Land Restoration Effectiveness Assessed by Satellite-Based Remote Sensing Technologies as A New Monitoring Approach

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Keywords: Restoration actions, Mediterranean, Land Degradation, Satellite Imagery.

1. Abstract

The Mediterranean region faces increasing land degradation, desertification, and climate change threats. Traditional assessment methods for land restoration are often time-consuming and subjective. This study leverages satellite-based remote sensing, specifically Sentinel-2 and Sentinel-1 data, to provide a comprehensive and objective approach to monitoring restoration initiatives in food forest in Beit Lehem of the Galilee, northern Israel. Sentinel-2 high-resolution multispectral imagery enables detailed tracking of vegetation health through indices like SAVI, PSRI, and NDWI. Additionally, Sentinel-1 SAR data offers insights into microtopography changes and soil moisture monitoring. Our comparative analysis of restored and non-restored areas reveals significant improvements in vegetation health, soil moisture, and microtopographic stability in restored sites. By utilizing remote sensing technologies and a comparative approach, this study offers a detailed assessment of long-term restoration processes in the Mediterranean region, contributing to sustainable land management and ecosystem restoration practices. This work provides valuable insights for policymakers and land managers seeking to implement effective restoration strategies in the Mediterranean region.

2. Introduction

The Mediterranean region is highly vulnerable to environmental issues, recognized as a climate change hotspot. Land degradation, driven by factors such as unsustainable land use and changing management practices, poses a significant threat to Mediterranean ecosystems, impacting vital resources (Hill et al., 2008). These challenges are intensified by increasing temperatures and altered precipitation patterns, leading to socio-economic challenges and threatening the long-term health and sustainability of the region (Daliakopoulos et al., 2017). The combination of human activities and natural disturbances creates complex interactions that can overwhelm the resilience of these environments (Baeza et al., 2007; Hill et al., 2008).

Anthropogenic pressures, such as intensive farming and deforestation, have significantly contributed to desertification in the Mediterranean (Hill et al., 2008). These long-term human activities have disrupted natural ecosystems, leading to increased water stress and a drier climate. Unsustainable land use practices further exacerbate the vulnerability of the region, threatening its long-term health and sustainability (Daliakopoulos et al., 2017; Hill et al., 2008). The need for sustainable land management is evident to mitigate the ever-growing negative impacts on the region.

Land degradation and climate change in the Mediterranean pose significant socio-economic challenges by threatening essential natural resources (Daliakopoulos et al., 2017). The overexploitation of land resources can exceed the region's long-term productivity potential, further exacerbating these challenges (Hill et al., 2008). These environmental pressures can intensify poverty, highlighting the urgent need for effective management and restoration strategies (Zdruli, 2012). Addressing land degradation is crucial for achieving Sustainable Development Goal 15.3, which aims for Land Degradation Neutrality by implementing environmentally effective, socially acceptable, and economically viable solutions (Wang et al., 2023). Sustainable land management practices are crucial for mitigating these negative impacts and promoting overall sustainable development in the region (Zdruli, 2012).

Effective strategies for combating land degradation include the extensive adoption of sustainable land management (Zdruli, 2012). Technologies such as conservation agriculture, organic farming and reforestation can be implemented (Zdruli, 2012). Engaging local communities in decision-making, and developing cost-effective measures are also crucial (Zdruli, 2012).

Continuous monitoring and research are essential to refine climate projections and develop adaptive land and water management strategies, especially given the projections of expanding drylands and intensifying droughts in the region (Zdruli, 2012). Considering the limited soil and water resources, monitoring programs are needed to investigate local and national drought impacts (Zdruli, 2012). Establishing a continuous, harmonized soil monitoring system at national and regional scales in the Mediterranean region could provide comparable datasets and chart the spatial extent and temporal changes in soil degradation (Ferreira et al., 2022).

Remote sensing technologies offer significant potential for enhancing the monitoring and evaluation of restoration efforts, providing valuable insights for sustainable land governance (Wang et al., 2023). These technologies offer a wide view field, high efficiency, low cost, and real-time information acquisition compared to traditional field investigations (Wang et al., 2023). By using remote sensing technology, it is possible to monitor soil degradation in relation to SDGs (Wang et al., 2023). Examples of such indicators include soil mineral composition, organic matter, surface roughness, soil erosion, salinity, desertification area, and pollution condition (Wang et al., 2023). Also, continuous, harmonized soil monitoring system at national and regional scales in the Mediterranean region could provide comparable datasets and chart the spatial extent and temporal changes in soil degradation (Ferreira et al., 2022).

Sentinel-1 and Sentinel-2 satellite data offer a powerful combination for monitoring land restoration efforts, particularly in Mediterranean ecosystems. Sentinel-2, with its multispectral sensor operating in the visible, near-infrared, and shortwave infrared ranges, provides valuable data for soil and vegetation analysis.

Sentinel-1 and Sentinel-2 offer a powerful combination for environmental monitoring. Sentinel-2's Multispectral Instrument is considered a successor to the Landsat instruments, providing valuable data for land cover monitoring (Kaplan & Avdan, 2018). Sentinel-2 provides multi-spectral imagery with 13 spectral bands covering the visible, near-infrared, and shortwave infrared regions (Irfan et al., 2025). Sentinel-1, with its C-band SAR, is valuable because SAR data is sensitive to soil disturbances (Sacandé et al., 2021). Furthermore, Sentinel-1 intensity data can be used to detect interventions by mechanized ploughing of degraded lands (Sacandé et al., 2021).

To conclude, specific case studies, such as the restoration project in Beit Lehem of the Galilee, northern Israel, from a monoculture to a food forest model, demonstrate the practical application of remote sensing methodologies in assessing restoration strategies. These technologies provide valuable insights for sustainable land governance, highlighting the effectiveness of restoration activities in enhancing ecosystem resilience to seasonal and climatic variations. Continuous monitoring and adaptive management, supported by robust scientific evidence, are essential for achieving long-term restoration success and resilience against climate change.

3. Study area and materials

3.1 The Food Forest Project

The "Bethlehem of Galilee food forest" (32.704° N and 35.205° E) in Israel is a project initiated in 2017 to address soil degradation and biodiversity loss stemming from conventional agricultural practices. The forest, which covers an area of about 20 dunams, aims to implement agroforestry and permaculture principles in a Mediterranean climate in order to restore natural ecosystems. Soil and water conservation is done through drip irrigation, rainwater harvesting, and mulching techniques while promoting high species diversity and growing a variety of rare species of plants.

It is a nature-based solution where the food forest technique is aimed for the growth of multiple food species in a single system like natural forests (Albrecht & Wiek, 2021). It encourages healing the soil, preventing erosion, increasing biodiversity, providing food security for endangered species, increasing biomass, sequestering CO_2, creating high-quality compost that keeps the soil healthy and helps create conditions for a stable and diverse system resilient to pests and diseases. This is all done while producing fruits and vegetables for human consumption and teaching the population sustainable practices to use and enhance the resources of the system for our development and that of future generations. You want, like a food forest, for your system to sustain itself as much as possible. In this way, we use fewer external resources (rainwater, energy, fertilizers, money, labor) and let the system be able to be nourished from the resources present within the system itself and this process over time makes it a stable and resilient system a sustainable system. According to Albrecht and Wiek (Albrecht & Wiek, 2021), imitating nature in food production is a common practice of indigenous and traditional agricultural production systems, and food forests have been used as a concept since the 1980's in Europe (Albrecht & Wiek, 2021).

This food forest in Beith Lehem of the Galilee mimics nature, showing that sustainable food can be grown to create an ecosystem that does not harm but rather improves biodiversity and creates green social livelihoods that alleviate the damage done by industrial agriculture.

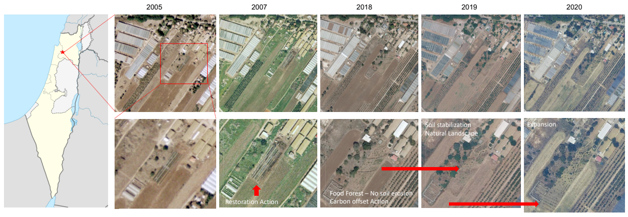

Figure 1. Orthophoto above the food forest.

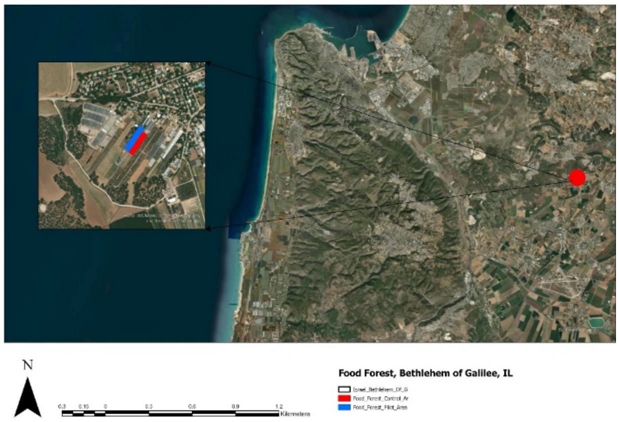

Figure 3. Restored and Control areas in the food forest.

3.2 Alonie Aba, Natural Forest

The Alonie Aba Forest Mountain in northern Israel is part of the Alonim Hills, north of the Nazareth Mountains and Tiran Valley. This area boasts ecological, historical, and cultural significance, featuring a Mediterranean climate with diverse landscapes, including low chalky hills, steep mountains, river valleys, and extensive olive groves.
As a key ecological corridor, the region connects the Jezreel Valley to the Galilee coastal plain and the Lower Galilee to Mount Carmel. It is home to rare and endangered plant species, traditional agricultural lands, and important archaeological and historical sites, such as Beit She'arim and Usha.
Although facing urban expansion and habitat fragmentation, significant open spaces remain, highlighting the need for conservation to maintain biodiversity, ecological connectivity, and scenic landscapes. Conservation strategies should prioritize the protection of native forests. Adjacent to the Alonie Aba Forest Mountain, this area's diverse landscapes and rare plants underscore conservation needs amid urban expansion, connecting the Jezreel Valley to the Galilee coastal plain. This study will assess how the food forest mimics the ecological functions of the natural forest using remote sensing methods.

Figure 2. Alonie Aba, Natural Forest.

4. Methodology

4.1 Data Sets

This study leverages the synergistic capabilities of Sentinel-1 and Sentinel-2 data to assess land restoration effectiveness in the Food forest in Beith Lehem of the Galilee. We incorporate Sentinel-1 radar data, which provides crucial information on soil moisture and is less affected by cloud cover, a significant advantage in the Mediterranean climate. Sentinel-2 data complements this with high-resolution optical imagery, enabling detailed vegetation analysis. Data were acquired from Summer 2015 to Spring 2024, divided into four seasons, with a shorter winter and longer summer to reflect the region's arid climate. Sentinel-1 data with a spatial resolution of 5x20m was used, along with Sentinel-2 bands.

This refined methodology, incorporating both Sentinel-1 and Sentinel-2 data and tailored to the specific conditions of the Alonie Aba Forest Mountain, provides a robust framework for assessing land restoration effectiveness.
A comparative approach paired restored area with nearby baselines, applying nine indicators to evaluate success. Findings shared with the principal investigator, informed future strategies, highlighting the value of remote sensing in monitoring restoration effectiveness and resilience.

4.2 Selected Indicators

We selected nine indicators to comprehensively evaluate the restoration efforts over time. These indicators were carefully chosen to capture different aspects of soil and vegetation health, providing a holistic view of ecosystem recovery. The rationale behind each indicator's selection is detailed below, along with its formula and expected value range:

1. Soil-Adjusted Vegetation Index (SAVI):

   Huete (1988) introduced this indicator to enhance the vegetation signal in areas with a significant soil background by incorporating a soil brightness correction factor (L) in its formula.

$$SAVI = \frac{NIR - RED}{NIR + RED + L} * (1 + L)$$

   Where red and near-infrared wavelengths are used to account for soil-vegetation interactions.

2. Normalized Difference Water Index (NDWI):

   As discussed in this paper (Gao, 1996), this indicator detects liquid water content in vegetation canopies using NIR (0.86 µm) and SWIR (1.24 µm) wavelengths, and is calculated as:

$$NDWI = \frac{NIR - SWIR2}{NIR + SWIR2}$$

3. Plant Senescing Reflectance Index (PSRI):

   This index assesses leaf senescence and fruit ripening by measuring chlorophyll degradation and carotenoid retention, using the formula:

$$PSRI = \frac{RED - BLUE}{RED\ EDGE2}$$

   Where Red band (678 µm) measures reflectance in the red region, indicating chlorophyll degradation; Blue band is in (500 µm) that measures reflectance in the blue-green region, indicating carotenoid retention; and Red Edge2 band (750 µm) measures reflectance in the near-infrared, normalizing structural variations (Merzlyak et al., 1999).

4. Normalized Difference Infrared Index (NDII):

   This index was found to be superior to the vegetation index for moisture content detection.

$$NDII = \frac{NIR - SWIR}{NIR + SWIR}$$

   According to (Hardisky et al., 1983), NIR measurements reflect vegetation structure and leaf biomass. While the middle infrared band (1.55 to 1.75 µm) is sensitive to water content.

5. Normalized Difference Vegetation Index (NDVI):

   This indicator is used to assess vegetation health, biomass, and coverage, and is highly sensitive to green plant material.

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

   NDVI uses the red band (~660–680 µm) to measure chlorophyll absorption, indicating photosynthetic activity, and the near-infrared band (~840–870 µm) to measure leaf cellular structure, reflecting vegetation structure and leaf biomass (Huang et al., 2021).

6. Structure-Insensitive Pigment Index (SIPI):

   This index is designed to estimate the ratio between carotenoid and chlorophyll alpha concentrations Car/Chla, minimizing the confounding effects of leaf surface and mesophyll structure (Peñuelas, Baret, & Filella, 1995).

$$SIPI = \frac{NIR - AER}{NIR - RED}$$

   It uses reflectance at three wavelengths, 800 µm, ~ 455 µm, and ~ 680 µm. While the near-infrared region

(NIR) is under 800 µm wavelength and it is sensitive to leaf and canopy structure. It detects high reflectance in healthy vegetation due to internal cell structure and serves as a reference to reducing sensitivity to canopy architecture. While the Aerosol band in region ~455 µm is sensitive to carotenoids and anthocyanins; it reflects pigment absorption, especially in stressed or senescing vegetation, providing information on carotenoid content, which is more stable than chlorophyll under stress. Finally, the red band in region ~680 µm indicates chlorophyll concentration as it is sensitive to the chlorophyll a absorption peak; strong absorption occurs in healthy vegetation, resulting in lower reflectance when chlorophyll is abundant (Peñuelas, Baret, & Filella, 1995).

7. Photochemical Reflectance Index (PRI):

As (Garbulsky et al., 2011) documented in his meta-analysis review, this indicator is used to remotely assess photosynthetic efficiency, and it is calculated as:

$$PRI = \frac{BLUE - GREEN}{BLUE = GREEN}$$

Where 531 µm band (blue in the case of Sentinel-2) is located in a region of the spectra where atmospheric transmission is high, while the 570 µm band (green in the case of Sentinel 2 was found useful at a single leaf scale as noted by (Garbulsky et al., 2011).

8. Normalized Shortwave Infrared Difference Soil-Moisture (NSDS):

This index enhances bare soil signals and assess soil moisture based on the differential absorption of shortwave infrared light by water (Nguyen et al., 2021).

$$NSDS = \frac{SWIR1 - SWIR2}{SWIR1 + SWIR2}$$

As demonstrated in previous research by (Nguyen et al., 2021), SWIR1 uses the 1.57–1.65 µm wavelength and SWIR2 uses the 2.11–2.29 µm wavelength.

9. Soil Moisture Content Index (SMCI):

$$SMCI = 100 - |\frac{BIP - dry}{dry}| \times 100$$

This approach is commonly used in bare or low-vegetation conditions and described in SAR soil moisture review paper, such as (Paloscia et al.2013).

While BIP is: $10^{\frac{\sigma^0}{10}}$, this conversion transforms Sentinel-1 backscatter from decibels (dB) to linear power, providing a more physically interpretable value for normalization and comparison. The dry reference is defined as the backscatter intensity in power under known dry soil conditions, either from historical observations or in-situ data.

Index	Indicator name with reference	Index Data	
		Value Range	Bands used in the equation
SAVI	Soil Adjusted Vegetation Index (Huete, 1988)	(-1)- (1)	((NIR - Red) / (NIR + Red + L)) * (1 + L)
NDWI	Normalized Difference Water Index (Gao, 1996)	(-1)- (1)	(NIR – SWIR2) / (NIR + SWIR2)
PSRI	Plant Senescence Reflectance Index (Merzlyak et al., 1999)	(-1)- (1)	Red- Blue/ Red Edge2
NDII	Normalized Difference Infrared Index (Hardisky et al., 1983)	(-1)- (1)	(NIR - SWIR) / (NIR + SWIR)
NDVI	Normalized Difference Vegetation Index (Rouse et al., 1974)	(-1)- (1)	(NIR-RED/ NIR+RED)
SIPI	Structure-Insensitive Pigment Index (Peñuelas et al., 1995)	(0)- (2)	(NIR - AER) / (NIR - Red)
PRI	Photochemical Reflectance Index (Garbulsky et al., 2011)	(0)- (1)	(BLUE-GREEN/BLUE+GREEN)
NSDS	Normalized Shortwave Infrared Difference Soil-Moisture (Nguyen et al., 2021)	(-1)- (1)	(SWIR1-SWIR2)/(SWIR1+SWIR2)
SMCI	Soil Moisture Content Index (Paloscia et al., 2013)	0- 100 (%)	**VV band used in the developed algorithm:** The radar signals are transmitted vertically and received vertically. This is often used for detecting water bodies.

Table 1. Main characteristics of the selected indicators from Sentinel 1 and Sentinel 2 satellites.

4.3 Pre-processing

Before analysis, the satellite imagery underwent a series of pre-processing steps to ensure data quality and accuracy. These steps were implemented using Google Earth Engine due to its efficient data handling and processing capabilities.

Following the pre-processing steps, the selected spectral indices were calculated for each image in the database of total images of the satellite. The formulas used for each index are provided in Table. 1. These calculations were performed within Google Earth Engine (GEE) using its built-in mathematical functions and band operations. The results were then averaged for each image to reduce noise and create composite images for each time step.

4.4 Data Acquisition and Analysis

The data acquisition and analysis involved several key steps. First, the Google Earth Engine platform was utilized to access and process satellite imagery (Sacandé et al., 2021). GEE's ImageCollection feature grouped images, such as Sentinel-1 data, and filtered data based on the defined timeframes, area extent, and cloud cover percentage. A script was created to check for cloud-free image availability within the specified timeframe. An area of interest was defined to limit the image availability check and subsequent analysis to the study area. Next, a cloud masking function was implemented to reduce cloud interference. The image collection was then filtered to include only the images within the desired time range, and timeframes were labeled according to seasons to facilitate seasonal analysis. Relevant calculations were performed on the images, and the results were averaged for each image. Finally, images and raw results were exported for further analysis and visualization. GEE's data catalog and indexing functionality allowed for efficient data calls and processing, streamlining the data inference process. Initial soil disturbances due to ploughing and time of occurrence were detected using Sentinel-1 radar imagery (Sacandé et al., 2021).

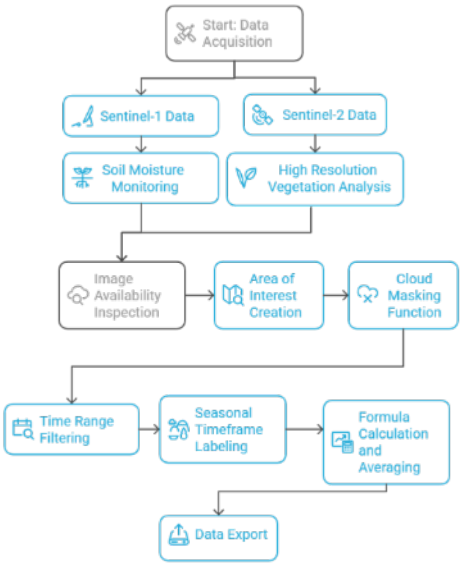

Figure 4. Top- Down Approach schema

5. Results

The findings from our analysis of soil and vegetation health, derived from Sentinel-2 satellite data, are presented with a focus on three key indicators out of all those tested. The data, spanning from summer 2015 to winter 2024, captures both seasonal changes and long-term trends in the restored and control areas in the food forest.

By comparing these areas, the effectiveness of the restoration efforts can be evaluated, and improvements in vegetation resilience to environmental stressors can be identified.

The following sections will describe the seasonal and temporal patterns observed in the selected indicators, providing insights into the successes and challenges encountered during the restoration projects.

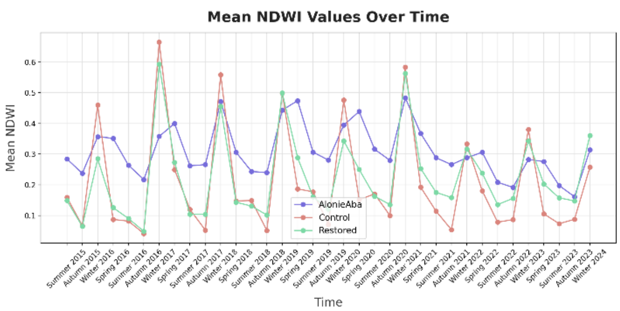

Figure 5. NDWI measurements for restored and control area in the food forest Vs. the natural forest reserve- Alonie Aba.

Figure 5. in the study elucidates the dynamics of the NDWI- within both the restored and control zones across several seasons, spanning from summer 2015 to winter 2024. During the wetter periods of winter and spring, elevated NDWI values signify an enhanced water content within the vegetation. Conversely, the desiccated periods of summer and autumn correspond to diminished moisture levels. Initially, the control area exhibits superior NDWI values when contrasted with the restored area. However, as time elapses, both areas converge towards similar patterns, with the restored area demonstrating superior NDWI values during the wet seasons. Both areas, restored and control manifest analogous seasonal trends, yet the restored area showcases greater stability and resilience, exhibiting fewer sharp declines in NDWI values. Considering that the natural forest, Alonie Aba, exhibits high and favorable NDWI values, the observation that the food forest's restored area is beginning to mirror these characteristics is quite promising.

This suggests that the restoration efforts in the food forest are effectively enhancing vegetation water content, stability, and overall health, driving it towards a state comparable to that of a thriving, established natural forest ecosystem like Alonie Aba.

This trend underscores the beneficial influence of restoration endeavors on the moisture content of the vegetation.

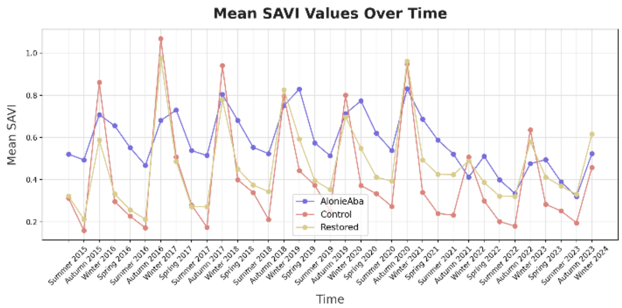

Figure 6. SAVI measurements for restored and control area in the food forest Vs. the natural forest reserve- Alonie Aba.

The trend of SAVI indicator in the restored area in the food forest gradually approaching these higher values is indicative of positive development. Higher SAVI values during winter and spring typically indicate healthier vegetation, while lower values during summer and autumn reflect reduced vegetation health due to seasonal variations.

The convergence of SAVI values implies that the restored area is on a favorable trajectory, showcasing heightened stability and ecological performance over time. At the beginning of the timeframe, the control area is showing high SAVI assessments but overtime, both, the restored and control areas tend toward each other. This underscores the potential for well-executed restoration endeavors to emulate and ultimately attain the ecological benchmarks established by natural, undisturbed ecosystems, resulting in a healthier and more sustainable landscape

Given that SAVI values in Alonie Aba are consistently higher than those in the food forest, it suggests that the natural forest exhibits a greater abundance of healthy vegetation and minimal soil exposure. We anticipate that the implementation of these restoration actions will yield significant positive impacts on ecosystem services and overall landscape resilience. This means that, the restored area will start to shift highly with the natural forest plot.

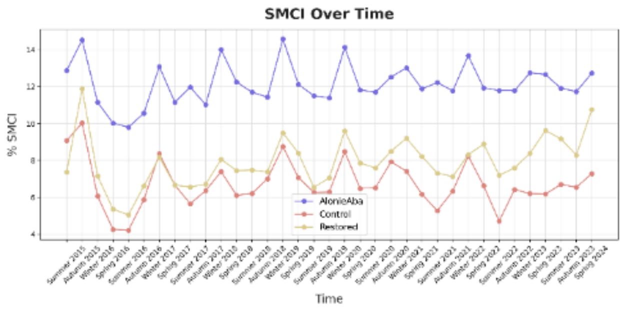

Figure 7. SMCI measurements for restored and control area in the food forest Vs. the natural forest reserve- Alonie Aba.

Spanning 2015-2024, Soil Moisture Content Index results reveal the impact of restoration on soil moisture dynamics in the food forest, compared to a control area and the natural forest reserve, Alonie Aba. As Figure 7 depicts, restoration efforts demonstrably enhance soil moisture content, likely due to improved soil structure and increased organic matter. In contrast, non-restored areas exhibit reduced soil moisture levels, potentially from increased vegetation water use and evapotranspiration. Alonie Aba consistently displays superior soil moisture retention, highlighting the benefits of a healthy, established ecosystem where a cooler atmosphere and lush vegetation thrive and felt when you step into it, supported by the soil's ability to retain water, reduce erosion, and sustain abundant plant life. These findings underscore the importance of adaptive management strategies that integrate soil hydraulic functions, local conditions, and long-term sustainability goals for effective restoration planning.

6. Conclusion

This study demonstrates the utility of employing remote sensing-derived indicators to evaluate the long-term effectiveness of top-down approach for restoration initiatives in Mediterranean ecosystems. Through the analysis of temporal trends in indicators such as NDWI, SAVI and SMCI and more (Table 1.) the impact of restoration efforts can be quantitatively assessed by comparing restored and control areas. The convergence of NDWI and SAVI values in the restored area of the food forest towards those observed in the natural forest, Alonie Aba, suggests a positive trajectory towards enhanced vegetation health, water content, and overall ecosystem resilience. This approach facilitates a comprehensive understanding of restoration outcomes, supporting adaptive management strategies and informed decision-making for future projects.

7. Discussion

The comparison of these indicators between the restored area and Alonie Aba, serves as a benchmark for restoration success. These findings underscore the importance of continuous monitoring using remote sensing technologies to guide restoration practices and ensure the long-term sustainability of restored landscapes. By integrating remote sensing data with on-the-ground observations, restoration practitioners can gain a more holistic understanding of ecosystem recovery and adapt their strategies to optimize outcomes. This aspect is part of an ongoing research within the same project of REACT4MED that will be detailed further.

Future research will focus on developing a predictive model based on a Hidden Markov Model to forecast the success of restoration actions in the Mediterranean. This model will incorporate the selected environmental health indicators as input features and will be trained to identify distinct states of restoration success. By analyzing the transitions between these states, the HMM will predict the likelihood of achieving desired restoration outcomes under different scenarios, informing adaptive management strategies and optimizing resource allocation.

We are optimistic that the restoration strategies employed will foster long-term ecological recovery and enhance the provision of ecosystem services, benefiting both the environment and local communities.

8. Contributions

The REACT4MED project employs a multiscale approach to land restoration monitoring. This study contributes by utilizing a top-down approach, integrating satellite data into the LanDS platform (The multi-operational Land degradation Decision-Support Toolbox) to facilitate real-time environmental monitoring and enhance land degradation assessments. This integration enables tracking changes in land productivity and identifying degradation trends essential for sustainable management. While REACT4MED also includes bottom-up approaches through field assessments and community engagement, those aspects are beyond the scope of this paper. Additionally, a scoring model will be developed using collected data and machine learning techniques to predict restoration project success based on biophysical and socio-economic conditions. This supports effective decision-making and enhances land restoration strategies. Overall, remote sensing is a powerful tool for monitoring vegetation health and water content, providing critical insights for ecosystem restoration.

9. Acknowledgments

This research was supported in part by the REACT4MED grant: Inclusive Outscaling of Agro-Ecosystem Restoration Actions for the Mediterranean. REACT4MED Project (Grant Agreement No. 2122) is funded by PRIMA, a Program supported by Horizon 2020, the European Union’s Framework Program for Research and Innovation.

10. References

Albrecht, S., & Wiek, A. (2021). Food forests: Their services and sustainability. *Journal of Agriculture, Food Systems, and Community Development, 10*(3), 91–105. https://doi.org/10.5304/jafscd.2021.103.014

Baeza, M.J., Valdecantos, A., Alloza, J.A. and Vallejo, V.R. (2007), Human disturbance and environmental factors as drivers of long-term post-fire regeneration patterns in Mediterranean forests. *Journal of Vegetation Science, 18*: 243-252. https://doi.org/10.1111/j.1654-1103.2007.tb02535.x

Daliakopoulos, I. N., Panagea, I. S., Tsanis, I. K., Grillakis, M. G., Koutroulis, A. G., Hessel, R., Mayor, A. G., and Ritsema, C. J. (2017) Yield Response of Mediterranean Rangelands under a Changing Climate. *Land Degrad. Develop.*, 28: 1962–1972. https://doi.org/10.1002/ldr.2717

Daliakopoulos, Ioannis, and Saskia Keesstra. "TERRAenVISION: science for society. Environmental issues today." *Science of the Total Environment* 704 (2020): 135238. https://doi.org/10.1016/j.scitotenv.2019.135238

Ferreira, C. S. S., Seifollahi-Aghmiuni, S., Destouni, G., Ghajarnia, N., & Kalantari, Z. (2022). Soil degradation in the European Mediterranean region: Processes, status and consequences. *Science of the Total Environment, 805*, 150106. https://doi.org/10.1016/j.scitotenv.2021.150106

Gao, B.-C. (1996). NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment, 58*(3), 257–266. https://doi.org/10.1016/S0034-4257(96)00067-3

Garbulsky, M. F., Peñuelas, J., Gamon, J., Inoue, Y., & Filella, I. (2011). The photochemical reflectance index (PRI) and the remote sensing of leaf, canopy and ecosystem radiation use efficiencies. *Remote Sensing of Environment, 115*(2), 281–297. https://doi.org/10.1016/j.rse.2010.08.023

Hardisky, M. A., Klemas, V., & Smart, R. M. (1983). The influence of soil salinity, growth form, and leaf moisture on the spectral radiance of *Spartina alterniflora* canopies. *Photogrammetric Engineering and Remote Sensing, 49*(1), 77–83.

Hill, Joachim, et al. "Mediterranean desertification and land degradation: Mapping related land use change syndromes based on satellite observations." *Global and Planetary Change* 64.3-4 (2008):146-157. https://doi.org/10.1016/j.gloplacha.2008.10.005

Huang, S., Tang, L., Hupy, J. P., Wang, Y., & Shao, G. (2021). A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. *Journal of Forestry Research, 32*(1), 1–6. https://doi.org/10.1007/s11676-020-01155-1

Huete, A. R. (1988). A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment, 25*(3), 295–309. https://doi.org/10.1016/0034-4257(88)90106-X

Irfan, A., Li, Y., E, X., & Sun, G. (2025). Land use and land cover classification with deep learning-based fusion of SAR and optical data. *Remote Sensing, 17*(7), 1298. https://doi.org/10.3390/rs17071298

Kaplan, G., & Avdan, U. (2018). Sentinel-1 and Sentinel-2 data fusion for wetlands mapping: Balikdami, Turkey. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII–3*, 729–734. https://doi.org/10.5194/isprs-archives-XLII-3-729-2018

Merzlyak, M. N., Gitelson, A. A., Chivkunova, O. B., & Rakitin, V. Y. (1999). Non-destructive optical detection of pigment changes during leaf senescence and fruit ripening. *Physiologia Plantarum, 106*(1), 135–141. https://doi.org/10.1034/j.1399-3054.1999.106119.x

Nguyen, C. T., Chidthaisong, A., Kieu Diem, P., & Huo, L.-Z. (2021). A modified bare soil index to identify bare land features during agricultural fallow-period in Southeast Asia using Landsat 8. *Land, 10*(3), 231. https://doi.org/10.3390/land10030231

Paloscia, S., Pettinato, S., Santi, E., Notarnicola, C., Pasolli, L., & Reppucci, A. (2013). Soil moisture mapping using Sentinel-1 images: Algorithm and preliminary validation. *Remote Sensing of Environment, 134*, 234–248. https://doi.org/10.1016/j.rse.2013.02.027

Pandit, S., Tsuyuki, S., & Dube, T. (2018). Estimating Above-Ground Biomass in Sub-Tropical Buffer Zone Community Forests, Nepal, Using Sentinel 2 Data. *Remote Sensing, 10*(4), 601. https://doi.org/10.3390/rs10040601

Peñuelas, J., Baret, F., & Filella, I. (1995). Semi-empirical indices to assess carotenoids/chlorophyll a ratio from leaf spectral reflectance. *Photosynthetica, 31*(2), 221–230.

Sacande, M., Martucci, A., & Vollrath, A. (2021). Monitoring large-scale restoration interventions from land preparation to biomass growth in the Sahel. *Remote Sensing, 13*(18), 3767. https://doi.org/10.3390/rs13183767

Wang, J., Zhen, J., Hu, W., Chen, S., Lizaga, I., Zeraatpisheh, M., & Yang, X. (2023). Remote sensing of soil degradation: Progress and perspective. *International Soil and Water Conservation Research, 11*(4), 429–454. https://doi.org/10.1016/j.iswcr.2023.03.002

Zdruli, P. (2014). Land resources of the Mediterranean: Status, pressures, trends and impacts on future regional development. *Land Degradation & Development, 25*(4), 373–384. https://doi.org/10.1002/ldr.2150