AI-Based Early Detection of Climate-Induced Water Stress in Olive Orchards Using Google Earth Engine: A Case Study of Ghafsai, Morocco

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Abstract

The Mediterranean basin, particularly the Maghreb, is facing unprecedented aridity. This study investigates the use of Artificial Intelligence (AI) and multi-sensor remote sensing to detect water stress early in olive orchards (*Olea europaea* L.) in Ghafsai, Morocco. Using Google Earth Engine (GEE), we processed terabytes of data from Sentinel-2, MODIS, CHIRPS, and SMAP satellites covering the 2019-2024 drought. We propose a framework using Random Forest (RF) for soil moisture downscaling and Long Short-Term Memory (LSTM) networks for forecasting vegetation health. Results show that while traditional NDVI lags in detecting stress in the 'Picholine Marocaine' cultivar, Short-Wave Infrared (SWIR) and Thermal Infrared (TIR) indices offer a lead time of up to three months. The study also identifies soil-dependent vulnerability gradients, aiding precision management aligned with Morocco's "Generation Green 2020-2030" strategy.

1 Introduction

1.1 The Climatological and Hydrological Crisis in the Maghreb

- **Climate Hotspot:** North Africa is warming faster than the global average, with Morocco facing chronic water deficits Frontiers [2025].
- **Severe Drought (2019-2024):** The country experienced its longest/most severe drought sequence, with 2023 being the driest year in 80 years (rainfall ¡100mm in many areas) Frontiers [2025].
- **Water Crisis:** Dam filling rates dropped to 28.5% in 2024 despite capacity expansion Frontiers [2025].
- **Impact:** Agriculture (80% of water use) is devastated, especially rainfed (Bour) areas like Taounate.

1.2 The Olive Sector: Resilience Under Siege

- **Economic Pillar:** Olives cover 1.2 million ha in Morocco (65% of fruit tree area) inr [2025].
- **'Picholine Marocaine':** The dominant cultivar is historically drought-resilient but now threatened by intensified farming and climate change mdp [2022].
- **Intensification Issues:** Shift to high-density planting competes for dwindling groundwater mdp [2023].
- **"Silent Stress":** Olives close stomata to save water, staying green (high NDVI) even when stressed. Visual signs come too late (leaf shedding), necessitating early detection rdi.

1.3 The Paradigm of Remote Sensing and AI

- **Solution:** Earth Observation (EO) via Google Earth Engine (GEE) overcomes ground monitoring limitations Goo [b].
- **Multi-Sensor Approach:**
  - **Optical (Sentinel-2):** Vegetation structure Goo [b].
  - **SWIR (Sentinel-2/MODIS):** Canopy water content Res.
  - **Thermal (MODIS):** Land Surface Temperature (LST) / stomatal conductance Goo [a].
  - **Microwave (SMAP):** Root zone soil moisture Goo [c].
- **AI Methods:**
  - **Random Forest (RF):** For handling non-linear relationships in spectral data hes [2024].
  - **LSTM (RNN):** For forecasting temporal drought trajectories lst [2020].

2 Study Area: The Ghafsai Circle

2.1 Geographical and Topographical Setting

- **Location:** Pre-Rif domain, Northern Morocco (between Saïss plain and Rif mountains).
- **Terrain:** Rugged hills and deep valleys, promoting rapid runoff.

2.2 Geological and Pedological Context

- **Soils:**
  - **Vertisols/Luvisols (Valleys):** High clay, good water holding but prone to cracking.
  - **Lithosols (Slopes):** Shallow, skeletal, low water storage.
- **Challenge:** Heavy clay soils cause waterlogging in winter and hardness in summer.

2.3 Agro-Ecological Characteristics

- **Systems:** Mostly extensive 'Picholine' agroforestry (intercropped with cereals).
- **Phenology:** Warmer winters are disrupting chill hour accumulation, affecting flowering (April-May).

3 Materials and Data Acquisition

3.1 Satellite Constellations

- **Sentinel-2 MSI:** 10m resolution. Key for resolving small orchards and calculating NDVI/NDWI.
- **MODIS:** High frequency (8-day). Used for Evapotranspiration (ET) and LST.
- **CHIRPS:** Gridded rainfall data (5.5km) for drought monitoring (SPI).
- **SMAP:** Root zone soil moisture (9km), crucial for deep-rooted olives.

3.2 Auxiliary Data

- **Topography:** NASA SRTM DEM for slope/aspect.
- **Land Use:** Custom olive orchard mask.

4 Methodology

4.1 Development of Water Stress Indices

- **Meteorological:** SPI (3 and 6 month) from CHIRPS UN-.
- **Agricultural:** Vegetation Health Index (VHI) combining VCI (Vegetation) and TCI (Temperature). Threshold: VHI ¡ 40 = Stress NOA.
- **Physiological:**
  - **NDWI:** Leaf water content (NIR vs SWIR) Res.
  - **ETDI:** Evapotranspiration Deficit Index from MODIS mdp [2021].

4.2 Machine Learning: Spatial Downscaling (Random Forest)

- **Goal:** Downscale SMAP soil moisture (9km) to orchard scale (10m).
- **Inputs:** Sentinel-2 indices, LST, topography.
- **Output:** 10m Soil Moisture Map.
- **Interpretability:** SHAP values used to rank feature importance fro [2022].

4.3 Deep Learning: Forecasting (LSTM)

- **Goal:** Forecast VHI 1-3 months ahead.
- **Model:** 2 stacked LSTM layers with Dropout.
- **Input:** 12-month sequence of Precip, Soil Moisture, VHI.
- **Testing:** Trained on 2017-2021, Tested on 2022-2024 (drought years).

5 Results and Analysis

5.1 Meteorological Drought (2017-2024)

- **Timeline:** 2019 onset $\rightarrow$ 2022/2023 Extreme Drought (-56% rainfall anomaly).
- **SPI:** Cumulative SPI-24 dropped below -3.0, indicating cessation of groundwater recharge.

5.2 Vegetation Health Evolution (VHI)

- **2017-18:** Healthy (VHI ¿ 60).
- **2019-20:** Warning phase (VHI 40-50). Lagged behind meteorological drought due to soil buffering.
- **2022-24:** Collapse (VHI ¡ 35). 68% of orchards severely stressed. South-facing slopes degraded first.

5.3 Spectral Sensitivity: NDVI vs. NDWI vs. LST

- **NDVI:** Poor early warning ($R^2 = 0.45$). Lags stress because leaves stay green.
- **NDWI:** Good early warning ($R^2 = 0.72$). Lead time +1 month. Detects turgor loss.
- **LST:** Best early warning ($R^2 = 0.68$). Lead time +1.5 months. Detects stomatal closure (heating).

5.4 AI Model Performance

- **Random Forest (Downscaling):** $R^2 = 0.82$. Captured micro-variability (e.g., ”wet islands” in deep soils).
- **Feature Importance:** NDWI (28%) and LST (22%) were top drivers, validating physiological stress theory.
- **LSTM (Forecasting):**
  - **1-Month:** Accurate (MAE 4.5).
  - **3-Month:** Correctly predicted trend direction in 78% of cases. Useful for seasonal planning.

6 Discussion

6.1 The "Silent Stress" Paradox

- 'Picholine' prioritizes survival over yield ("green but no olives").
- Stomatal closure happens early; visual signs happen late.
- **Takeaway:** Must monitor LST/NDWI, not just NDVI.

6.2 Soil Influence

- **Clay (Vertisols):** Buffered early drought but cracked in later years, damaging roots.
- **Calcareous:** Highly sensitive to "flash droughts" (no buffer).

6.3 Policy Implications (Generation Green)

- **Zoning:** Use AI maps to ban intensification on shallow soils/steep slopes.
- **Varieties:** Need for more xeric rootstocks beyond Picholine.
- **Advisory:** Use LSTM forecasts for early warning apps (triggering pruning/irrigation).

7 Conclusion

- **Crisis:** 2019-2024 drought challenges olive viability in Ghafsai.
- **Method:** Multi-sensor fusion (Optical + Thermal + Microwave) is mandatory.
- **Findings:** SWIR/Thermal indices beat NDVI (1-3 month lead time).
- **Tools:** RF and LSTM effectively downscale data and forecast stress.
- **Future:** AI-driven management is a survival imperative for the Maghreb.

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