Journal of Agrometeorology 13 (2): 110-115 (Dec 2011)

Comparison of satellite derived water and radiation use efficiency based wheat yield models over semi-arid regions

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ABSTRACT

Water use efficiency (WUE) and radiation use efficiency (RUE) based approaches were attempted to predict wheat yield of major wheat growing districts over semi-arid agro ecosystem of Gujarat. RUE approach through CASA (Carnegie-Ames-Stanford) model was found to produce better yield prediction accuracy (RMSE 17.7 % of reported mean) as compared to the RMSE (18 % of reported mean) from WUE approach. Moreover, the correlation coefficient between predicted and reported district yield was also found to be higher (r = 0.90) in RUE based approach than the other one (r = 0.80). District mean WUE were computed for three growth stages viz. vegetative, flowering and grain filling of wheat using MODIS AQUA derived evapotranspiration (ET) values. It was found that the WUE were generally higher in vegetative and flowering stages as compared to grain filling. The wheat yield prediction from water use and stage specific WUE were carried out for same seasons. The better correlation found from 0.57 to 0.77 at flowering stage.

Key words: Yield prediction, ET, MODIS, WUE, RUE

In India, wheat is the second highest staple food grain after rice with average net sown area of 28.4 million hectare spread over sub-humid, semi-arid and arid climates grown mainly with irrigated conditions, excluding certain pockets having rainfed farming. There is a wide variability in wheat grain yield. The vulnerability of wheat grain yield is more in semi-arid and arid climate driven by timeliness of irrigation water availability as well as anomalies in ambient temperature at critical growth stages.

Early prediction of crop yield is important for planning and taking various policy decisions. Many countries use the conventional techniques of data collection for crop monitoring and yield estimation based on ground – based visits and reports. Now satellite derived data using NOAA AVHRR imagery is being used to monitor vegetation changes that are used indirectly to assess crop condition and yields.

Different methods have been developed to estimate crop yields using of satellite data (Dadhwal and Sridhar, 1997); among them water use efficiency (WUE) and radiation use efficiency (RUE) are commonly used. Light use efficiency (LUE) based models are less complex and easily amenable to remotely sensed data, which has made them widely acceptable to map primary production of the terrestrial biosphere (Ruimy *et al.* 1996; Goetz *et al*. 1999; Potter et al. 2003) over large areas. Satellite data-driven LUE models such as C-Fix (Veroustraete 1994), CASA (Field *et al*. 1995), GLO-PEM (Prince and Goward 1995), SDBM (Knorr and Heimann 1995), TURC (Ruimy *et al.* 1996), and MODIS NPP algorithm (Running *et al.* 2004) have been developed and tested to analyze spatio-temporal pattern of NPP over continents or global land surface (Sabbe *et al.* 1999; Potter *et al.* 2003; Zhao *et al.* 2005).

Manjunath *et al* (2002) found better multiple regression (r = 0.9) between 20-day NOAA AVHRR district mean wheat NDVI and reported yield in Rajasthan. Bhattacharya *et al* (2007) found that errors from single source, AET/ET estimates increase as the surface heterogeneity increases. Therefore, accuracy of yield prediction from single source ET estimates diminishes from homogenous wheat growth conditions (e.g. Punjab) to heterogeneous conditions (e.g. Rajasthan, M. P.). A two source formulation (Anderson *et al*., 2000) from satellite data captures both homogenous and heterogeneous conditions because it considers separate couplings of soil and canopy with atmosphere. The comparison of two-source and single source ET estimates showed better ET estimates from two source scheme (Timmermans *et al.*, 2007). The use of two source ET formulation and generation of district WUE from multiple years may predict regional wheat yield better than the present accuracy in semi-arid heterogeneous conditions in Gujarat.

Accuracies from present model are comparable to accuracies of district yield obtained through LAI forcing to WTGROWS crop simulation model to simulate district wheat yield of Haryana state (Sehgal *et al.*, 2002). Real time yield forecast assessment for wheat (Nain *et al.,* 2003), district- level forecast for Nainital (Nain *et al.,* 2000) and state level wheat yield for Uttar Pradesh (Nain *et al.,* 2002) have been demonstrated using multi-crop simulation framework available in DSSAT (Nain *et al.,* 2003). The full season is required to simulate crop yield. Moreover, its spatial implementation requires lot of soil, weather variables as well as cultivar specific genetic coefficient to be generated on spatial scale or zone wise.

MATERIALS AND METHODS

Study area and data used

The study region represents a semi-arid agricultural ecosystem in the Gujarat State of western India. Twelve districts spread over north and middle Gujarat and Saurashtra regions were selected for the study by setting the criterion that more than 50% *rabi* crop area is under wheat cultivation. The dominant soil types in these areas are black, grey and brown, and old alluvial representing inceptisols and aridisols order of soils. Among them, a 5 km X 5 km continuous wheat growing patch in the Kheda district (middle Gujarat agro-climatic zone) was demarcated for in situ measurements.

MODIS AQUA eight-day 250 m surface reflectance data (MYD09Q1) in the red and near infrared (NIR) bands were acquired from November to March for three consecutive *rabi* growing seasons (2002- 03, 2003-04 and 2004-05), to generate wheat crop mask over the study region. Tiles of MODIS AQUA eight-day LST V004 product MYD11A2) at 1 km spatial resolution and seven band surface reflectance product (MYD09A1) at 500 m spatial resolution covering Gujarat state were acquired through EOS (Earth Observing Systems) data gateway (http://lpdaac.usgs.gov).

Water use efficiency (WUE) based approach

MODIS AQUA derived eight-day ET were accumulated for the wheat growth period between emergence to physiological maturity

$$Yield = WUE \sum_{i=1}^{n} ET_i \qquad (1)$$

The district average water use efficiency (WUE) of wheat for the effective growth period was computed for year 2003-04.

The district wise WUE was derived from (2002-03, 2003-04 and 2004-05) district average yield and seasonal accumulated AET. Wheat mask was generated for all major wheat growing districts of Gujarat using MODIS AQUA 250 meter eight day composite, so only wheat pixels could be extracted for AET accumulation. The eight day AET composite was derived from MODIS-AQUA at 1km. The derived district wise WUE was used to predict districtwise crop yield at the end of crop season.

In order to predict crop yield well in advance and before physiological maturity, accumulation period needed to be varied district wise. It was reduced octad by octad from physiological maturity in each step and then WUE was computed for each step using historical grain yield and accumulated AET (Dakhore *et al.,* 2008). These methods were repeated till 50% of length of growing period was reached. Moreover, crop stagewise WUE was also computed and further used to predict final yield.

Average WUE of wheat over different agro-climatic zones were computed in advance from the reported district yield averaged over an agro-climatic zone and MODIS derived CWU during 2003-04.

Radiation use efficiency (RUE) based approach

The RUE approach (Monteith 1977) implemented within the CASA model represents that NPP is directly proportional to product of absorbed photosynthetically active radiation (APAR) and maximum light use efficiency term (ε*) which is adjusted for spatio-temporally varying stress scalars such as temperature and moisture. The crop yield was derived by product of total net primary productivity (NPP) accumulated during whole crop growth and harvest index (HI) which was taken as 0.24 for wheat crop ((Lunagaria, 2004).

$$YIELD = \sum_{i}^{n} NPP_i \ X \ H \qquad (2)$$

The NPP was estimated on spatial (x) (1km) and temporal (t) (8 day) domain by using LAI derived fAPAR (fraction of photosynthetically active radiation) and maximum radiation use efficiency (RUE) of crop. The maximum RUE was constrained by using temperature scalars and water scalar following CASA (Carinege Ames Stanford Approach) approach.

$$NPP = S(x,t)\ fAPAR(x,t)\ RUE\max T_1(x,t)\ T_2(x,t)\ W(x,t) \qquad (3)$$

Here $S(x,t)$ is solar insolation (MJ m^{-1}), determined by applying eight-day average atmospheric transmittance (ta) which was computed from the measured insolation from AWS during 2005-06. $fAPAR(x,t)$ is fraction of photosynthetically active radiation absorbed by crop, RUEmax is maximum radiation use efficiency, $T_2(x,t)$ and $T_1(x,t)$ are temperature scalars and $W(x,t)$ is water scalar.

APAR was calculated at each time step as the product

Table 1: Stage wise WUE over different districts during 2003-04

District	WUE ($kg\ ha^{-1}$ -mm)		
	Vegetative	Flowering	Grain filling
Ahmedabad	18.95	16.46	8.05
Amreli	79.93	50.36	39.17
Anand	23.80	19.45	24.13
Dahod	42.36	45.75	18.03
Gandhinagar	40.96	37.37	17.38
Jamnagar	64.97	38.99	28.46
Junagadh	74.56	51.80	36.93
Kheda	25.00	34.70	13.49
Mehsana	75.98	84.37	38.30
Rajkot	62.76	42.89	38.38
Sabarkantha	37.74	39.88	16.36
Vadodara	42.02	40.23	23.11

Table 2: Error statistics of WUE based district yield prediction using different accumulation period for seasonal water use

Accumulation period	*rabi* 2002-03			*rabi* 2004-05		
	MAE	RMSE	r	MAE	RMSE	r
G	12	14	0.63	17	21	0.81
G-1	12	14	0.61	16	21	0.80
G-2	14	17	0.46	15	19	0.80
G-3	19	23	0.25	13	18	0.73

Table 3: Error statistics of district wheat yield prediction from WUE based approach using stage wise water use

Stage wise accumulation	*rabi* 2002-03			*rabi* 2004-05		
	MAE	RMSE	r	MAE	RMSE	r
Vegetative	22	27	0.16	14	21	0.75
Flowering	15	18	0.57	29	34	0.77
Grain filling	28	39	0.66	28	42	0.31

of PAR and fAPAR, PAR was calculated as 45 % of the daily total solar surface irradiance. Temperature scalars in this approach were used to capture two aspects of physiological regulation of the plant growth by temperature. One of the scalars $T_1(x,t)$ sets limits on acclimation, reflecting the evidence that inherent biochemical constraint on photosynthesis act to reduce NPP at both very low and high temperatures (Field *et al.*, 1995).

$$T_1(x,t) = 0.8 + 0.02 * T_{opt}(x) - 0.0005 * [T_{opt}(x)]^2 \quad (4)$$

The second $T_2(x,t)$ scalar expressed the hypothesis that, at every site, growth acclimated to the temperature during the month of greatest NDVI and NPP was suppressed by temperature warmer or cooler than that during the month of maximum NDVI.

$$T_2(x,t) = \frac{1}{\{1+\exp[0.2(T_{opt}(x) - 10 - T(x,t))]\}} * \frac{1}{\{1+\exp[0.3(-T_{opt}(x) - 10 + T(x,t))]\}} \quad (5)$$

Where, T is the mean temperature and T_{opt} the optimum temperature during the month of maximum NDVI. The month of maximum wheat NDVI in this study region corresponds to January.

The water scalar was calculated as evaporative fraction (Λins) i.e. the ratio of λE and Q (approximated to sum of latent and sensible heat fluxes), was used as substitute for water limiting factor.

$$W = \Lambda ins \quad (6)$$

The Λins was estimated using LST - albedo two dimensional scatter based on warm-wet edge concept given by Roerink *et al.* (2000) separating both energy limiting and water limiting conditions. This was further used by Mallick et al. (2009) over diverse Indian agroecosystems. The instantaneous (Q_{ins}) available energy at satellite overpass time

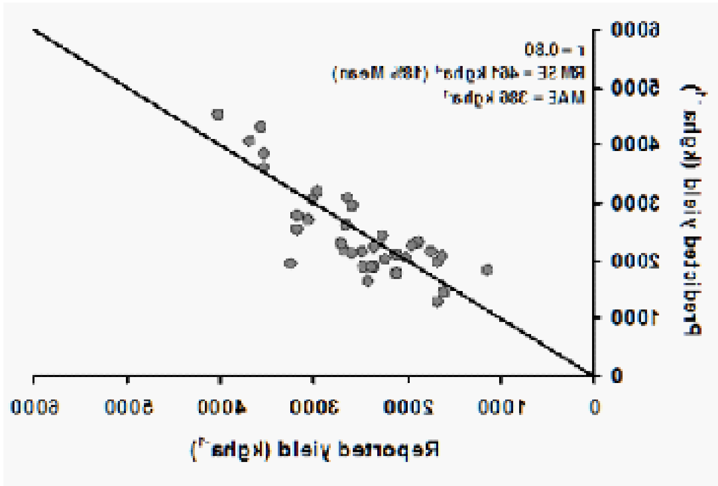

Fig. 1: Predicted and reported district yield using WUE approach

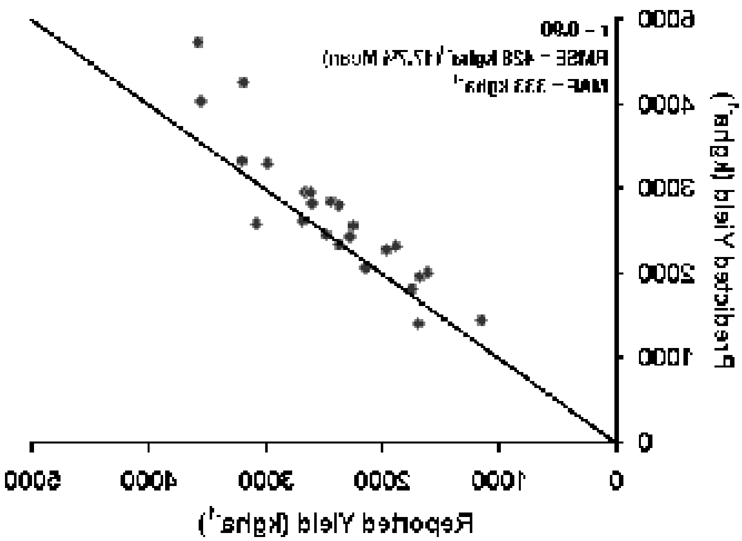

Fig. 2: Predicted and reported district yield of wheat using RUE approach

was estimated from clear-sky insolation, surface albedo from channel reflectances, NDVI and air temperature (Mallick *et al.*, 2009).

T_1 and T_2 scalars were derived by calibrating MODIS AQUA day-night land surface temperature (LST) mean with ground based daily observed mean air temperature of 13 different agromet surface observatory over Gujarat.

RESULTS AND DISCUSSION

Calibration of seasonal consumptive water use(CWU)

Seasonal consumptive water use (CWU) was estimated by summing MODIS Aqua 8-day AETi (×8) over different octads (assuming same evapotranspiration rate for a given 8-day period) between spectral emergence to physiological maturity for three successive *rabi* seasons. The district mean WUE was also computed for 2002-03 and 2003-04 using reducing accumulation period for water use by one octad from effective growth period (G). These accumulation periods are G-1, G-2, and G-3. These were carried out to investigate the capability of this technique to forecast district yield at least one month before the crop attained maturity.

District mean WUE were also computed for three critical wheat growth stages, vegetative, flowering and grain filling using the ratio of reported yield and stage specific water use in 2003-04. WUE were generally higher in vegetative and flowering stages as compared to grain filling. It varied between 19.95 – 74.56 kgha-mm^{-1}, 16.46-84.37 kg ha-mm^{-1} and 8.05-39.17 kgha-mm^{-1}, in vegetative, flowering and grain filling, respectively (Table 1). Atmospheric thermal regime in Gujarat is generally higher than intensive wheat growing regions such as Punjab, Haryana, and Rajasthan especially during the conversion of photosynthates. This could possibly lead to less realization of yield from consumptive water use.

Validation of WUE based yield prediction

The district mean WUE and AQUA based seasonal water use for preceding (2002-03) and succeeding (2004-05) years were used to predict district wheat yield. The correlation between reported and predicted yield was 0.80 (Fig.1) with RMSE 461 kg ha^{-1} (18% of mean).

Error statistics of district wheat yield prediction from WUE approach

Little lower correlation and relatively higher percent RMSE were obtained for predicted wheat yield with reducing accumulation periods (G-1, G-2 and G-3). The correlation varied from 0.25 to 0.80 (Table 2) and RMSE were found to vary between 14 – 21 % of reported mean.

The wheat yield prediction from water use and stage specific WUE were carried out for same seasons. The error statistics are given in Table 3. A consistent better correlation (0.57 to 0.77) was found in both the seasons for prediction from flowering stage water use and WUE as compared to other two critical stages. The RMSE ranged between 18-34% of observed mean for prediction from this stage.

Validation of RUE based yield prediction

Net primary productivity (NPP) of wheat was estimated using CASA model for 2002-03 and 2004-05. The actual wheat yield was obtained from NPP and average wheat harvest index (0.24) in the region. The district average CASA estimated wheat, yield were found to produce RMSE of the order of 428 kg ha^{-1} (17.7 % of reported mean) with correlation coefficient (r) of 0.90 for data pooled over 2002-03 and 2004-05. The 1:1 validation plot is shown in Fig. 2.

Comparison of regional wheat yield distribution from both approaches

The present yield prediction approaches showed relatively better district yield estimates with accuracies more than conventional spectral yield models using single multi-date NDVI (Quarmy *et al.*, 1993) or vegetation condition index (VCI) (Hayes and Decker, 1996) with coarser resolution RS data. These statistical models could explain only upto 55% yield variability. Recently combination of land surface temperature (LST), NDVI and soil moisture from coarser resolution data (e" 8 km) were used to develop statistical models to predict IOWA state wheat and soyabean yield (Prasad *et al.*, 2006). These yielded to little higher prediction accuracy than VI based models.

CONCLUSION

Present approaches estimate surface as well as process variables to predict yield without any dependence on ancillary ground based inputs. Therefore these are easy to implement for real time yield assessment. The one more advantage of these approaches is estimating intra district variability in the yield. The NPP based approach is more robust especially for wheat season because it incorporates effect of both water and temperature scalars. But the WUE based approach considers only water stress.

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Received: October 2010; Accepted: August 2011