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SCUOLA DI INGEGNERIA INDUSTRIALE
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Executive Summary of the Thesis

Use of satellite data and a physically-based model for the evaluation of Water Use Efficiency at 30 meters resolution

Laurea Magistrale in Agricultuural Engineering

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1. Introduction

Water Use Efficiency (WUE) is a key indicator for evaluating the coupling between carbon assimilation and water consumption in terrestrial ecosystems, in facts it quantifies the amount of carbon fixed per unit of water lost through evapotranspiration, thus providing an integrated measure of ecosystem functioning at the interface between the carbon and water cycles. From an agronomic perspective, it represents a fundamental metric for the sustainable management of irrigation resources.

Currently available satellite-based WUE products, such as those derived from MODIS, are limited to a maximum spatial resolution of 500 m, which is insufficient to resolve field-scale variability in heterogeneous agricultural landscapes. At such resolution, intra-field variability and soil heterogeneity cannot be adequately resolved, leading to potential aggregation errors and reduced interpretability for farm-scale applications. The objective of this study was to estimate WUE at 30 m spatial resolution by integrating high-resolution satellite observations from Landsat and Sentinel-2 with a physically-based modeling framework, and to assess its reliability across two maize croplands located in contrasting climatic regions: the Heihe River Basin in Northwest China, characterized by an arid climate and intensive irrigation, and the Chiese River Basin in Northern Italy, characterized by a temperate sub-continental regime.

The comparison between the two croplands was performed after validating all the internal variables of the WUE framework using measurements from two eddy covariance towers, which were employed to assess the performance of the main modeling approach adopted in this study.

2. Materials and Methods

WUE is defined in this study as the ratio between net primary production (NPP) and evapotranspiration (ET):

$$\mathrm{WUE} = \frac{\mathrm{NPP}}{\mathrm{ET}}, \tag{1}$$

where NPP is evaluated as:

$$\mathrm{WUE} = \mathrm{NPP} - \mathrm{ET}, \tag{2}$$

with MR representing maintenance respiration evaluated following MOD17 NPP product [1]. The workflow adopted is summarized in Fig. 1, which illustrates the data sources and processing chain leading to the final WUE estimate.

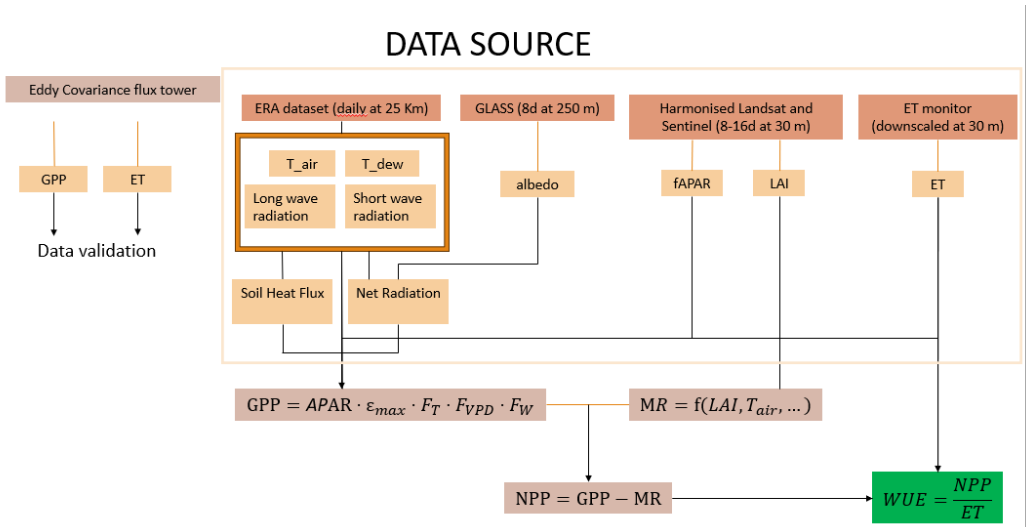

Figure 1: Workflow and data sources.

GPP is estimated using the EF–LUE framework proposed by Jiang et al. [1], which extends traditional light-use efficiency models by introducing the evaporative fraction (EF) as a dynamic water stress indicator:

$$\mathrm{GPP} = \mathrm{APAR} \cdot \varepsilon_{\max} \cdot F_T \cdot F_{\mathrm{VPD}} \cdot F_W \tag{3}$$

where APAR is the absorbed photosynthetically active radiation, $\varepsilon_{\max}$ is the maximum light-use efficiency and was optimized using the climate classification. F_T, F_{VPD} and F_W are scalar constraints ranging between 0 to 1, accounting for temperature, atmospheric water demand, and surface water availability respectively. Specifically, F_T accounts for the metabolic limitations imposed by air temperature on photosynthesis, while F_{VPD} represents the atmospheric water demand. Since these terms are strictly linked to local climatic characteristics, they require the specific optimization framework proposed by Jiang et al. [1].

The F_W factor represents the main innovation of this modeling framework, it is physically derived from the surface energy balance. It is defined through the Evaporative Fraction (EF), calculated as:

$$\mathrm{EF} = \frac{LE}{R_n - G} \tag{4}$$

where LE is the latent heat flux (corresponding to Evapotranspiration), R_n is the net radiation, and G is the soil heat flux. By integrating these energy and water flux components, F_W provides a direct link to actual water availability in the soil-plant system. This allows the model to capture the real-time water status of the vegetation, making the GPP estimation more robust and physically consistent with the hydrological cycle.

ET is provided by the ETMonitor model [2], a physically-based framework that integrates multi-source satellite observations to estimate daily evapotranspiration at 1 km resolution. For the Chinese site, ET was further downscaled to 30 m following the approach of Long and Cui [3], using high-resolution NDVI and spectral information from Harmonized Landsat and Sentinel-2 (HLS) data as spatial predictors, while preserving the large-scale water balance of the 1 km resolution product.

Vegetation indices (NDVI, FVC, LAI, fPAR) and surface reflectance were derived from HLS data at 30 m resolution. Meteorological forcing was obtained from ERA5 reanalysis at 25 km and downscaled using a DEM-based lapse-rate correction. Model outputs were validated against eddy covariance flux tower measurements available at both sites, using a 500 m × 500 m spatial averaging window centered on the tower location as a pragmatic approximation of the flux footprint.

As the tower provided the H_2O and CO_2 fluxes over the cropland, the validation of the two main internal variables were possible. ET is calculated by converting half-hourly latent heat flux measurements into water depth via the latent heat of vaporization, followed by daily integration. GPP was derived by partitioning the tower's measured Net Ecosystem Exchange into photosynthetic uptake and respiratory losses.

3. Results

ET validation at the Heihe site showed strong agreement with flux tower observations, with $R^2 = 0.90$ and RMSE $= 0.58$ mm d^{-1}, confirming the reliability of the downscaled product as model input.

GPP validation before the calibration revealed different levels of model performance between the two sites. At the Chinese site, the EF–LUE framework produced satisfactory results ($R^2 = 0.67$, RMSE $= 5.23$ gC m^{-2} d^{-1}, Bias $= +1.56$ gC m^{-2} d^{-1}), correctly reproducing the seasonal dynamics of ecosystem productivity while showing a systematic overestimation during peak growing season.

At the Italian site, performance was substantially lower ($R^2 = 0.22$, RMSE $= 7.22$ gC m^{-2} d^{-1}, Bias $= -4.76$ gC m^{-2} d^{-1}), with the model unable to reproduce peak productivity values.

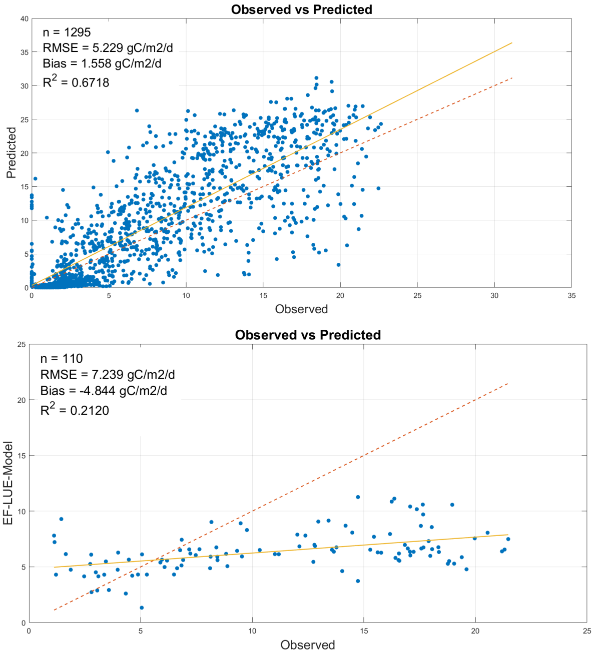

Figure 2: EF-LUE-Model performances before the optimization.
Top: Heihe Basin
Bottom: Chiese Basin

An analysis of the individual stress scalars revealed that the main source of discrepancy was the VPD sensitivity parameter VPD$_0$, whose value assigned by the Köppen–Geiger optimization was too conservative for the Italian site, resulting in an excessive stomatal limitation during high-productivity periods.

A site-specific recalibration of VPD$_0$ was therefore performed empirically for both sites, setting the parameter to 2.2 kPa. After calibration, performance improved substantially at the Italian site ($R^2 = 0.32$, RMSE $= 4.96$ gC m^{-2} d^{-1}), while at the Chinese site the improvement was more moderate ($R^2 = 0.74$, RMSE $= 3.43$ gC m^{-2} d^{-1}), confirming that the baseline parameterization was already well-suited to the arid climate of the Heihe Basin.

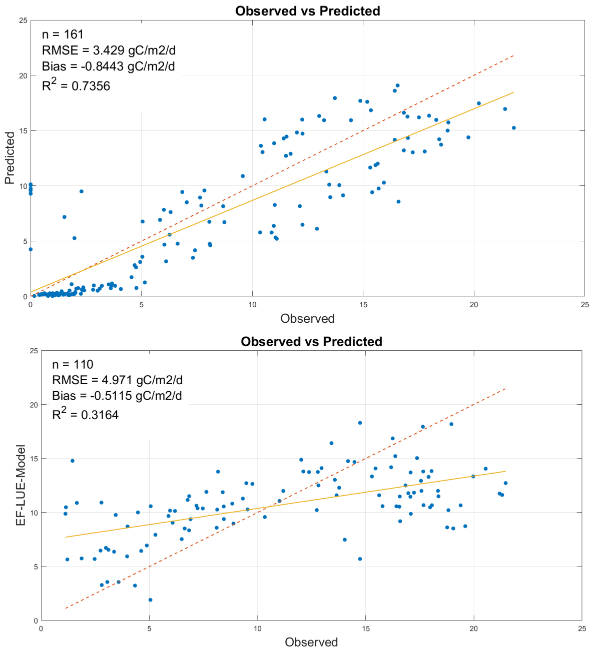

Figure 3: EF-LUE-Model performances after the optimization (2018).
Top: Heihe Basin
Bottom: Chiese Basin

The resulting WUE values, reported in Tables 1 and 2, show a remarkable degree of similarity between the two sites despite their contrasting climatic conditions, with mean annual values ranging between approximately 1.9 and 2.5 gC kg^{-1} H_2O in the Heihe Basin and between 1.9 and 2.1 gC kg^{-1} H_2O in the Calcinato cropland.

Table 1: Mean annual values of WUE, ET and NPP in the Heihe Basin.

Anno	**Annual WUE** (g C/kg H_2O/yr)	**Annual ET** (mm/yr)	**Annual NPP** (gC/m^2/yr)
2014	2.2131	670.8103	1488.8030
2015	2.4683	668.3580	1654.4639
2016	2.3360	661.5786	1552.4089
2017	2.2984	600.1245	1385.0911
2018	1.9236	623.8131	1201.1532
2019	2.2543	678.2376	1530.5099
2020	2.1132	649.9511	1377.7924

Table 2: Mean annual values of WUE, ET and NPP in the Calcinato cropland.

Anno	**Annual WUE** (g C/kg H_2O/yr)	**Annual ET** (mm/yr)	**Annual NPP** (gC/m^2/yr)
2017	2.1050	410.2659	863.2996
2018	1.8799	572.3114	1075.683

Interannual variability in WUE was found to be primarily driven by changes in NPP rather than ET, which remained comparatively stable across years. At the Heihe site, the high spatial resolution of the 30 m ET product allowed the identification of fine-scale heterogeneity in WUE, clearly resolving field boundaries and irrigation patterns. At the Italian site, the absence of a downscaled ET product limited the spatial detail of WUE maps, resulting in a more fragmented and less contrasted spatial distribution.

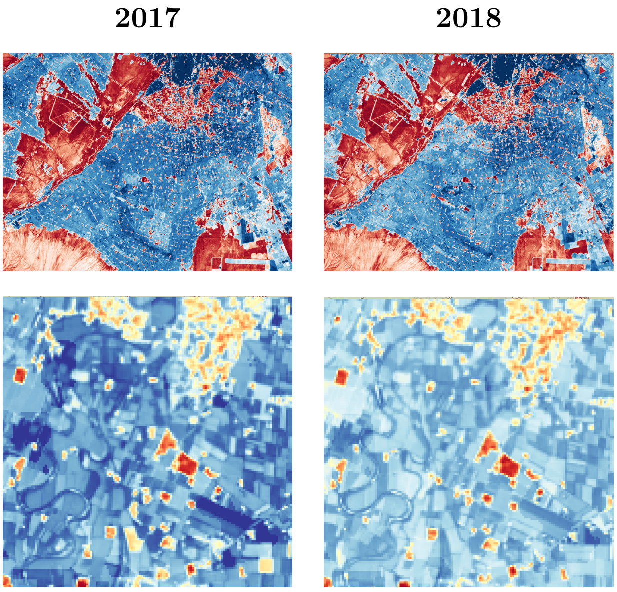

Figure 4: WUE spatial distribution results.
Top: Heihe Basin.
Bottom:Chiese Basin

4. Conclusions

This study demonstrated that WUE can be reliably estimated at 30 m spatial resolution by integrating high-resolution satellite observations with the EF–LUE modeling framework, providing agronomic and environmental insights that are not accessible at coarser resolutions. The results confirmed that the adopted framework performs satisfactorily at both sites after site-specific recalibration of the VPD sensitivity parameter, suggesting that macro-climatic parameterizations based on Köppen–Geiger classification may not be fully transferable to fine spatial scales without local adjustment. The similar WUE values obtained across the two climatically distinct maize croplands support the hypothesis that crop systems regulate carbon assimilation and water consumption in a relatively consistent manner under different environmental conditions, though further investigation across a wider range of sites and crop types would be required to generalize this finding. High-resolution WUE mapping represents a promising operational tool for irrigation management, crop monitoring, and the assessment of agricultural responses to climate variability.

References

[1] M. Jiang, C. Zheng, L. Jia, and J. Chen, “A 20-year dataset (2001–2020) of global cropland water-use efficiency at 1-km grid resolution,” *Scientific Data*, vol. 12, p. 574, Apr. 2025.

[2] C. Zheng, L. Jia, and G. Hu, “Global land surface evapotranspiration monitoring by ETMonitor model driven by multi-source satellite earth observations,” *Journal of Hydrology*, vol. 613, p. 128444, Oct. 2022.

[3] X. Long and Y. Cui, “Spatially Downscaling a Global Evapotranspiration Product for End User Using a Deep Neural Network: A Case Study with the GLEAM Product,” *Remote Sensing*, vol. 14, p. 658, Jan. 2022.