Integrating Remote Sensing and Soil Analysis for Long-Term Land Restoration Assessment in Mediterranean Ecosystems

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This study integrates remote sensing and ground-based soil analysis to assess long-term land restoration in Mediterranean ecosystems. By combining top-down satellite-derived indicators with bottom-up soil health metrics, the research provides a robust framework for monitoring restoration dynamics. Sentinel-2 data were employed to track vegetation and soil changes over time, while detailed field analyses—including chemical, physical, and spectroscopic tests—offered site-specific insights into soil health. The integration of these approaches enables the development of a predictive model, linking remotely sensed data with soil parameters to support continuous monitoring and adaptive management. The findings highlight the potential for scalable, accessible tools to assist land managers and farmers in evaluating restoration progress and guiding sustainable practices.

Keywords—Remote Sensing, Top-Down Analysis, Bottom-Up Analysis, Restoration Assessment, Soil Health Monitoring

I. INTRODUCTION

The Mediterranean region's arid and semi-arid agro-ecosystems are increasingly vulnerable to land degradation and desertification, driven by both human activities and natural processes [1,2]. Intensive agriculture and deforestation, coupled with the region's high climatic and topographical variability, have created an environment prone to instability [3-5]. This situation is further compounded by extreme weather events such as fires, floods, and droughts, which disrupt livelihoods, exacerbate poverty, and drive migration [6,7]. Climate change has intensified these challenges, posing a significant threat to critical natural resources such as water and soil, which are essential for sustaining agriculture and forestry [8]. The Mediterranean region, recognized as a climate change hotspot, is undergoing accelerated dryland expansion and a transition to drier climates [9]. Projections indicate heightened risks of water scarcity, with droughts becoming more frequent and severe [10]. Addressing these interconnected threats requires robust scientific knowledge and comprehensive environmental monitoring. Enhanced assessments of land degradation and desertification trends are vital for developing sustainable land and water management strategies, as well as for guiding effective ecosystem restoration efforts [11]. Achieving Land Degradation Neutrality (LDN) depends on solutions that are both environmentally sustainable and economically and socially viable [12].

Although progress has been made in restoration science, significant gaps remain. Socio-economic barriers, limited policies, and insufficient knowledge continue to hinder the adoption of sustainable land management practices and discourage investments in restoration activities [13]. Remote sensing technologies have emerged as critical tools for addressing these challenges. By utilizing satellite data, these methods provide essential top-down indicators for assessing vegetation and soil quality, enabling continuous, large-scale monitoring of environmental changes over time [14]. These indicators allow for efficient tracking of restoration efforts and facilitate data-driven decision-making aimed at enhancing ecosystem resilience. While remote sensing provides a broad-scale perspective, it inherently lacks the detailed, site-specific information necessary to fully understand soil health. Ground-based analyses, or bottom-up approaches, complement remote sensing by offering localized insights into soil chemical, physical, and biological processes. Parameters such as nutrient levels, organic carbon dynamics, soil structure, and water infiltration offer a comprehensive view of soil functionality that cannot be captured through satellite imagery alone. Integrating these bottom-up analyses with remote sensing enables a more holistic approach to monitoring, ensuring that restoration progress is assessed across multiple scales and dimensions. This integration reduces the risk of missing critical indicators of soil health, which are vital for guiding adaptive management strategies.

This study focuses on the transition of agricultural land in Beit Lehem of the Galilee into a food forest model, serving as a case study to illustrate the complementary strengths of combining remote sensing and bottom-up soil analyses. By leveraging these approaches, the research aims to develop an integrated framework for assessing soil and ecosystem health, providing valuable insights to support sustainable land management practices in Mediterranean ecosystems.

II. METHODOLOGY

The methodology employed in this study integrates bottom-up and top-down approaches to evaluate soil health and restoration progress in a food forest transitioning from a monoculture agricultural field. By combining detailed soil analyses with remote sensing data, a unified model was developed to assess land restoration at multiple scales. The flowchart (Figure 1) illustrates the comprehensive process, from data collection and analysis to the integration and application of the results.

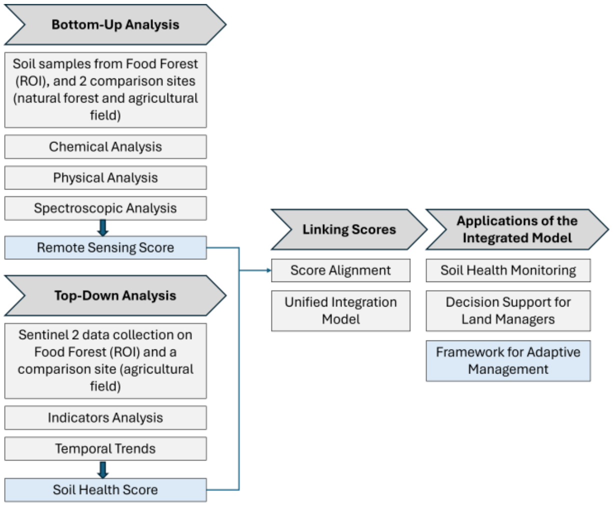

Fig. 1. Methodology Flowchart

A. Bottom-Up Analysis: Field-Based Soil Assessments

(1) Study Sites and Sampling Design

Soil samples were collected from three distinct sites to provide a comparative framework: (a) Food Forest: The primary case study, representing a restored agroecosystem transitioning from a monoculture field to a diverse and sustainable system; (b) Agricultural Field: A nearby monoculture field, representing the initial state of the food forest, prior to restoration actions; (c) Natural Oak Forest: A nearby undisturbed oak forest, representing the target ecosystem in terms of soil health, organic matter, and carbon dynamics. Multiple sample points were selected within each site to capture spatial variability. Samples from each site were aggregated to ensure a representative average for analysis. al assessment.

(2) Chemical Analysis

The chemical analysis focused on a range of soil health indicators, providing insights into the biological, chemical, and physical functions of the soil: **(a) Nutrient Levels (Nitrogen and Phosphorus):** These nutrients are critical for plant growth and microbial activity. Nitrogen (N) supports the development of proteins and enzymes in plants and soil microorganisms, while phosphorus (P) is essential for energy transfer and root development. Low levels can indicate nutrient depletion, while balanced levels reflect improved soil fertility and restoration progress; **(b) Carbon Dynamics: Total Organic Carbon (TOC) and Total Inorganic Carbon (TIC):** TOC reflects the soil's capacity to store and cycle organic matter, while TIC provides information on carbonate content, which can influence soil pH and stability; **(c) Active Carbon:** A fast-cycling fraction of TOC, active carbon serves as a readily available energy source for soil microorganisms and is an early indicator of changes in soil organic matter; **(d) Particulate Organic Carbon (POC) and Mineral-Associated Organic Carbon (MOC):** POC indicates short-term organic matter inputs, such as plant residues, while MOC represents longer-term carbon stabilization, crucial for building soil structure and resilience; **(e) Soil Acidity and Salinity (pH and Electrical Conductivity, EC):** pH: Indicates soil acidity or alkalinity, which directly affects nutrient availability and microbial activity. Restoration often aims to bring pH to a level optimal for plant and microbial life. **(f) Electrical Conductivity (EC):** Reflects soil salinity, which can influence water uptake and plant health. Reduced salinity is typically an indicator of improved soil quality in degraded lands.

(3) Spectroscopic Analysis (FTIR)

Following the chemical analysis, soil samples were analyzed using Fourier-Transform Infrared Spectroscopy (FTIR) to obtain detailed spectroscopic profiles. These profiles provide insights into the organic and inorganic molecular composition of the soil, complementing traditional chemical metrics and enabling the identification of specific soil health signatures.

(4) Physical Analysis

To further evaluate soil health, the following physical tests were conducted on-site: **(a) Slake Test:** To assess soil aggregate stability, an indicator of soil structure and erosion resistance; **(b) Accumulative Infiltration Test:** To measure water infiltration rates, reflecting soil porosity and permeability; **(c) Penetration Pressure Test:** To evaluate soil compaction, which affects root growth and water movement.

B. Top-Down Analysis: Remote Sensing

(1) Data Collection

Sentinel-2 data were collected for the Food Forest region and a nearby agricultural field seasonally over multiple years to capture temporal trends in restoration progress. The agricultural field served as a baseline for comparison, enabling the identification of changes attributable to restoration activities in the food forest.

(2) Top-Down Indicators

Remote sensing indicators were used to monitor vegetation and soil conditions: (a) Normalized Difference Vegetation Index (NDVI) - Indicates vegetation health and productivity; (b) Soil-Adjusted Vegetation Index (SAVI) - Enhances vegetation signal by accounting for soil background effects; (c) Normalized Difference Water Index (NDWI) - Assesses vegetation water content and soil moisture; (d) Plant Senescence Reflectance Index (PSRI) - Identifies vegetation stress and senescence; (e) Normalized Difference Infrared Index (NDII) - Measures vegetation water status, particularly under drought conditions; (f) Structure Insensitive Pigment Index (SIPI) - Reflects vegetation pigment concentrations, which are sensitive to health and stress.

TABLE I. INDICATORS

Index	Index Data		
	Purpose	***Range***	***Notes***
NSDI	Normalized Shortwave Infrared Difference index	(-1) - (1)	SWIR1 - Band11, SWIR2 = Band12
SAVI	Soil Adjusted Vegetation Index	(-1) - (1)	L = 0.5
PSRI	Plant Senescing Reflectance Inde	(-1) - (1)	RED EDGE2 = Band5
SIPI	Structure Insensitive Pigment Index	(0) - (2)	
NDII	Normalized Difference Infrared Index	(-1) - (1)	SWIR1 = Band11
NDWI	Normalized Difference Water Index	(-1) - (1)	MIR = Band12

To evaluate the restoration progress of the food forest, a comparative methodology was employed. The agricultural field, a nearby area of similar size and environmental conditions, was selected as a baseline representing the non-restored state prior to intervention. This approach minimizes the influence of external environmental variables and provides a direct comparison between restored and non-restored areas. The six remote sensing indices were calculated for both the food forest and the agricultural field, enabling a comparative analysis of temporal trends. By examining the differences in indicator performance between the two sites, the effectiveness of the restoration efforts in the food forest was assessed, highlighting the impact of restoration interventions on soil and vegetation health.

C. Integrating Bottom-Up and Top-Down Approaches

A unified scoring model was developed to integrate soil and remote sensing data, facilitating a comprehensive assessment of soil health and restoration dynamics.

(1) Unified Scores

(a) Soil Health Score: A composite score was calculated from the bottom-up soil analyses, incorporating parameters such as carbon dynamics, nutrient levels, and physical stability. **(b) Remote Sensing Score:** A composite score was derived from the satellite indices, weighted based on their sensitivity to soil and vegetation health metrics.

(2) Linking the Scores

The relationship between the soil health score and the remote sensing score was mapped to ensure alignment between the two approaches. A calibration function was applied to adjust the remote sensing score to match site-specific conditions identified in the soil analyses.

(3) Application of the Model

The integrated model provides tools for continuous monitoring of restoration progress using satellite data, reducing reliance on invasive sampling. It enables adaptive management by identifying areas of improvement and directing restoration efforts where they are most needed. The framework supports decision-making for land managers, offering actionable insights for sustainable land restoration.

This integrated methodology demonstrates the complementary strengths of bottom-up and top-down approaches in evaluating restoration outcomes. By linking field-based and satellite-derived data, it provides a scalable, cost-effective framework for monitoring soil health and supporting evidence-based land management practices.

III. Priliminary Results

The results presented in this study are preliminary and provide an initial evaluation of the restoration progress in the food forest compared to the adjacent agricultural field. These findings incorporate both bottom-up soil analyses and top-down satellite-derived indices to offer a comprehensive perspective on the state of soil and vegetation health. The soil analyses focus on key chemical, physical, and structural parameters, while the remote sensing indices highlight trends in vegetation condition and soil moisture.

The slake test results, as presented in Figure 2, reveal notable improvements in soil structure stability in the food forest compared to the agricultural field. The food forest shows moderate aggregate stability, indicating that restoration practices are contributing to the development of a more cohesive soil structure resistant to erosion. In the agricultural field, aggregate stability remains poor, with soil prone to disintegration under water exposure. These findings further validate the effectiveness of the restoration interventions in improving the structural integrity of the soil in the food forest.

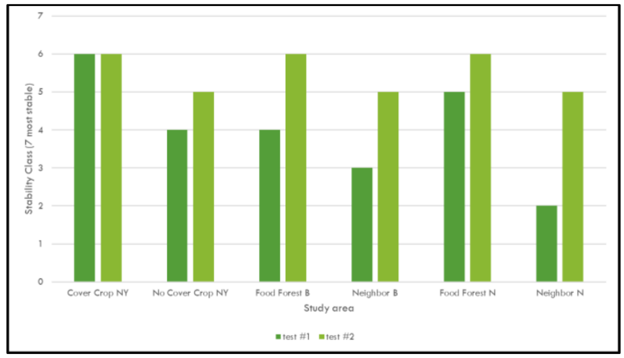

Fig. 2. Slake Test Results

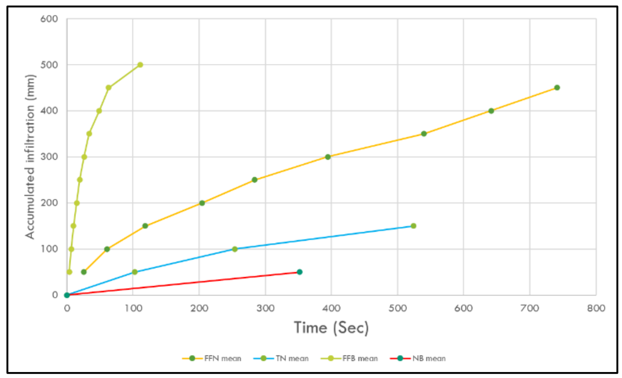

Fig. 3. Accumulative Infiltration Test Results

The water infiltration rates, measured through the accumulative infiltration test (Figure 3), further emphasize the improvements in the food forest compared to the agricultural field. In the food forest, infiltration rates are significantly higher, reflecting a developing soil structure that allows for greater water absorption and permeability. In contrast, the agricultural field exhibits the lowest infiltration rates, which correspond to its compacted soil and limited porosity. This difference highlights the role of restoration efforts in enhancing the food forest's capacity to retain and manage water, a critical factor in building resilience in arid and semi-arid ecosystems.

The macronutrient analysis (Figure 4) demonstrates the impact of restoration practices on soil fertility. Nitrogen (N) and phosphorus (P) levels in the food forest are significantly higher than those in the agricultural field, suggesting the incorporation of organic matter and nutrient enrichment resulting from restoration actions. In contrast, the agricultural field shows depleted nutrient levels, reflecting the consequences of intensive management without replenishment. While the food forest exhibits substantial improvements in nutrient availability, there remains room for further enrichment to fully restore fertility levels and support sustained ecological function.

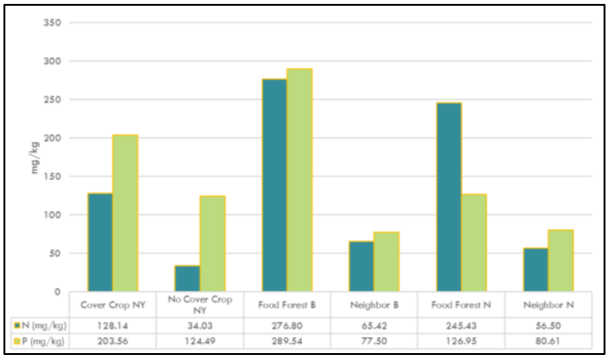

Fig. 4. N, P Tests Results

Figure 5 presents the temporal trends of NSDI, SAVI, and PSRI indices calculated for the food forest and the adjacent agricultural field from Winter 2020 to Autumn 2023. Across all indices, seasonal fluctuations are observed in both areas, with peaks typically occurring in the wetter seasons and troughs in drier periods. The NSDI values demonstrate higher levels during winter months in both the food forest and the agricultural field, with a more pronounced decline in drier seasons. SAVI shows seasonal variation, with peaks in vegetation productivity observed during winter and spring, and lower values during summer and autumn. The PSRI values reveal an opposite trend, with higher values during the summer months, reflecting seasonal shifts in vegetation condition. In all three indices, differences between the food forest and the agricultural field are evident, with the trends showing varying degrees of divergence across seasons and years.

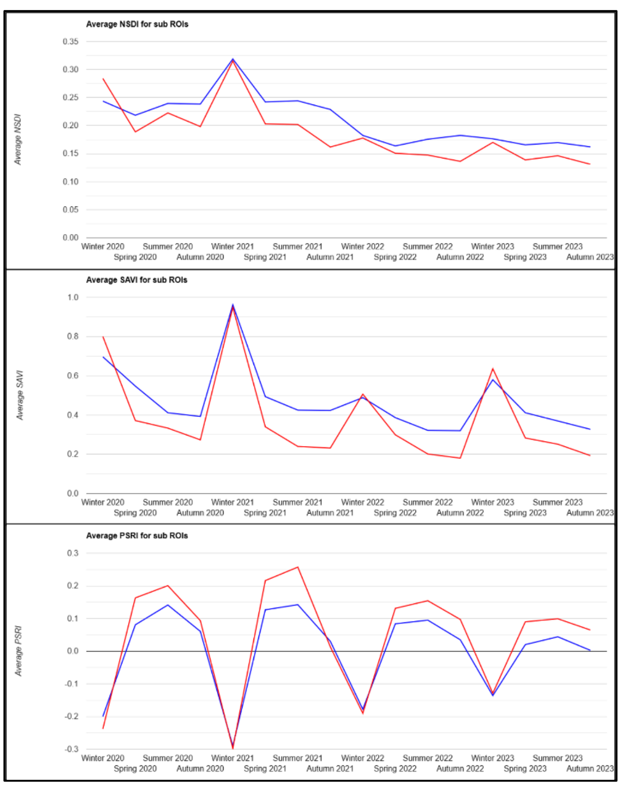

Fig. 5. Indicators Results

IV. Conclusion and Discussion

The results presented in this study highlight the effectiveness of soil restoration efforts in the food forest, as evidenced by significant differences observed between the food forest and the adjacent agricultural field, which continues to operate under conventional agricultural practices. Both the bottom-up soil analyses and the top-down remote sensing indices reveal clear trends that demonstrate the impact of conservation and restoration actions on soil and vegetation health. The soil analyses show improvements in key parameters such as nutrient levels, soil structure, and water infiltration in the food forest, indicating enhanced soil functionality and resilience. These improvements contrast sharply with the degraded conditions observed in the agricultural field, where soil compaction, lower nutrient availability, and reduced water infiltration remain evident. The remote sensing indices further corroborate these findings, showing consistent differences in vegetation health, moisture retention, and stress levels between the two sites. Seasonal patterns in the remote sensing data emphasize the food forest's ability to maintain stability and resilience across environmental fluctuations, a key outcome of effective restoration practices.

These findings underscore the potential of integrating bottom-up and top-down approaches to monitor and evaluate land restoration efforts. The consistency between the ground-based measurements and remote sensing indicators demonstrates the feasibility of leveraging satellite data to track restoration progress over time. This integrated approach provides a comprehensive understanding of soil and ecosystem health, enabling informed decision-making for land managers and stakeholders.

Looking ahead, the next phase of this research will focus on conducting more comprehensive analyses and implementing the unified model proposed in the methodology. This model will link soil parameters derived from bottom-up analyses with remote sensing indicators to calibrate satellite data for site-specific conditions. Once calibrated, the remote sensing tools can be used for continuous, non-invasive monitoring of restoration progress, providing an accessible and scalable decision-support system for farmers and foresters. By enabling ongoing monitoring and adaptive management, this system has the potential to guide sustainable land restoration efforts effectively.

The approach demonstrated in this study offers a practical and scalable model for restoring degraded lands on a broader scale. By combining the detailed insights of ground-based analyses with the efficiency and accessibility of remote sensing, this methodology provides a pathway for long-term soil health monitoring and ecosystem resilience. The results emphasize the importance of integrating these methods to achieve sustainable land management outcomes and highlight the potential for applying this approach to other regions facing similar challenges.

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