Synergistic Use of VSWIR and TIR Satellite Data for Sugarcane Water Use Efficiency Assessment

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INTRODUCTION

In the context of growing water scarcity, optimizing water-use efficiency (WUE) is essential for sustaining crop yields and safeguarding global food security. Hyperspectral remote sensing offers a powerful tool to address this challenge; for instance, the PRISMA satellite provides continuous spectral data streams, offering a significant accuracy in providing insights into plant parameters. By leveraging PRISMA's high spectral resolution within a time-series framework, accurate early-season estimates of crop yield can be achieved, while evapotranspiration (ET) as retrieved from thermal infrared (TIR) satellite data. However, a critical gap exists in the seamless integration of available ET products across an entire growing season. Products such as WaPOR (www.fao.org) offer high temporal resolution but are limited by coarse spatial resolution (300 m), while moderate-resolution products like Landsat (30 m) lack temporal continuity. This issue is compounded by the diversity of retrieval algorithms (SSEB, TSEB, PT-JPL, STIC) used to generate these products, making data harmonization a significant challenge. This research aims to bridge this gap by harmonizing ET estimates from Landsat, ECOSTRESS, and WaPOR and combining them with high-resolution yield data offered by PRISMA timeseries. The objective of this study is to combine these different data sources to conduct a comprehensive assessment of field level water-use efficiency (express as yield produced per unit of water consumed) for sugarcane cultivation on two study cases: Iran and South Africa.

MATERIAL AND METHODS

One study area is the Sugarcane Research Institute (SASRI) research farm, located in Mount Edgecombe, South Africa (29°42′00″S, 31°03′00″E). While the other are: the Mirza Koochak-Khan (MKK) (30°55′00″N, 48°16′00″E), the Amir Kabir (AK) (31°02′00″N, 48°17′00″E), and the Debal (31°04′00″N, 48°31′00″E) sugarcane farming and industrial lands in Iran. Table 1 reports the PRISMA hyperspectral dataset from 2020–2024 growing seasons in Iran and a 2025 growing season in SASRI has been summarized in a total of 77 images of Iranian sites and 20 images of the SASRI site have been used in this study. The PRISMA-L2D standard products (geocoded spectral reflectance) were processed. Pre-processing included geometrical correction refinement (using the AROSICS algorithm and Sentinel-2 image), bad band removal (46 out of 234) and spectral smoothing (using a Savitzky-Golay filter with a frame size of 7 and a 3rd-degree polynomial). Then, time-series PRISMA imagery was used as input for the CNN-LSTM method to estimate sugarcane yield.

In this research, the ET product of ECOSTRESS, which is calculated from the Priestley-Taylor Jet Propulsion Laboratory (PT-JPL) algorithm, has been used (Table 1).

At the end, the WUE was calculated by integrating yield and ET data using Equation 1.

$$WUE = \frac{Yield\ Estimated\ by\ PRISMA\ Time\ Seris\ Data}{Sum\ of\ \ Growing\ Season\ ET\ Estimated\ by\ ECOSTRESS} \quad (1)$$

RESULT AND DISCUSSION

The results underscore the robustness of the CNN-LSTM method for sugarcane yield estimation using PRISMA hyperspectral time-series imagery. Seasonal model validation revealed strong predictive performance; for example, at the MKK farm, the R^2 values for the 2020 and 2024 seasons reached 0.74 and 0.79, respectively (Figure 1).

Analysis of the relationship between ET and yield revealed a non-linear response. Productivity increased with ET up to an optimal threshold of approximately 450 mm. Beyond this point, additional water application no longer enhanced yield, resulting in diminished WUE. From the analysis of the WUE/Yield data, it has been observed that Variety CP69-1062 (see Figure 2, rightmost graph, yellow bar) achieved the highest WUE among those studied, while from an agronomical management point of view, it can be derived that a six-year rotation cycle incorporating cereals or fallow appears to be an optimal scenario for sustaining higher sugarcane productivity (Figure 2, central plot).

CONCLUSION

The integration of hyperspectral PRISMA and thermal ECOSTRESS data proved effective for assessing water use efficiency in sugarcane farms. While temporal observation frequency offered by the current EO missions is still a severe constraint in the continuous monitoring. These issues can be mitigated by harmonizing existing multi-source products (e.g., Landsat, Sentinel, WaPOR) and leveraging the improved revisit frequencies of future satellite missions. Such advancements will significantly enhance the precision and operational value of WUE assessments.

Table 1. Summary statistics for sugarcane yield data and PRISMA image availability per growing season.

Farm	Season (Year)	EO data		N. Field	Field Data (ton/ha)			
		N. PRISMA	N. ET		Min	Median	Max	std
Debal (IR)	2020	15	26	365	30.8	96.7	155.7	23.5
MKK (IR)	2020	11	26	402	36.3	88.8	116	19.3
	2021	16	31	430	18.8	61.9	128.9	16.4
	2022	12	34	335	19.7	66.1	128.9	15.2
	2023	10	37	400	33.8	83.3	117.9	19.1
	2024	28	32	399	45.3	88	143.1	16.5
AK (IR)	2020	12	26	400	23	74.9	129.8	18.1
	2021	15	31	400	23.4	63.9	123.8	17.9
	2022	12	34	400	19	54.8	112.4	14.6
	2023	10	37	400	32.8	79.1	134.6	18.9
SASRI (SA)	2025	20	N.A.	12	31.8	53.6	93.9	15.4

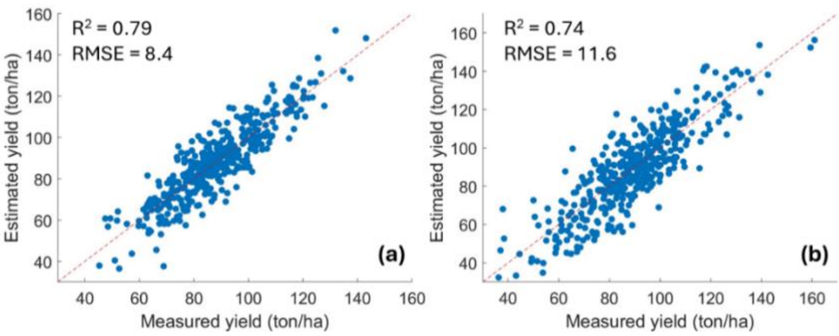

Fig. 1. Scatter plot comparing observed versus model-predicted sugarcane yield for the MKK farm for (a) the 2024 and (b) the 2020 growing seasons.

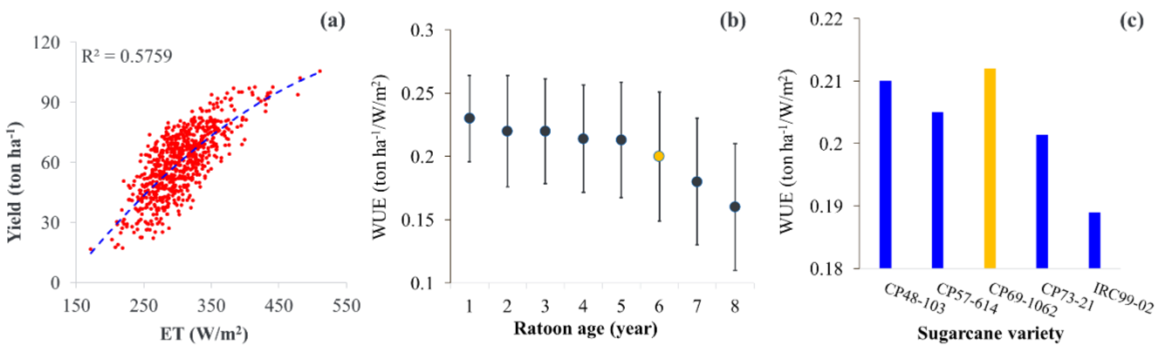

Fig. 2. (a) Relationship between ET and sugarcane yield; (b) optimal ratoon age for maximum WUE prior to rotation (plow); (c) WUE of the evaluated sugarcane varieties.