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Application of the METRIC Model to Estimate Soybean Crop Evapotranspiration

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Abstract

Estimating soybean crop evapotranspiration (ETa) is crucial for effective water management under varying climatic conditions. In this case a suitable and accurate models of crop evapotranspiration estimation with spatial technologies in the cloud are essential for irrigation water management and to enhance water use efficiency. The aim of this study was to estimate soybean crop evapotranspiration using METRIC (Mapping Evapotranspiration at High Resolution with Internalized Calibration) model in the Google Earth Engine platform. Soybean crop was monitored with six Landsat images during its growth period. Soybean ETaestimated using METRIC model was compared with the ETa estimated using FAO-56 approach. ETa estimated using METRIC varied from 2.89 to 4.39 mm with mean value of 3.87 mm and ETa estimated using FAO 56 approach varied from 1.10 to 6.41 mm with mean value of 3.05 mm.METRIC model overestimated seasonal ETa by 21.09% compared to FAO-56 approach. ETa estimated by METRIC model showed moderate agreement with ETa estimated by FAO 56 approach, with IA of 0.61, RMSE of 1.06 mm day^{-1} and NRMSE of 0.30 mm day^{-1}. These results obtained in this study indicated that METRIC modelhas the potential to estimate field scale ETa. However, further validation across the multiple years and locations is needed to assess the broader applicability of the model.

Key words : Evapotranspiration, FAO-56 approach,METRIC, soybean.

Accurate estimation of crop evapotranspiration (ETa) is of great importance for the calculation of irrigation water requirements, water resources management and determination of seasonal water budget in both irrigated and rainfed agriculture. The most common and standard method to estimate crop water requirement and crop evapotranspiration is the FAO-56 approach described by Allen et al., (1998). The main limitation of this approach is a spatial estimation of evapotranspiration and therefore the lack of understanding of field scale spatial variation in evapotranspiration. Other methods to estimate and measure ETa include lysimeters, the Bowen ratio, the eddy covariance (EC), the scintillometer (SC), sap flow and remote sensing (Allen et al., 2011). In this scenario, the use of remote sensing based models are the good alternatives to estimate crop water requirement (Suwanlertcharoen et al., 2023). Several remote sensing-based models and algorithms have been developed and used to estimate ETa. Most of them are based on the surface energy balance. These includes: Two-Source Energy Balance (TSEB) (Kutas and Norman 1996; Norman, Kustas, and Humes 1995), the Atmosphere-Land Exchange Inverse (ALEXI) (Anderson et al. 1997), Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al. 1998, 2005), Simplified Surface Energy Balance Index (S-SEBI) (Roerink, Su, and Menenti 2000), Surface Energy Balance System (SEBS) (Su 2002), the North American Land and Data Assimilation System (NLDAS) (Cosgrove et al. 2003), the disaggregated ALEXI model (DisALEXI) (Norman et al. 2003), and Mapping Evapotranspiration at High Spatial Resolution with Internalized Calibration

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(METRIC) (Allen, Tasumi, and Trezza 2007). METRIC is one of the most popular and widely adopted method, (Foolad et al. 2018). METRIC model estimates the crop water requirement using the residual energy balance equation on surface (Allen et al., 2007). This model has demonstrated adequate performance for ETa estimation in various crops and regions, and it has been validated with results obtained using different measurement instruments such as lysimeters, eddy covariance towers, and atmometers (French et al., 2015; Khan et al., 2019; Lima et al., 2020; Kadam et al., 2021). Processing ET models using remote sensing data requires cloud platforms with high performance computing that give collections of satellite images and climate database, which can be used to monitor fields at different temporal and spatial scales (Laipelt et al., 2021). In this way, there are following free platforms for estimation of ETa viz. SEBAL or Py-SEBAL FAO Water Productivity Open-access portal (WaPOR), METRIC-EEFLux and METRIC GIS Toolbox (Ramirez-Cuesta et al., 2020). There is version of METRIC that runs on Google Earth Engine (GEE) platform (http://eeflux-level1.appspot.com). In this study,METRIC model that runs on GEE platform is used to estimate soybean crop ETa using Landsat images. This study evaluated performance of METRIC model that could be used for operational irrigation scheduling methods. For this evaluation soybean crop cultivated in *Kharif* season of 2023 was used. The aims of this study were (1) to estimate ETa using METRIC model in Google Earth Engine (GEE) with Landsat images for soybean field and (2) to compare the ETa estimates with FAO-56 approach using statistical parameters.

Materials and Methods

Study area : The study was conducted at Climate Smart Research Block developed under the Centre for Advanced Agriculture Science and Technology on Climate Smart Agriculture Water Management, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra (Fig. 1) during *Kharif* season 2023. The geographical location of the study area is 19°19' 19.70" N latitude, 74°39'27.27" E longitude and elevation of 547 m.

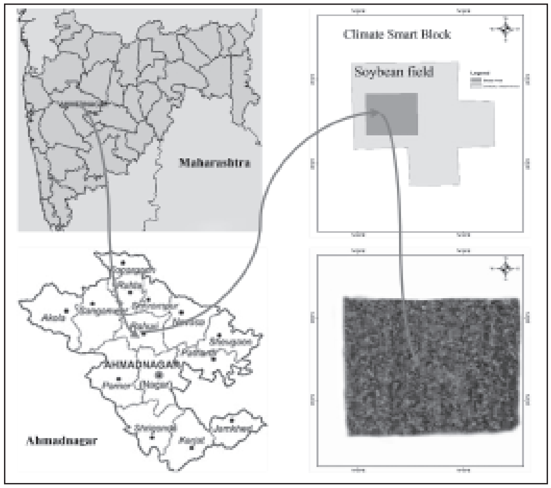

Fig. 1. Location of study area

Weather data : The weather of the region is semi-arid, with annual average rainfall of 540 mm. The rainy season starts in June and Finishes in September. Daily weather data were obtained from India Meteorological Department (IMD) weather station located at AICRP on Irrigation Water Management, MPKV, Rahuri. The data include daily maximum and minimum temperature, maximum and minimum relative humidity, wind speed, sunshine hours, and rainfall. The average weather conditions over the study area during the Soybean crop growing seasons (Kharif) 2023 are presented in Table 1.

Crop details : Soybean is the most commonly cultivated pulse crop during the Kharif season in the study region. The soybean crop was sown on July 10, 2023 and harvested on October 10, 2023 covering 107 days crop cycle. The soil of the study area was clay

Table 1. Average Meteorological data during the crop growth period 2023

Weather parameter	Minimum	Maximum	Average
Tmin, °C	18.7	25.9	23.3
Tmax, °C	24.6	35.0	30.6
RHmin, %	29	92	56.2
RHmax, %	72	98	84.3
Sunshine hours, hrs	0.0	10.3	4.1
Wind speed, m/s	0.7	27.0	10.9
Total rainfall, mm	314.4		

(20.92% sand, 23.08% silt and 56% clay) and bulk density of 1.27 g cm-3. Field capacity (FC) and permanent wilting point (PWP) were determined in laboratory using pressure plate apparatus. The soil moisture content was 39 % at FC and 17% at PWP, respectively. The soybean crop was irrigated using surface irrigation method and irrigations were applied as per the critical growth stages with cumulative crop evapotranspiration.

Remote sensing data : Sixclear-sky Landsat images (three Landsat 9 images for 147/47 path/row and four Landsat 8 images for 147/47 path/row) were available for the study area during the soybean crop growth period. These images were selected based on the acquisition date, temporal coverage and cloud-free conditions and they were processed on the GEE platform.

Estimation of ETa using FAO-56 approach : FAO-56 approach methodology (Allen et al., 1998) was used to estimate crop evapotranspiration (ETa). The crop evapotranspiration is estimated using equation,

ETa = Kc x ETr

Where, ETr is reference crop evapotranspiration (mm/day) and Kc is single crop coefficient that averages crop transpiration and soil evaporation.

The daily crop coefficients for soybean crop were estimated by using the functions developed form the lysimeter data as;

$$Kc = 0.494 + 0.26*(t/T) + 5.862*(t/T)^2 - 8.761*(t/T)^3 + 0.14*(t/T)^4 + 2.647*(t/T)^5$$

Where, t is the day and T is total crop growth period

The reference crop evapotranspiration (ETr) was estimated empirically using the FAO-Penman-Monteith formula (Allen et al., 1998) based on the meteorological data measured in the field during the crop growth period soybean.

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Where, ETr is reference crop evapotranspiration (mm/day); Rn is net radiation at the crop surface (MJ/m2/day); G = soil heat flux density (MJ/m^2/day); T is mean daily air temperature at 2 m height (°C); u^2 is wind speed at 2 m height (m/s); es is saturation vapour pressure (kPa); ea is actual vapour pressure (kPa); es - ea is saturation vapour pressure deficit (kPa); Δ is slope vapour pressure curve (kPa/°C); and γ is psychromatric constant (kPa/°C).

METRIC model : METRIC model is based on satellite image processing to estimate actual evapotranspiration (ETa). In METRIC, ETa is computed as a residual of surface energy balance. ETa is estimated with equation:

$$\lambda ET = Rn - G - H$$

Where; λET is latent heat flux (latent energy consumed by ET, W/m^2); Rn is net radiation (energy available on surface, W/m^2); G is soil heat flux (energy needed to heat the soil, W/m^2); H is sensible heat flux (energy used to heat the air, W/m^2). A detailed description of the theoretical bases and principles is presented by Allen et al. (2007)

1) Net radiation flux (Rn) : Rn was calculated suing the equation given by Morse et. al., (2000);

$$R_n = (1-\alpha) R_S\downarrow + (R_L\downarrow - R_L\uparrow) - (1 - \varepsilon_0) R_L\downarrow$$

Where, Rn is net radiation flux (W/m^2); α is surface albedo unitless; $R_s\downarrow$ is incoming short-wave radiation (W/m^2); $R_L\downarrow$ is incoming longwave radiation (W/m^2); was measured with a pyranometer. $R_L\uparrow$ is outgoing long-wave radiation (W/m2) and ε0surface emissivity (W/m^2).

2) Soil heat flux (G) : Soil heat flux (G) was estimated as a function of Rn, a vegetation index, Rn, Ts, and α using the following equation (Bastiaanssen et. al.,2000);

$$G = [(T_s - 273.15) \times (0.0038 + 0.0074\alpha) \times (1-0.98\ NDVI^4)]\ R_n$$

Where, NDVI is Normalized Difference Vegetation Index calculated by following equation proposed by Rouse et. al (1974)

NDVI=(NIR-RED)/(NIR+RED)

Where, NIR and RED are the reflectances at sensor in near infra-red and red regions respectively.

3) Sensible heat flux (H) : The sensible heat flux (H) proposed by Bastiaanssen et al., 2000 was estimated using equation;

$$H = \rho_a\ Cp_a \frac{dT}{r_{ah}}$$

Where, H is sensible heat flux (W/m^2); ρa is air density (kg/m^3); Cpais specific heat of dry air (1;004 J/kg/K); and dT is temperature gradient (°C)and ($dT = a + bT_s$) and rahis aerodynamic resistance (s/m).

4) Calculation of actual evapotranspiration (ETa) : The first step to calculate ETa is to estimate the instantaneous evapotranspiration (ET_{inst})

$$ET_{inst} = 3600 \frac{\lambda ET}{\lambda}$$

Where, ETinst is the instantaneous evapotranspiration (mm/hr); λET is the value of the latent heat of vaporization due to evapotranspiration and λ is latent heat of vaporization (J/kg) and calculated as

$$\lambda = \left[2.501 - \left(0.00236(T_s - 273.15)\right)\right](10^6)$$

Finally actual daily evapotranspiration (ETa) was calculated using following equation;

$$ETa = ETrF * ETr_{24}$$

Where, ETa is the actual daily evapotranspiration (mm/day); ETr_{24} is cumulative 24-h ETr for the day (mm/d) and ETrF is reference evapotranspiration fraction (W/m^2) and it is calculated as;

$$ETrF = \frac{ET_{inst}}{ETr}$$

Where, ETr is reference evapotranspiration at the time of image acquisition (mm/hr)

Statistical Parameters : The actual crop evapotranspiration estimated by using different methods will be compared with ETa calculated with FAO-56 approach (FAO-56-ETa). Using thefollowing statistical parameters;

a) The root mean square error (RMSE) calculated as;

$$RMSE = \frac{\sum_{i=1}^{N}(Oi - Pi)^2}{n}$$

where n is the number of ET values, Oi is the FAO-56 ETa values, and Pi is the estimated ETa value.

b) The normalized root mean square error (NRMSE) calculated as;

$$NRMSE = \frac{RMSE}{\bar{O}}$$

Where O is the average FAO56-ETa value.

The lower limit of RMSE and NRMSE is 0, indicating perfect agreement between estimated and measured values.

c) The Willmott (1982) index of agreement (IA) (Willmott, 1982) calculated as;

$$IA = 1 - \frac{\sum_{i=1}^{n}(Oi - Pi)^2}{\sum_{i=1}^{n}(|Pi - \bar{O}| + |Oi - \bar{O}|)^2}$$

The index of agreement ranges between 0 and 1, where a value of 1 indicates perfect agreement and 0 indicates no agreement at all.

Results and Discussions

Reference evapotranspiration (ETr) : ETr was estimated using the FAO-56 Penman-Monteith Method with weather data from the Indian Meteorology Department located at AICRP on Irrigation Water Management, Mahatma Phule Krishi Vidyapeeth, Rahuri during the 2023 Soybean growing season. The daily variation of reference evapotranspiration (ETr) during the soybean crop growth period is presented Fig. 2. The descriptive statistics of daily ETr showed that ETr varied from 1.73 mm to 6.31 mm with a mean value of 3.5 ± 0.10 mm over the Soybean crop growth period. The seasonal ETr was 374.32 mm. Daily ETr values showed moderate variation during the soybean crop growth period with a SD of 1.08 and a CV of 30.85 %.

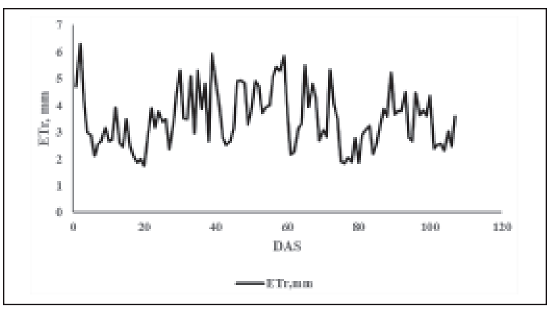

Fig. 2. Daily values of reference evapotranspiration during soybean growing season

Estimation of ETa by METRIC Model : Actual Evapotranspiration were estimated by processing the Six-satellite image using the METRIC model. ETa estimated using this approach is termed as METRIC-ETa. The daily METRIC-ETa values were generated using the cubic spline interpolation technique. The daily variation of METRIC-ETa estimated during the soybean crop growth period are presented Fig. 3. The descriptive statistics of daily METRIC-ETa showed that ETa varied from 2.89 to 4.39 with a mean value of 3.87 ± 0.04 mm over the Soybean crop growth period. The seasonal METRIC-ETa was 413.90 mm. Daily METRIC-ETa values showed low variation during the soybean crop growth period with a SD of 0.41 and a CV of 10.59%.

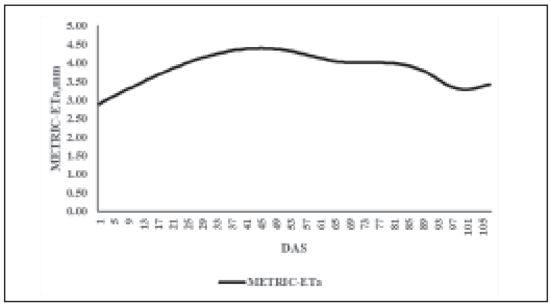

Fig. 3. Daily ETa estimated using METRIC model

Estimation of ETa by FAO-56 approach : The daily values of ETa were estimated using the FAO-56 approach as the product of reference evapotranspiration and crop coefficient. ETa estimated using this approach is termed as FAO56-ETa.The daily variation of FAO56-ETa during the soybean crop growth period is presented Fig. 4. The descriptive statistics of daily FAO56-ETa showed that ETa varied from 1.10 to 6.41 with a mean value of 3.05 ± 0.13 mm over the Soybean crop growth period. The seasonal FAO56-ETa was 326.58 mm. Daily FAO56-ETa values showed high variation during the soybean crop growth period with a SD of 1.3 and a CV of 42.62 %.

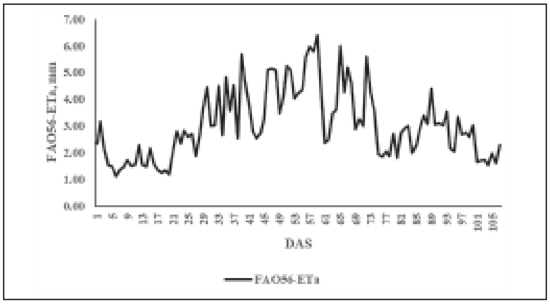

Fig. 4. Daily ETa estimated using FAO-56 approach

Comparison of ETa : The comparison of ETa was done for the Landsat image acquisition dates during soybean crop growth period. The results showed that METRIC model tends to overestimate soybean crop ETa when compared with the FAO-56 approach. The estimated ETa values are presented in the Table 2 with the satellite image acquisition dates.

The estimated ETa using METRIC were compared with FAO56-ETa based on Index of Agreement (IA), Root Mean Square Error (RMSE), and Normalised Root Mean Square Error (NRMSE). The METRIC model overestimated seasonal ETa by 21.09 % as compared with ETa estimated by FAO-56 approach. Similar overpredictions can be seen from figures presented in published METRIC evaluations (Singh et. al, 2011 and Singh et. al., 2016), but the cause of this problem has not been addressed. METRIC model showed moderate correlation between the estimated ETa and the FAO56-ETa with IA of 0.61, RMSE of 1.06 mm/day and NRMSE of 0.30 mm/day.Allen et al. (2007) reported departures between lysimeter and METRIC ET for a sugar crop at Kimberly, ID, USA for 8 days of available images ranging from −26% to 34%. Khan et al. (2019) reported standard errors (SSE; similar to RMSE) of METRIC ET estimations of 0.34 mm/day for satellite overpass. This indicated that the results obtained are similar as reported by earlier researchers.

Table 2. ETa estimated by METRIC model and FAO-56 approach on the satellite image acquisition dates

Date	DAS	METRIC-ETa (mm)	FAO-56-ETa (mm)	Satellite
28-08-2023	50	4.36	4.07	L9
05-09-2023	58	4.20	5.80	L8
13-09-2023	66	4.03	4.27	L9
07-10-2023	90	3.73	3.04	L8
15-10-2023	98	3.31	2.75	L9
23-10-2023	106	3.39	1.59	L8

Conclusion

The results obtained during the study conducted to estimate soybean crop evapotranspiration using METRIC model FAO-56 approach showed a 21.09% overestimation by METRIC model compared to the FAO-56 approach. Additionally, the study revealed a moderate correlation between the estimated METRIC-ETa and the FAO56-ETa with IA of 0.61, RMSE of 1.06 mm/day and NRMSE of 0.30 mm/day.These findings support the potential use of METRIC model for estimating Soybean ETa. However, further assessments across multiple years and locations are necessary to determine its broader suitability for regional ETa estimation.

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