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Mapping daily evapotranspiration at field scales over rainfed and irrigated agricultural areas using remote sensing data fusion☆,☆☆

C. Cammalleri[a,*], M.C. Anderson[a], F. Gao[a], C.R. Hain[b], W.P. Kustas[a]

[a] *U.S. Department of Agriculture, Agricultural Research Service, Hydrology and Remote Sensing Laboratory, Beltsville, MD, USA*
[b] *Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA*

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ABSTRACT

Continuous monitoring of daily evapotranspiration (ET) at field scale can be achieved by combining thermal infrared remote sensing data information from multiple satellite platforms, given that no single sensor currently exists today with the required spatiotemporal resolution. Here, an integrated approach to field-scale ET mapping is described, combining multi-scale surface energy balance evaluations and a data fusion methodology, namely the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM), to optimally exploit spatiotemporal characteristics of image datasets collected by the Landsat and Moderate resolution Imaging Spectroradiometer (MODIS) sensors, as well as geostationary platforms. Performance of this methodology is evaluated over adjacent irrigated and rainfed fields, since mixed conditions are the most challenging for data fusion procedures, and in two different climatic regions: a semi-arid site in Bushland, TX and a temperate site in Mead, NE. Daytime-total ET estimates obtained for the Landsat overpass dates suggest that the intrinsic model accuracy is consistent across the different test sites (and on the order of 0.5 mm d^{-1}) when contemporaneous Landsat imagery at 30-m resolution is available. Comparisons between tower observations and daily ET datastreams, reconstructed between overpasses by fusing Landsat and MODIS estimates, provide a means for assessing the strengths and limitations of the fused product. At the Mead site, the model performed similarly for both irrigated and rainfed fields, with an accuracy of about 0.9 mm d^{-1}. This similarity in performance is likely due to the relatively large size of the fields (≈50 ha), suggesting that the soil moisture dynamics of the irrigated fields are reasonably well captured at the 1-km MODIS thermal pixel scale. On the other hand, the accuracy of daily retrievals for irrigated fields at the Bushland site was lower than that for the rainfed field (errors of 1.5 and 1.0 mm d^{-1}, respectively), likely due to the inability of the model to capture ET spikes right after irrigation events for fields substantially smaller than MODIS data resolution. At this site, the irrigated fields were small (≈5 ha) compared to the MODIS pixel size, and sparsely distributed over the landscape, so sporadic contributions to ET from soil evaporation due to irrigation were not captured by the 1-km MODIS ET retrievals. However, due the semiarid environment at Bushland, these irrigation-induced spikes in soil evaporation are not long-lived and these underestimations generally affect the irrigation dates only and they do not seem to influence negatively the estimates at the seasonal scale. ET data fusion is expected to perform better over agricultural areas where irrigation is more spatially continuous, resulting in moisture fluxes that are more uniform at the MODIS pixel scale. Overall, the model accurately reproduces the ET temporal dynamics for all the experimental sites, and is able to capture the main differences that were observed between irrigated and rainfed fields at both daily and seasonal time scales.

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* Corresponding author at: European Commission, Joint Research Centre, Institute for Environment and Sustainability, TP280 Via E. Fermi 2749, I-21027 Ispra (VA), Italy. Tel.: +39 (0)332 78 9869.
E-mail addresses: cammillino@gmail.com, carmelo.cammalleri@jrc.ec.europa.eu (C. Cammalleri).

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1. Introduction

Agricultural areas occupy approximately 3,730,000 km^2 (38%) of the total land area in the U.S. (www.agcensus.usda.gov). Of this agricultural land, about 5–7% is routinely irrigated to enhance crop yield and quality (Ozdogan and Gutman, 2008). This small portion generates about 50% of the total amount of agricultural crop income (Schaible and Aillery, 2012). In 2005, 490,000 million m^3 per day of water were used for irrigation, corresponding to 62% of total freshwater withdrawals if thermoelectric power is excluded (http://ga.water.usgs.gov/edu/wuir.html). These statistics highlight the need for accurate monitoring of water use at field scales over large irrigated agricultural areas, such as irrigation districts, to facilitate optimization of water use and allocation among different competing uses.

In the last two decades, major improvements in large-area estimates of actual evapotranspiration (ET) have been obtained through remote sensing methods based on thermal infrared (TIR) data, which have become increasingly available from a variety of satellite systems. The land-surface temperature (LST) derived from these observations plays a key role in the partitioning of available energy between turbulent fluxes of sensible and latent heat, the latter of which describes the land-surface water loss to the atmosphere. As reported in several reviews (e.g., Kalma et al., 2008; Liang et al., 2010), these approaches appear to accurately reproduce ET over a wide range of conditions at both the satellite overpass time and daily time scales. For example, the multi-scale TIR-based ALEXI (Atmosphere-Land EXchange Inverse) model and associated flux disaggregation algorithm, DisALEXI, have been successfully applied across the U.S. (Norman et al., 2003; Anderson et al., 2012a), European Mediterranean regions (Cammalleri et al., 2012), as well as over Africa (Anderson et al., 2012b), using polar orbiting satellites (Landsat series, Moderate resolution Imaging Spectroradiometer – MODIS), geostationary platforms (Geostationary Operational Environmental Satellite – GOES, Meteosat Second Generation – MSG), and airborne datasets.

Despite these significant advances in both remote sensing technologies and environmental modeling, deficiencies in the current suite of thermal satellite data sources (e.g., data gaps, biases, inaccurate calibration, poor spatial or temporal resolution) can strongly limit the applicability of such procedures for continuous monitoring of ET at high spatiotemporal resolution (i.e., daily ET at field scale). The modeling of ET at such detailed temporal and spatial scales requires the ability to capture the principal traits of daily ET, including: (i) long-term (weekly/monthly) trends, primarily dictated by plant growth (changes in leaf area, fraction cover and canopy height) and variation in water availability in the root zone (water stress); (ii) day-to-day fluctuations related to changes in meteorological forcing (i.e., air temperature and humidity, solar radiation); and (iii) sporadic peaks, due to increase in soil evaporation fluxes after rainfall/irrigation events. These ET features are generally observable at different spatial scales: (i) large-scale (several km) dynamics, due to spatial patterns in meteorological forcing; (ii) mid-range (km) patterns, due to changes in water availability caused by rainfall events; and (iii) local (field)-scale variability, due to spatial heterogeneity in crop type and phenological stage as well as localized irrigation applications.

No single TIR satellite system currently operating is capable of capturing all of these features of ET dynamics across agricultural landscapes. Hence, the fusion of multiple data sources (e.g., GOES, MODIS and Landsat) seems a particularly appealing strategy for integrating the best qualities of each dataset within a multi-disciplinary mathematical modeling scheme. Because these different data sources are characterized by a wide range of spectral–temporal–spatial resolution and sensor view angles, a fundamental requirement of the adopted modeling framework must be to ensure consistency among ET estimates obtained from different sources at different scales.

The ET flux fusion methodology applied here is based on daily continental-scale ET estimates obtained from the ALEXI model using hourly thermal data from geostationary satellites at 10-km spatial resolution. Higher spatial resolution ET maps are obtained via the DisALEXI disaggregation procedure using both MODIS (1-km, daily) and Landsat (30-m, 16-day) data. The ET end-product, characterized by both fine spatial resolution and temporal frequency, is obtained by fusing MODIS and Landsat derived ET maps using the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM). The proposed approach aims at ensuring consistency among the ET maps obtained at different spatial resolutions by using the coarse-scale ALEXI estimates as a common normalization basis, while accounting for local-scale features and day-to-day dynamics by combining information from high spatial resolution Landsat and high temporal frequency MODIS imagery.

The performance of this ET data fusion methodology was demonstrated by Cammalleri et al. (2013) over a rainfed agricultural area in central Iowa, effectively capturing impacts on ET of rainfall events occurring between Landsat overpasses. In this paper, we evaluate the ability of this modeling system to correctly account for irrigation effects on ET fluxes. Over large districts of contiguous irrigated fields, the irrigation applications act like a leveling factor, reducing the variability in crop water availability among fields with the same crop species. This generally helps the data fusion process, which requires the presence of homogenous pixels at both high and coarse resolution. More problematic is the modeling of mixed areas, where sparsely distributed irrigated fields are surrounded by rainfed crops (or by natural vegetation). In this case, the availability of representative wet, coarse resolution pixels is more limited, especially when irrigated fields are significantly smaller than the coarse resolution pixel size. The response to irrigation applications may vary significantly between different soil–plant systems, and between climatic regions. In dry environments, soil response to the applied water is faster than under humid conditions; additionally, advective conditions will further increase the magnitude of ET fluxes from irrigated areas. Finally, the method of irrigation also plays a role in the process; while sprinkler systems generally result in large wetted areas (similar in some respects to rainfall), more parsimonious systems (e.g., drip irrigators, not considered here) substantially reduce the wetted area, and hence the soil evaporation losses.

The goal of this work is to evaluate the performance of this ET data fusion approach for two typical U.S. crops, corn and cotton, grown under different climatic conditions and under rainfed and irrigated management. With this aim, the model was applied at two test sites during the growing season (June–September): a dry environment in Bushland (TX) during 2008 and a humid environment in Mead (NE) in 2003. In these experiments both irrigated and rainfed fields were monitored using flux towers, representing two cases of mixed irrigated/unirrigated landscape. The collection of sites corresponds to a wide combination of management practices and meteorological conditions, which lead to large differences in crop water stress and spatial patterns in evaporative fluxes across the landscape. Hence these sites represent a challenging test of the fusion methodology's ability to accurately quantify the effects of irrigation at daily and seasonal scales in agricultural systems.

2. Methods

2.1. The ALEXI/DisALEXI model

Estimates of surface energy fluxes at the time of satellite overpass over heterogeneous agricultural landscapes can be obtained