, soil erosion measurements are being conducted in one sub-plot per treatment. These sub-plots feature a surface runoff collection system that enables efficient capture and separation of sediment samples following each rainfall event.

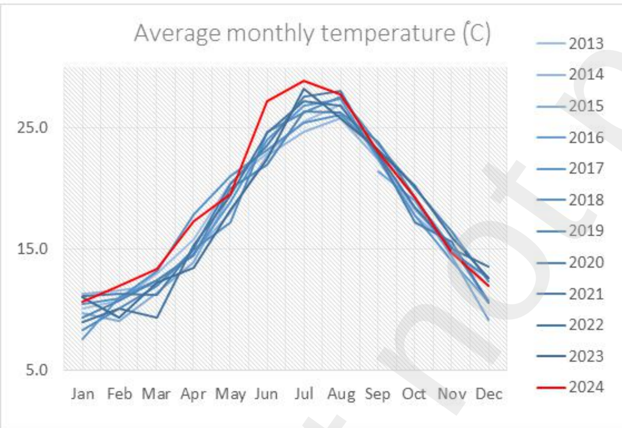
Figure 4: Experimental set up of the soil erosion monitoring network (left) and the installation for collecting the surface runoff (right).

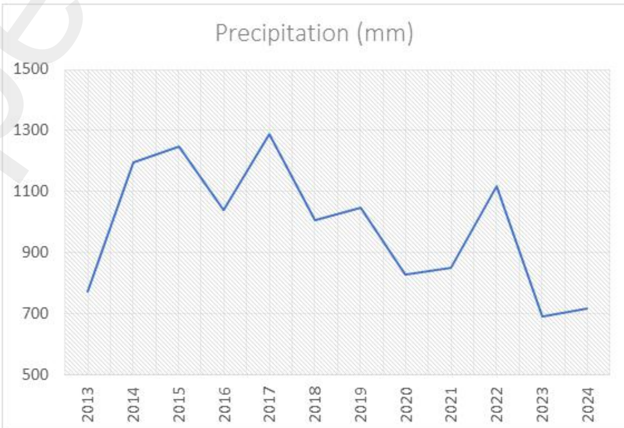
Metal sheets have been installed around the subplots to serve as boundaries, and a canal at the lower end of each subplot connects to a buried tank. The canal is designed to prevent rainfall from directly entering, ensuring that only surface runoff from the plots is collected. After each rainfall event, we extract the water from the tank, retrieve the settled sediments, and dry the samples in the laboratory for analysis. In addition to sediment collection, we conduct annual monitoring of soil chemical and physical properties, arthropod populations as a measure of biodiversity, and precipitation patterns. These data are critical for enhancing our understanding of the interplay between agricultural practices, soil health, and the long-term sustainability of farming in hilly terrains.

3. Results

3.1. Meteorological Conditions and olive oil production

The relationship between meteorological conditions—namely temperature and precipitation—and olive oil production from 2013 to 2024 is illustrated in the provided diagrams. These trends offer valuable insights into how climate variability affects agricultural outputs, specifically olive oil production. Temperature is a very important parameter for olive trees growth (Grillakis et al., 2022). The year 2024 (highlighted in red) demonstrates a notable deviation, showing an overall increase in temperature compared to previous years. A clear downward trend is observed, with 2024 exhibiting one of the lowest precipitation levels in the dataset. This reduction in rainfall is a critical concern for olive production, as sufficient water availability is essential for optimal tree growth and fruit development. Olive oil production has a moderate negative relationship (R2=0.5) with temperature which implies that as temperatures increase, olive oil production tends to decline. Higher temperatures during critical growing and maturation periods may stress olive trees, reducing yields and impacting oil quality. On the other hand, precipitation has a more substantial impact on olive oil production (R2=0.6) compared to temperature. Approximately 60% of the variation in olive oil production can be explained by precipitation levels. This highlights that adequate water availability is a critical factor for olive production, given the reliance of olive trees on rainfall for growth and fruit development. The findings suggest that while both temperature and precipitation influence olive oil production, precipitation is the dominant meteorological factor affecting yields. Therefore, adaptive strategies such as water management and drought mitigation may be more impactful in ensuring sustainable production than measures solely addressing temperature effects.





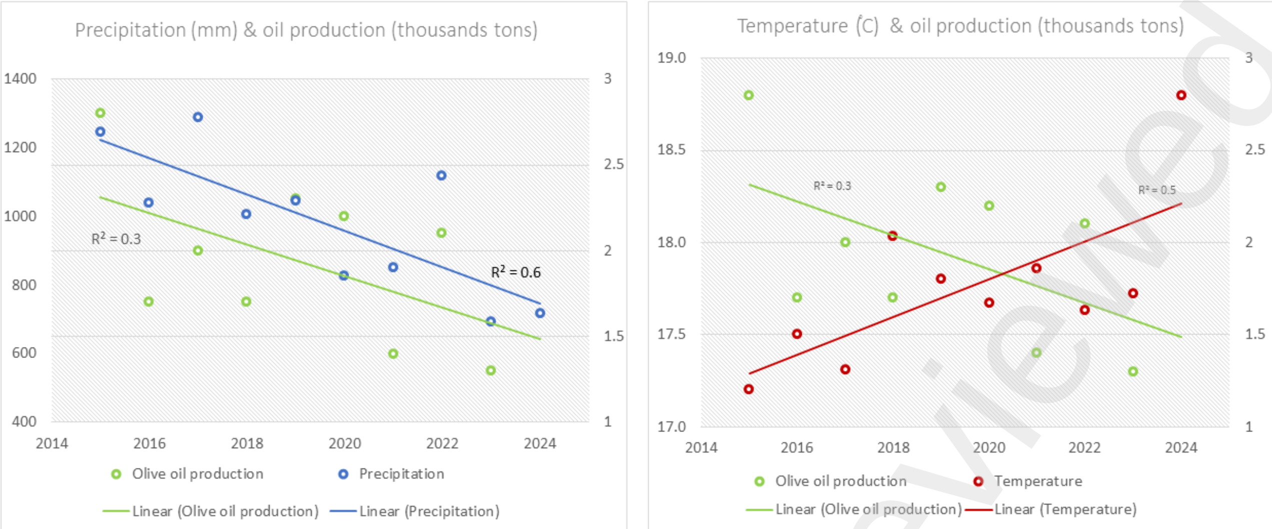


Figure 5: Average monthly temperature patterns from 2013 to 2024 (upper-left); annual precipitation levels from 2013 to 2024 (upper-right); relationship between precipitation and olive oil production (bottom-left); relationship between temperature and olive oil production (bottom-right).

3.2. Irrigation Experiment

In the first year of the study, olive oil quality improved across treatments, though no significant differences were observed in oil content between rainfed and irrigated plots. Physicochemical analysis confirmed that all nine olive oil samples complied with the European Commission's standards for extra virgin olive oil. Notably, the rainfed plots produced olive oil with lower acidity levels compared to the irrigated plots. Acidity, measured by free fatty acids, is a key quality indicator, reflecting the freshness of the olives at harvest and the overall condition of the oil. According to the European Commission, the maximum allowable acidity for extra virgin olive oil is 0.8%, with lower values indicating superior quality and freshness. However, the rainfed plots exhibited higher peroxide levels. Peroxides are generated when olive oil comes into contact with air during production, transport, or storage and serve as a marker of oxidation. Monitoring peroxide levels is crucial for assessing the extent of oxidation, as lower values signify fresher oil with a more preserved taste and aroma. The European Commission sets a peroxide value limit of 20 mEqO2/kg; exceeding this threshold can compromise the flavor and quality of the oil. The study also revealed that total phenol content, expressed as gallic acid equivalents, was higher in the irrigated plots. Phenols are natural antioxidants that protect olive oil from rancidity caused by oxygen and sunlight exposure. Olive oil with higher phenol content has enhanced longevity and quality.

Furthermore, oil content was higher in the irrigated plots, showing an 18% increase influenced by phenological factors and the expertise of the farmers.

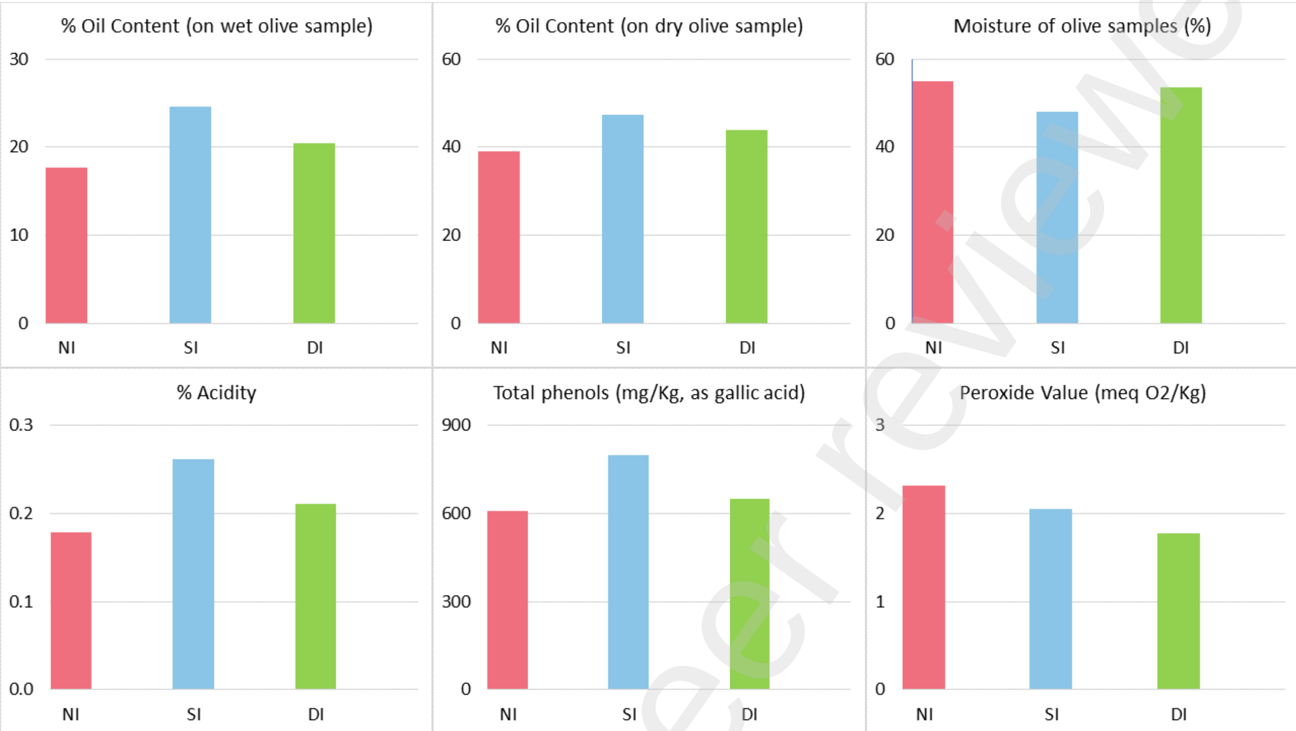


Figure 6: Olive oil quality results from the three treatments (NI: rainfed, SI: phenology irrigation, DI: farmer's experience irrigation).

3.3. Soil Erosion Experiment

The first year of the experiment (2022) we faced several technical challenges during the installation of the surface runoff collection system, which hindered our ability to consistently collect data. The graph below presents results from eight distinct rainfall events: two in October 2023, one in February 2024, two in March 2024, one in April 2024, and two in September 2024. While additional rainfall events occurred between October 2023 and February 2024, technical issues prevented us from obtaining measurements during that period.

The most intense rainfall event was recorded on October 11, 2023, when 40 mm of rain fell within 3.5 hours, creating extreme conditions for soil erosion. Preliminary data analysis reveals significant differences in soil loss across treatments. The herbicide-treated plot experienced nearly 4.5 times the soil loss observed in the plot seeded with cover crops and approximately 2.5 times the soil loss of the plot with natural vegetation. This trend of higher soil erosion in the herbicide-treated plot persisted across subsequent rainfall events, reinforcing the initial findings.

These results underscore the considerable impact of agricultural practices on soil erosion. Specifically, the use of herbicides was associated with significantly higher soil loss compared to the other treatments. This highlights the critical importance of evaluating and comparing management practices to mitigate soil erosion, protect soil health, and promote sustainable farming on hilly terrains.

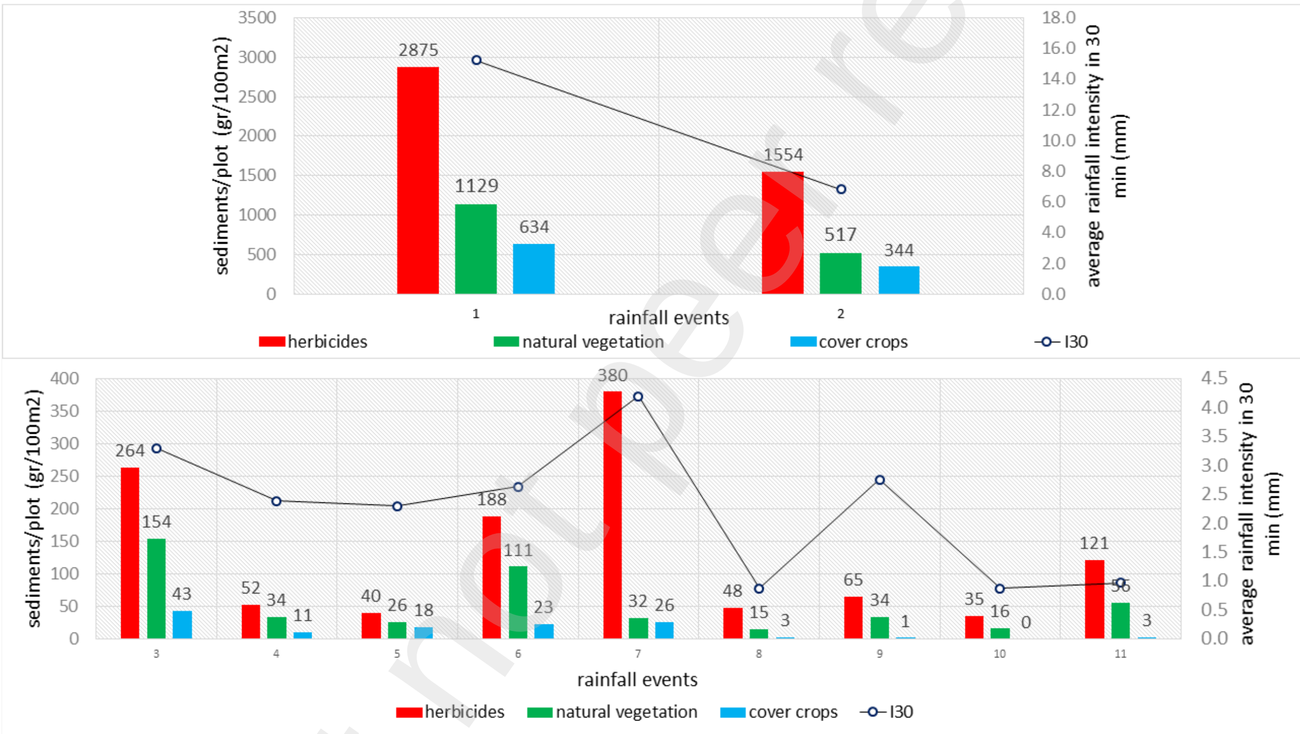


Figure 7: Soil erosion measurement expressed as kg of soil per $100m^2$, after 11 rainfall events. Average rain intensity of 30min is illustrated for each event.

4. Discussion

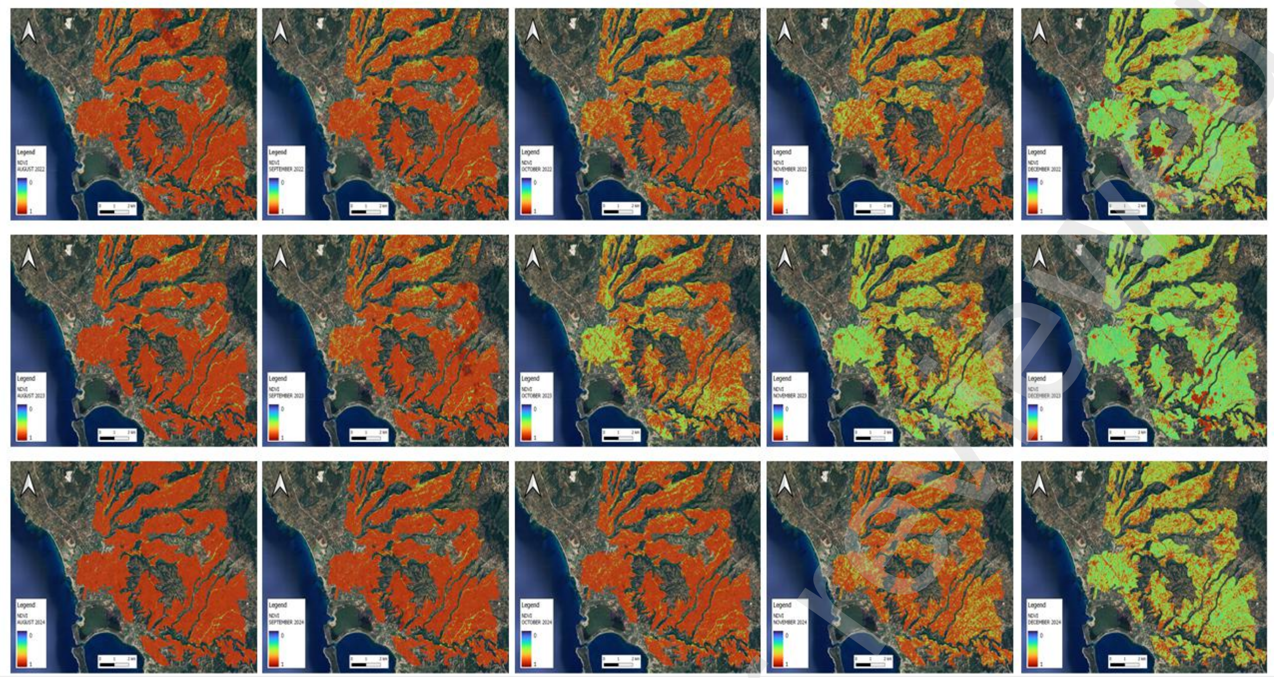
Long-term monitoring of meteorological parameters at the area of study shows that increasing temperatures and decreasing precipitation are followed by reduced oil production. Further analysis is however needed to quantify the impact of changes in different meteorological parameters on oil production.

Regarding olive oil quality, the study revealed that rainfed olive oil showed lower acidity levels than irrigated oil, indicating better freshness and overall oil quality. This result is consistent with earlier research suggesting that olive trees under rainfed conditions tend to produce oil of higher quality due to reduced water stress during fruit maturation. However, while the rainfed plots produced oils with lower acidity, they also had higher peroxide levels, suggesting that the oil had undergone greater oxidation. The higher peroxide levels in the rainfed treatment may be attributed to the limited irrigation, which could cause olive trees to undergo more stress, leading to higher rates of oxidative processes during oil extraction and storage. On the other hand, the irrigated plots had higher phenol content, which is beneficial for the oil's freshness and antioxidant properties. The higher phenolic content in the irrigated plots may reflect the positive impact of controlled water supply in maintaining tree health and improving the antioxidant capacity of the oil. These findings suggest a trade-off between higher oil quality (lower acidity) in rainfed plots and better oxidative stability (higher phenol content) in irrigated plots, which could guide future irrigation and olive oil production strategies depending on desired product characteristics.

Soil erosion was significantly influenced by the agricultural practices applied to the plots. Herbicide-treated plots experienced the highest soil loss, with erosion levels nearly 4.5 times greater than those observed in the cover crop plots and 2.5 times higher than the natural vegetation plots. These findings align with previous studies showing that herbicides can reduce ground cover, leaving soil more exposed to water erosion. In contrast, natural vegetation and cover crops provide a protective barrier, helping to reduce soil erosion by improving soil structure, increasing organic matter, and enhancing water infiltration. These results underscore the importance of adopting soil conservation practices that maintain or restore vegetative cover to minimize soil loss and degradation. The herbicide treatment's detrimental impact on soil erosion highlights the need for alternative, more sustainable management practices that align with ecological principles, such as agroecological farming or organic approaches. Furthermore, these findings suggest that managing vegetation cover within olive orchards is an effective strategy for mitigating soil erosion, especially in hilly landscapes.

The results of this study also have important implications for the sustainability of olive farming in the face of climate change. According to (Pozo et al., 2019) the Mediterranean region is expected to experience increased temperature and reduced precipitation in the coming decades, which could lead to increased irrigation needs and further exacerbate water scarcity issues. These projections align with the extreme climate conditions observed during the summer and autumn of 2024, characterized by exceptionally high temperatures and a prolonged lack of precipitation. Such conditions placed additional stress on water resources and underscored the urgent need for adaptive agricultural practices to ensure the viability of olive farming. The combination of intense heat and drought not only heightened irrigation requirements but also amplified the risk of soil degradation, reduced crop yields, and potential long-term impacts on soil health.

To better understand the impact of these conditions, we conducted a Normalized Difference Vegetation Index (NDVI) analysis, which confirmed the severity of the stress on vegetation. Sentinel-2 satellite images were used to run NDVI for the 3 last years (2022-2023-2024) in a crucial phenological period of olive trees, between August to December. The images were clipped to the CORINE Land Cover olive groves polygons. The series of maps illustrates the spatial and temporal variability of the NDVI index across the region of interest. NDVI is a widely used indicator of vegetation health and productivity (Cao et al., 2019; Eshetie et al., 2016; Ma et al., 2001; Reddy et al., 2024), with higher values (closer to green in the maps) reflecting dense, healthy vegetation and lower values (closer to red) representing sparse or stressed vegetation. A particularly notable and alarming observation emerges in November 2024, where NDVI values are substantially lower compared to the same period in 2022 and 2023. This decline is visible in the maps and supported by the temporal data (Figure 5), signaling widespread vegetation stress or reduced productivity during a critical phase of the growing season. While NDVI values generally increase from August to December across all years, reflecting post-summer vegetation recovery, the significantly lower values in November 2024 suggest a disruption in this trend. If this trend persists, it could pose serious challenges to agricultural productivity and land management in the region. Crops such as olives, which are highly dependent on seasonal rainfall and moderate temperatures, may experience reduced yields and lower-quality olive oil production.



	2022	2023	2024
August	0.27	0.29	0.26
September	0.30	0.30	0.29
October	0.34	0.37	0.30
November	0.38	0.42	0.36
December	0.47	0.48	0.43

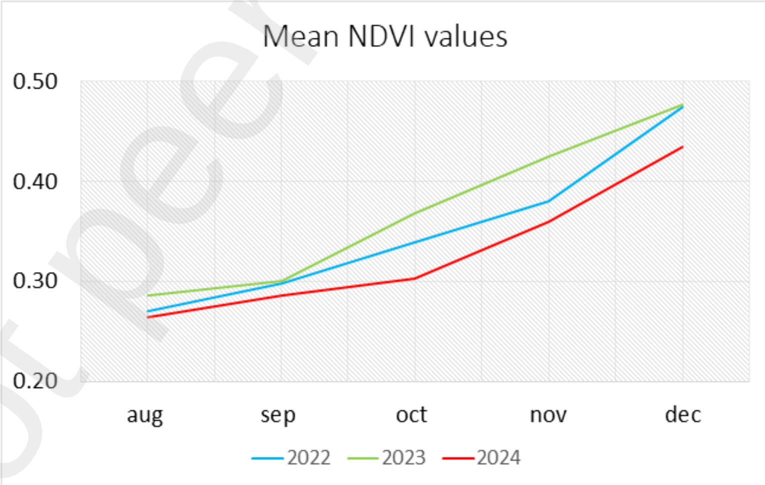


Figure 8: Monthly mean NDVI (Normalized Difference Vegetation Index) values for August to December across three years (2022, 2023, and 2024).

The comparison between the NDVI maps and the mean NDVI values highlights consistent trends, with both datasets emphasizing a significant decline in vegetation health during 2024, particularly in November. The maps strongly show reduced NDVI values across large areas in November 2024, aligning with the sharp dip observed in the corresponding line graph. While the maps provide spatial details of vegetation stress, the mean NDVI values offer a clearer temporal perspective, demonstrating that 2024 consistently lags behind 2022 and 2023. Together, these results confirm the worsening vegetation conditions in 2024 and underline the growing impact of climatic stressors on regional vegetation.

5. Conclusions

This study highlights the need for effective water management practices, such as phenology-based irrigation, which may optimize water use without compromising olive oil quality. Additionally, the trade-offs observed between rainfed and irrigated treatments emphasize the necessity for a balanced approach to irrigation, where water usage is carefully tailored to the needs of the trees while preserving soil health and oil quality. The integration of agroecological practices—such as planting cover crops and avoiding herbicides—has the potential to promote soil conservation while simultaneously improving the biodiversity. These practices not only help mitigate the risks associated with soil erosion but also contribute to the long-term resilience of olive orchards, ensuring that they can continue to provide high-quality products in a changing climate.

Our findings emphasize the critical importance of adopting sustainable farming practices, particularly NbSs such as cover crops, to mitigate the adverse effects of climate change and soil degradation on agricultural productivity.

Phenology-Based Irrigation

Phenology-based irrigation aligns the timing of water application with the distinct growth stages of crops. This approach considers factors such as plant development, water requirements, and environmental conditions to maximize water use efficiency. By tailoring irrigation to the actual needs of the crop, water usage is optimized, reducing the risk of water exploitation and scarcity. Adequate water supply during critical growth stages supports healthy plant development, potentially increasing yields. Moreover, targeted irrigation practices minimize water use, thereby reducing the environmental impacts associated with water consumption.

Benefits of Cover Crops

Cover crops provide numerous benefits when used as a soil treatment in tree crops. They enhance soil health and fertility, improve soil structure, and stimulate microbial activity. By competing with weeds, cover crops reduce the need for herbicides and contribute to soil moisture regulation by lowering evaporation and improving water retention, particularly during drought periods. Additionally, the protective layer formed by cover crops shields the soil from erosion, prevents topsoil loss, and enriches the soil with nutrients and organic matter during decomposition. Furthermore, they offer habitat and food for various beneficial organisms, fostering biodiversity within the ecosystem.

Improving Olive Orchard Resilience

Implementing such solutions could significantly enhance the resilience of olive cultivation to climate change while minimizing environmental impacts. Our ongoing research aims to equip local farmers with practical strategies to boost the sustainability and resilience of olive orchards. These efforts will contribute to reducing environmental degradation and improving agricultural productivity in the region.

While the first-year results are encouraging, it is important to recognize that these findings must be further verified and validated as the experiments progress. The ongoing nature of this study highlights the necessity of continuous monitoring and evaluation to confirm the long-term sustainability of the observed practices. Future results will be instrumental in assessing the consistent impact of these strategies on olive oil quality and soil health over time. Continued research will also offer deeper insights into the interactions between irrigation and soil management under varying climatic conditions, refining methods to optimize olive farming in the region.

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