Mapping yearly irrigation patterns across Italy using multiple satellite data from 2000 to 2025

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1. IMPORTANCE

- Irrigation represents the **largest share of freshwater use** in Italy, reaching up to 50–70%.
- Climate change is intensifying **water scarcity and drought frequency** (IPCC, 2023).
- There is still **limited knowledge of the spatial and temporal distribution** of irrigation at national scale.
- Reliable irrigation mapping is essential for **sustainable water management and climate adaptation**.

CHALLENGES

- Differentiating **irrigated and rainfed crops** from satellite observations remains difficult.
- Agricultural systems show **high spatial and temporal variability**.
- Long-term and consistent datasets are **limited or heterogeneous**.
- Ground-based data for validation are **sparse and uncertain**.

AIMS

- This study maps **yearly irrigation patterns across Italy from 2000 to 2025**.
- A **multi-sensor satellite framework** combining NDVI and soil moisture is developed.
- The analysis investigates **spatial distribution and temporal stability** of irrigated areas.
- The study evaluates **consistency and uncertainties** in irrigation detection.

2. MATERIALS & METHODS

STUDY AREA

- The analysis is conducted over Italy, a Mediterranean region characterized by diverse climates and agricultural systems.
- Major irrigated regions include the Po Valley, one of the most intensive agricultural areas in Europe.
- The study domain is defined using administrative boundaries.

DATASETS

1. Vegetation (NDVI - MODIS MOD13Q1)
   - 2000–2025 (25 years)
   - 250 m, 16-day composites
   - Masking (urban/water/forest)
   - DEM slope mask (>20% excluded)
2. Surface Soil Moisture (Copernicus SSM)
   - 1 km resolution
   - Temporal focus: Growing season (June–August 2018)May–Aug (2018)
   - DN → % (SSM = DN × 0.5)
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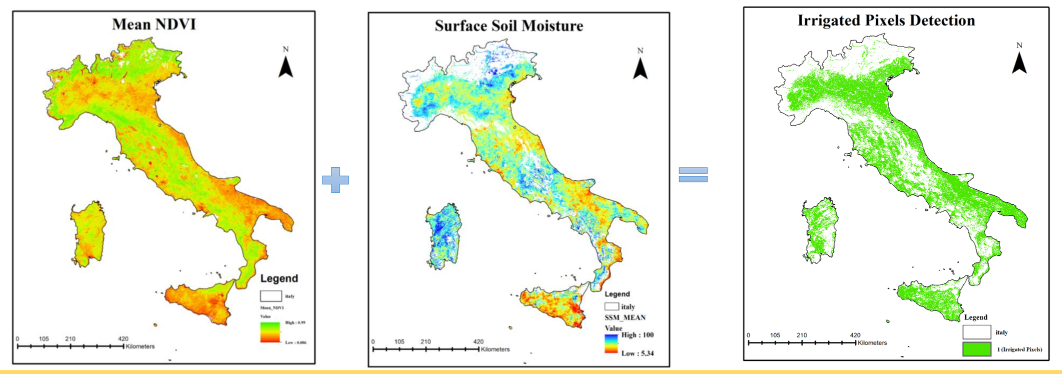
Dataset & Source	Spatial Resolution	Temporal Coverage
MODIS NDVI (MOD13Q1)	250 m	2000–2025
Copernicus Surface Soil Moisture (ESA CCI)	1 km	2015–2025
CORINE Land Cover	100 m	2000, 2006, 2012, 2018
Digital Elevation Model (SRTM DEM)	30 m	Static

VALIDATION FRAMEWORK AND METHODOLOGY

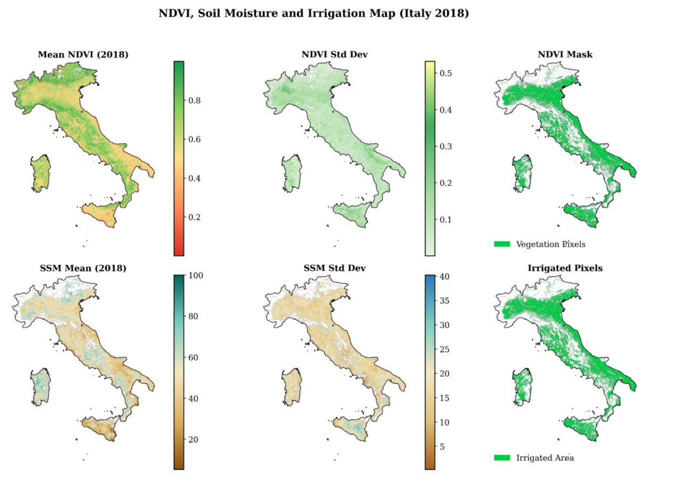
- **Multi-Source Comparison:**
  Annual irrigation maps (2000–2025) were validated against five global and regional datasets to quantify spatial agreement and thematic consistency.
- **Statistical Evaluation:**
  Model performance was assessed using **Precision, Accuracy, and F1-score**, measuring reliability in detecting active irrigation.
- **Ground Truth Validation:**
  High-resolution field polygons and irrigation consortium records were used to validate local-scale accuracy, enabling assessment at sub-pixel level.
- **Physical Consistency Check:**
  The relationship between NDVI and surface soil moisture (SSM) was evaluated using linear regression:
  $NDVI = 0.0040 \times SSM + 0.3987$
  confirming the physical basis of irrigation detection.
- **Spatiotemporal Irrigation Dynamics:**
- Irrigation patterns analyzed over **2015–2025** using annual map stacking.
- Generated **irrigation frequency map** to measure persistence of irrigation signals.
- Classified into **low to high-frequency irrigation zones (>90% persistence)**.
- Temporal trends used to assess **long-term changes in irrigated area (ha)**.



3. RESULTS: IRRIGATION DYNAMICS ACROSS ITALY

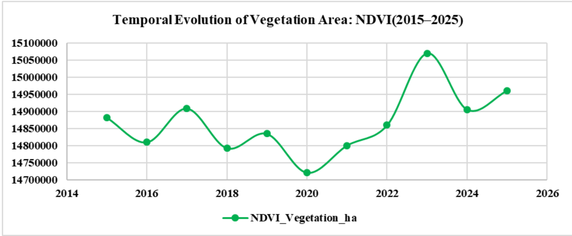
NDVI–SSM–IRRIGATION FRAMEWORK

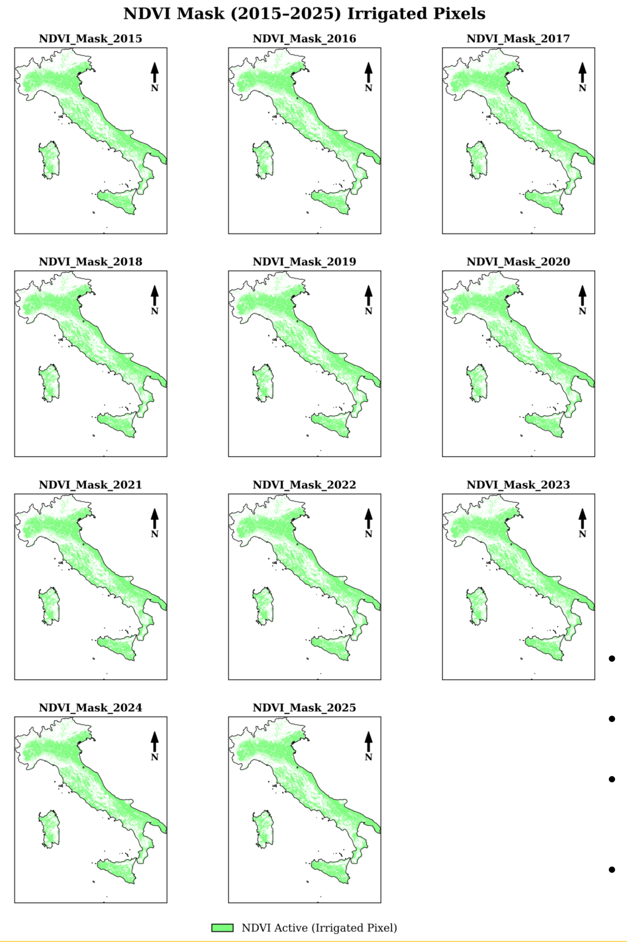
- Mean NDVI → vegetation intensity (crop zones clearly visible).
- NDVI Std Dev → strong seasonal variability in agricultural regions.
- SSM → soil water availability patterns.
- Stable SSM + moderate NDVI variability → **irrigated systems**
- High variability → **rainfed dependence**
- Integrated NDVI + SSM detects irrigated pixels with high spatial accuracy.

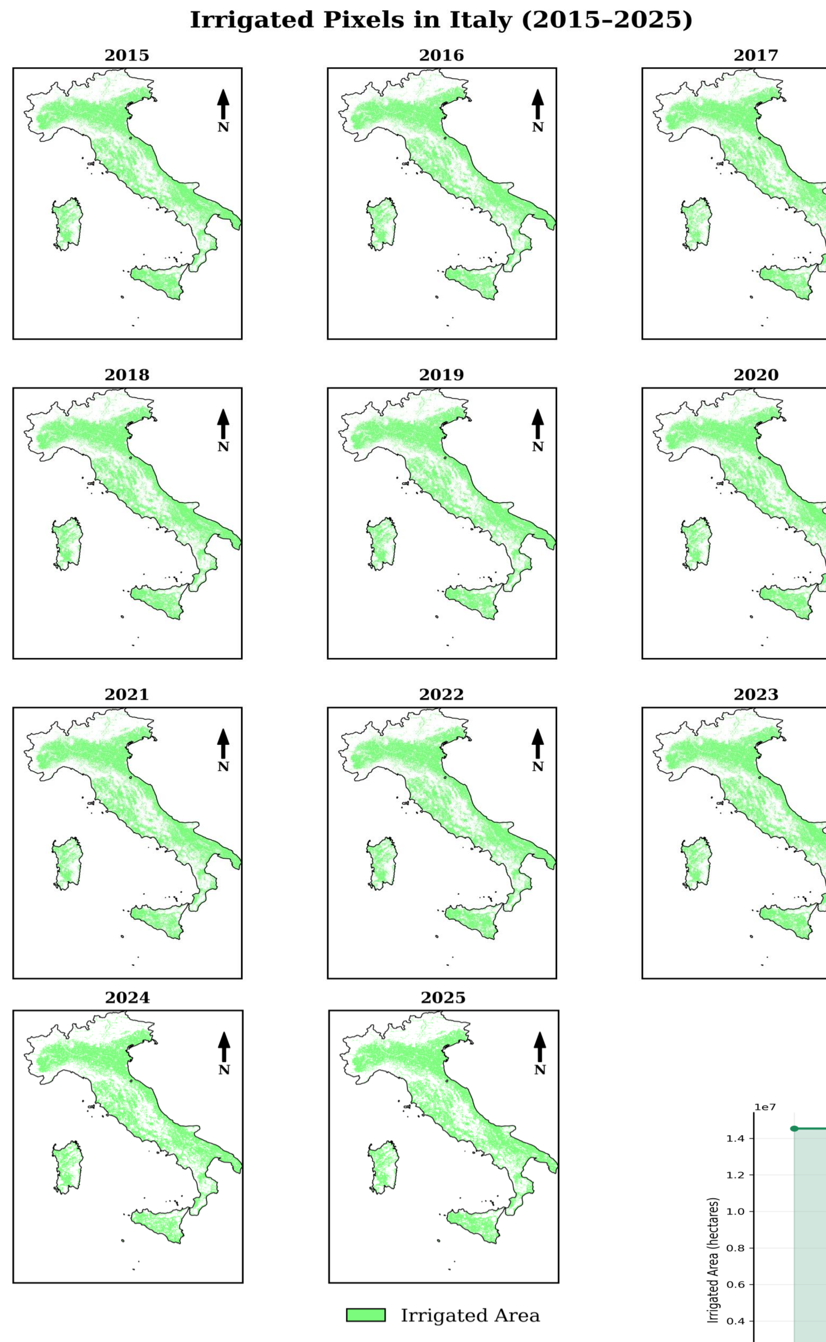


TEMPORAL DYNAMICS OF VEGETATED AREA (2015–2025)

- NDVI masks show stable spatial patterns of vegetation across Italy, mainly in agricultural zones.
- Persistent activity in the Po Valley and Southern plains indicates continuous irrigation and strong infrastructure .
- Vegetated area remains stable, ranging between ~14.7–15.1 million hectares.
- A decline in 2020 and peak in 2023 suggest climate-driven variability and recovery.
- Overall consistency confirms robust and reliable NDVI-based vegetation mapping.

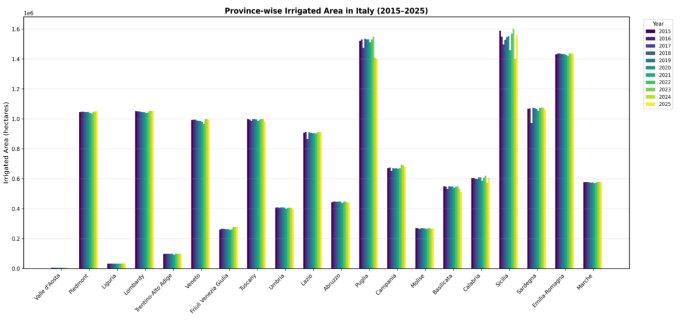






From yearly maps:

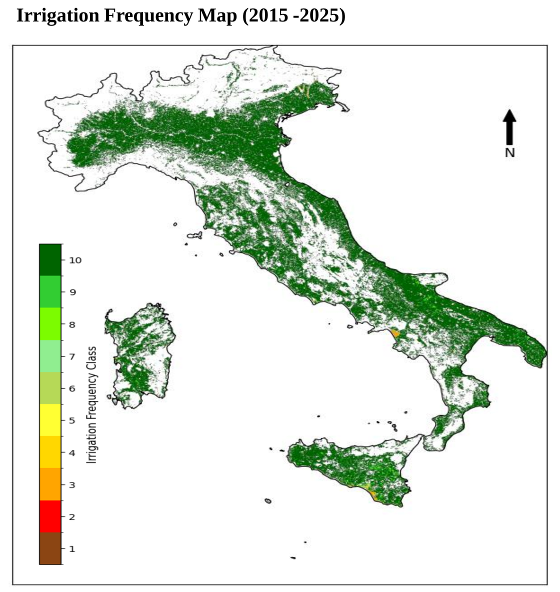
- Irrigation patterns in Italy are **highly persistent over time**, with strong regional contrast.
- Po Valley = **permanent irrigation hotspot**(most stable)
- Southern regions = **moderate variability**
- Northern systems → stable, infrastructure driven irrigation
- Southern systems → climate-influenced, variable irrigation



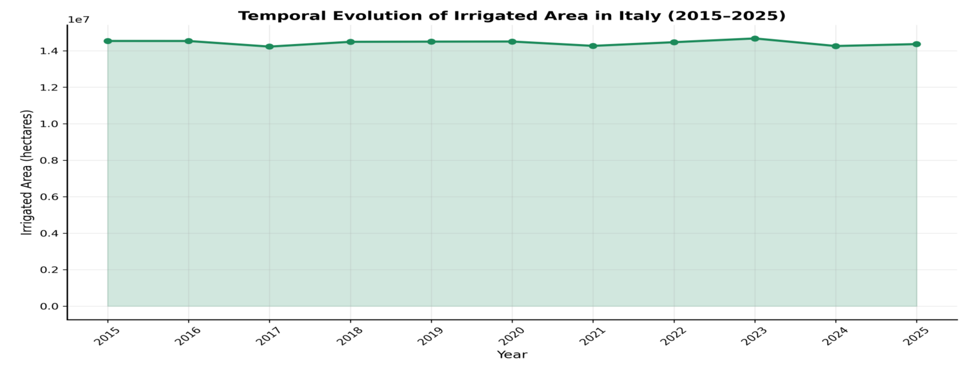
SPATIAL DISTRIBUTION OF IRRIGATION (Provinces)

- Irrigation is **strongly spatially clustered**, showing clear regional concentration across Italy.
- The most dominant agricultural zones are **the Po Valley (Northern Italy) and the Southern plains (Apulia and Sicily).**
- These regions represent the core of Italian irrigated agriculture due to favorable soils, water availability, and established irrigation infrastructure.
- Overall, irrigation is **not uniformly distributed**, but instead strongly driven by regional agricultural intensity and hydro-climatic conditions.

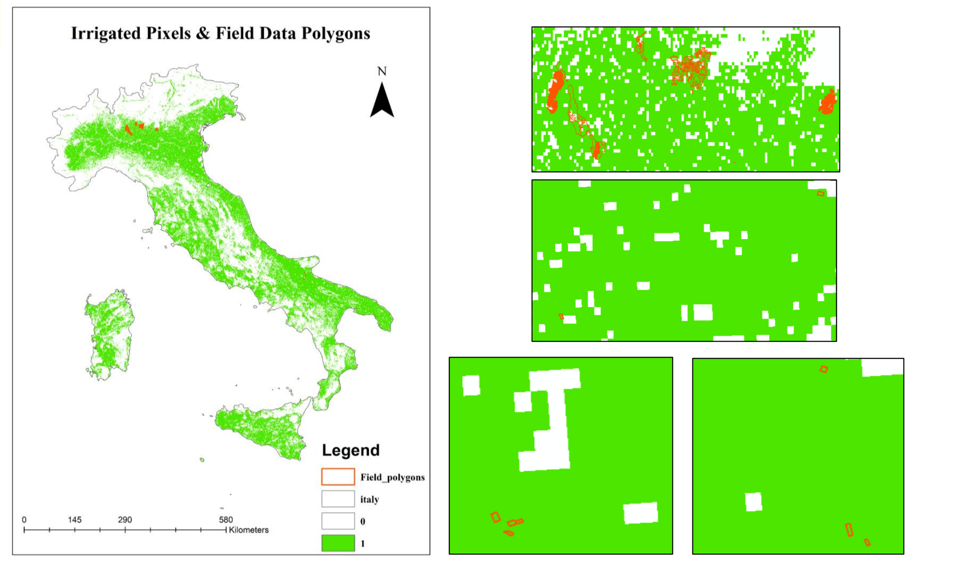
- **Irrigation frequency map** captures long-term water use patterns across agriculture.
- High-frequency pixels (~90%) represent permanent, intensively irrigated cropland.
- Low-frequency areas indicate marginal or drought-driven irrigation.
- Strong concentration observed in the Po Valley and Southern plains.



- Italy's irrigated agriculture shows **long-term structural stability**.
- Total irrigated area remains consistently around: **1.45 × 10⁷ hectares (14.5 million ha).**
- Only minor year-to-year fluctuations observed.
- No significant upward or downward trend.
- Mature irrigation infrastructure and stable land-use system.



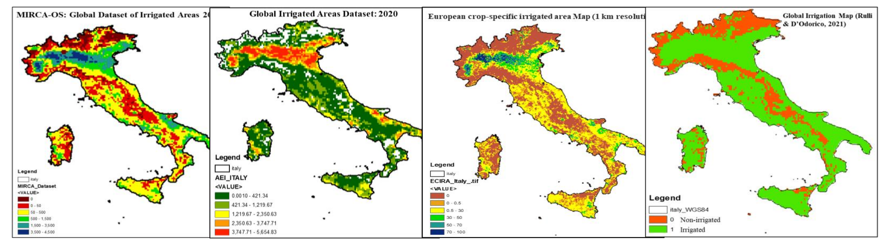
LOCAL-SCALE VALIDATION: GROUND TRUTH VS. PREDICTED IRRIGATION



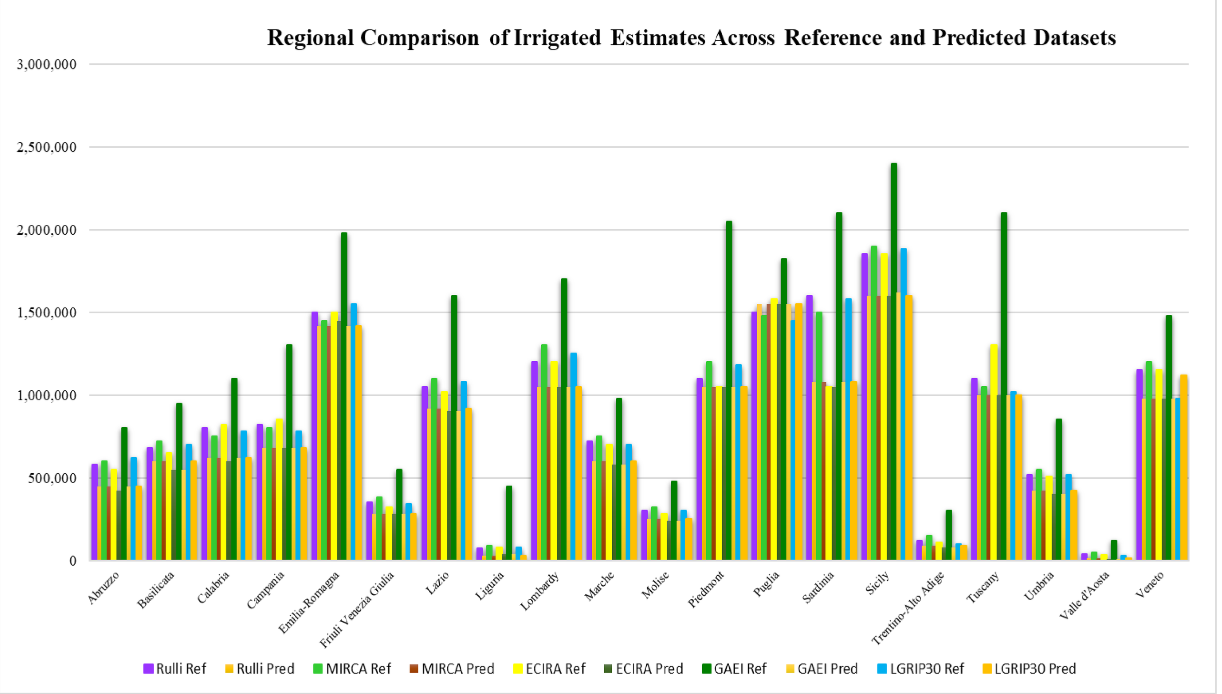
- The spatial agreement between predicted irrigated pixels and field-validated polygons demonstrates the model's ability to transition from regional-scale mapping to local-scale accuracy.
- This supports the high precision (0.8242) and F1-score (0.7609) observed in national-level validation.

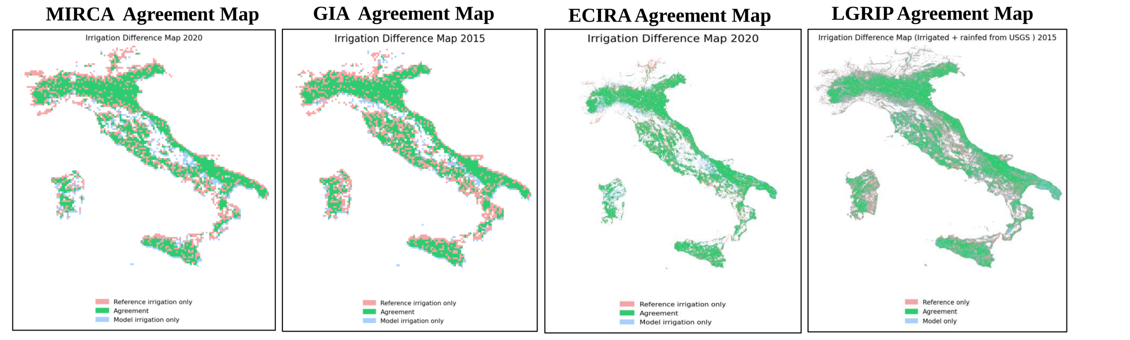
4. MULTICOMPARISON

EVALUATION OF IRRIGATION MAP AGREEMENT WITH EXISTING DATASETS



Dataset	Spatial Resolution	Temporal Coverage	Precision	Accuracy	F1-score
Global Irrigation Areas 2001-2015 (1)	5 arc-min (~9 km)	2015	0.85	53.18%	0.69
MIRCA-OS (Global dataset for irrigated vs. rainfed crop areas.) 2()	5 arc-min (~10 km)	2015, 2020	0.82–0.83	52–53%	0.69
ECIRA (European Crop-Specific Irrigated Area) (3)	1 km	2010–2020	0.84 -0.85	64 -65.%	0.79
GAEI (Global Area Equipped for Irrigation) (4)	~10 km (5 arc-min)	2000, 2005, 2010, 2015, 2020	0.93	50%	0.55
LGRIP30 (Landsat Global Irrigated Cropland) (5)	30 m × 30 m	2014–2017 (nominal 2015)	0.8242	61.41%	0.7609





Irrigation Map Comparison with MIRCA, ECIRA, LGRIP, GAEI, and GIA Datasets:

- The model shows consistently high precision (>0.83), indicating reliable detection of irrigated areas with minimal false positives across all reference datasets.
- Results indicate an underestimation of the irrigated extent, as evidenced by a higher number of reference-only pixels (68,297) than model-only pixels (35,070).
- Strong Geospatial Agreement: Best spatial consistency is observed in major agricultural regions such as Puglia, Sicily, and Emilia-Romagna, where predicted irrigation closely aligns with MIRCA-OS and LGRIP30 datasets.
- Lower agreement with GAEI (~50% accuracy) highlights that the model captures active irrigation dynamics rather than total irrigation infrastructure ("area equipped").
- The framework achieves strong overall performance (F1-score ≈ 0.76 with LGRIP30), demonstrating reliable applicability across diverse Italian agricultural landscapes.

5. DISCUSSION

DISCUSSION

- The framework captures active irrigation dynamics, providing a more realistic representation of agricultural water use based on vegetation response to hydrological conditions.
- It provides strong long-term consistency, which is rarely achieved in large-scale irrigation studies, allowing robust analysis of interannual stability and climate-related variability.
- The spatial analysis reveals a clear and physically meaningful organization of irrigation systems across Italy:
- Northern Italy (Po Valley) shows stable, low-variability patterns, consistent with infrastructure-driven and well-regulated irrigation systems supported by reliable water distribution networks.
- Southern regions exhibit higher temporal variability, reflecting stronger dependence on climatic conditions, intermittent water availability, and adaptive irrigation practices.
- The statistically significant NDVI–SSM relationship confirms that water availability is a dominant biophysical control on vegetation dynamics, thereby supporting the methodology's physical basis.
- Beyond mapping irrigation presence, the framework enables advanced spatiotemporal analysis, including detection of irrigation persistence, identification of intensive versus marginal systems, and assessment of agricultural resilience under climate stress.
- A significant NDVI–SSM correlation confirms that water availability is the primary driver of vegetation health in these areas, validating the physical foundation of the framework.

LIMITATIONS

- A key limitation arises from spatial scale mismatch, where NDVI (250 m) and soil moisture (~1 km) introduce mixed-pixel effects and aggregation uncertainty, particularly in fragmented agricultural landscapes.
- Surface soil moisture does not represent root-zone water availability, which is the primary driver of vegetation growth, contributing to the observed moderate NDVI–SSM correlation (R = 0.397).
- The assumption that stable soil moisture combined with variable vegetation indicates irrigation is not fully unique, as similar patterns may also result from:
  - shallow groundwater influence
  - soil hydraulic variability
  - localized precipitation events, therefore, irrigation detection remains probabilistic rather than deterministic.
- Validation datasets introduce additional uncertainty, as they represent different conceptual definitions of irrigation (e.g., "equipped area" vs "actively irrigated land"), leading to structural discrepancies rather than pure model error.
- Temporal constraints also affect interpretation, as fixed seasonal windows may not fully capture dynamic irrigation timing, especially in southern Italy where cropping calendars are more flexible and climate-driven.

6. CONCLUSION

- This study presents a scalable framework for detecting irrigation dynamics using long-term satellite observations.
- By integrating vegetation and soil moisture signals, the approach captures active irrigation behavior, moving beyond static representations of irrigated areas.
- The results reveal that irrigation in Italy is:
- Highly structured and spatially organized
- Persistent over time
- Characterized by strong regional contrasts between infrastructure-driven and climate-sensitive systems
- The significant NDVI–soil moisture relationship confirms that, water availability is the dominant control on vegetation dynamics
- While attribution uncertainty remains due to non-unique signals, the integration of LST enables a transition toward process-based irrigation detection, incorporating both water and energy constraints.

7. REFERENCES

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Abbreviations:
NDVI : Normalized Difference Vegetation Index
SSM: Surface Soil Moisture
GIA: Global Irrigation Areas

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ABSTRACT