DOI : <http://doi.org/10.22438/jeb/41/2/MRN-1200>

JEBTM p-ISSN: 0254-8704
e-ISSN: 2394-0379
CODEN: JEBIDP

Development of non-stress baseline of crop water stress index for wheat in humid sub-tropical climate in India

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Paper received: 06.06.2019

Revised received: 26.10.2019

Accepted: 27.11.2019

Abstract

Aim : A study was conducted to develop a new approach of non-stress baseline and evaluate different approach of determining non stress baseline for Crop Water Stress Index (CWSI).

Methodology : To observe maximum and minimum canopy temperature, two plots with three replications were maintained at fully stress (no irrigation) and no stress (fully irrigated) conditions, respectively. Portable weather station with data logger was installed at the middle of field to record continuous data at half an hour interval. Gypsum block soil moisture sensor were buried at 20 cm interval up to 100 cm and connected with data logger. Infrared radiometer was used to measure canopy temperature.

Results : The evaluation was based on five statistical indicators; correlation coefficient (R^2), root mean square error (RMSE), mean absolute error (MAE), mean bias error (MBE) and Wilmot index of agreement (d). It was found that new regression base line performed better than other existing approaches. The calculated value of RMSE, MAE, MBE, d and R^2 were 0.65, 0.51, 0.02, 0.79 and 0.83, respectively, for new baseline approach.

Interpretation : The newly developed multiple regression equation (incorporating three weather parameters (R_n , VPD and u) and two crop growth parameters (h and CC)) helped to reduce error in the calculation of non-stress baseline for wheat crop in humid subtropical climate.

Key words: Canopy temperature, Crop water stress index, Non-stress baseline, Wheat

How to cite : Pramanik, M., R. Ranjan, N.K. Garg, S.K. Tripathi and R. Singh: Development of non-stress baseline of crop water stress index for wheat in humid sub-tropical climate in India. *J. Environ. Biol.*, **41**, 234-239 (2020).

Introduction

Crop water stress index (CWSI) quantifies crop water stress relative to fully and non-stressed plants. The index is based on the canopy surface temperature measured with infrared thermometers or other remote infrared sensors. The canopy temperature increases from ambient temperature as water is limiting for evapo-transpiration. This phenomenon was used to quantify water stress in crops. Calculation of CWSI is based on lower and upper baseline which represents a non-water stress crop and fully water stress crop, respectively. The two popular definition of lower baseline was given by Idso *et al.* (1981) and Jackson *et al.* (1981, 1988). Jackson *et al.* (1981) presented a theory behind the energy balance that separates sun's net radiation into sensible heat that heats the air and latent heat used for transpiration and soil heat flux. Transpiration cools the surface of canopy than surrounding air temperature. Under water stress condition, transpiration decreases due to reduction in stomatal opening which leads to increase in canopy temperature. Change in canopy temperature is function of soil moisture, meteorological parameter and plant physiology. Thus, Jackson's approach considers all metrological and plant physiological parameters, while Idso *et al.* (1981) established that non stress baseline has a linear relationship with vapour pressure deficit under full sunshine hour in noon period.

Less number of input requirement in Idso's empirical model as compared to Jackson's theoretical model has made it more popular among users. The limitation of empirical model is that the temporal and spatial variability of baseline for even same crop. Thus, these limitations call for a new approach which can overcome the limitations of earlier approaches. CWSI has been successfully used for monitoring water stress as for irrigation scheduling tool in various crops (DeJonge *et al.*, 2015; Gontia and Tiwari, 2008; Han *et al.*, 2018), vegetatble (Tupe and Bote, 2008), grass (Bijanazadeh *et al.*, 2013) and tree (Osroosh *et al.*, 2016) under arid and semi-arid condition. But, vapour pressure deficit (VPD) variation remains narrow in humid subtropical climate as compared to arid and semi-arid climate. This leads to a large error in CWSI calculation, especially non-stress baseline due to small error in temperature measurement.

Two different methods have been used to develop non-stress baselines: (a) empirical and (b) theoretical approach. The empirical approach has advantage of less input data requirement than theoretical approach. The major drawback of empirical method is that non-stress baseline is location, crop and growth stage specific. In the empirical approach, all other parameters (climatic and plant growth) are taken as constant, except VPD, however, wind speed, solar radiation, relative humidity, plant height and leaf area index do change practically over the period and location. Different baselines for same crop from different regions have been documented (Idso *et al.*, 1981; Irmak *et al.*, 2000). Theoretical approach (Jackson *et al.*, 1981) needs a greater number of input data including aerodynamic and canopy resistance which are difficult to obtain.

Payero and Irmak (2006) developed a multiple linear regression equation non-stress baseline to overcome this constraint of empirical and theoretical approaches for corn and soybean. Multiple regression of non-stress baseline is the function of plant height, VPD, wind speed and solar radiation. But, still the changes in canopy architecture and canopy cover does not take into consideration important factors at different growth stages. Considering that only plant height did not sufficiently represent the energy transfer from the canopy. Keeping in view the above, the objective of the present study was to develop and evaluate a new non-stress baseline for wheat in humid subtropical climate.

Materials and Methods

Experimental details: A field experiment was conducted at the research farm of Indian Institute of Technology, Roorkee, India on wheat (*Triticum aestivum* L.) variety PBW-292 during two consecutive growing seasons of Rabi (December to April) 2008-09 and 2009-10. The soils at experimental site was well drained and classified as sandy loam having field capacity of $0.230 \text{ m}^3 \text{ m}^{-3}$, permanent wilting point of $0.073 \text{ m}^3 \text{ m}^{-3}$ with moderate fertility and no salinity. The site comes under humid subtropical climatic zone and receives an average annual rainfall of about 1200 mm. Summer is hot and dry with maximum temperature $43\text{--}44^\circ\text{C}$ during May-June whereas winter is mostly dry with feeble winds and minimum temperature often goes close to freezing point during December-January.

Wheat was sown in first week of December and harvested during first week of April during both the seasons. Standard package of practices was adopted for growing wheat crop. Plant stress index $[\text{PSI} = (T_c - T_{\text{cmin}}) / (T_{\text{cmax}} - T_{\text{cmin}})]$ where, T_{cmin} , T_{cmax} and T_c are the minimum, maximum and observed canopy temperature, respectively (Pramanik *et al.*, 2017)] based five irrigation treatments were used to initiate irrigation. In treatments T_1 (full irrigation), T_2 , T_3 , T_4 and T_5 , irrigation was applied when the PSI value reached to 0, 0.25, 0.50, 0.75 and 1.0 (non-irrigation), respectively. The measured quantity of irrigation was applied in respective treatments after calculating the soil moisture depletion up to 100 cm soil depth. In addition to this, a life-saving irrigation of 50 mm was applied to all treatments at crown root initiation stage (23 days after sowing, DAS), irrespective of treatment. Five treatments with three replications were carried out in a randomized block design in plot size of $2.0 \times 1.5 \text{ m}$.

Measurements: The meteorological data viz. net solar radiation (Wm^{-2}), air temperature ($^\circ\text{C}$), relative humidity (%), wind speed (ms^{-1}) and rainfall (mm) were recorded concurrently at every half an hour interval through automatic weather station installed near the experimental field. Canopy temperature (T_c) was recorded using infrared radiometers (Apogee model SI-111, Apogee Instruments Inc., Logan, UT, USA) having 22° half angle field of view (FOV). The recording of infrared temperature was started after 40 DAS when the plant canopy cover reached approximately 75-80% and thereafter, crop water stress treatments started.

Each plot had one infrared radiometer placed at a portable stand with adjustable height. The canopy temperature was recorded at 0.50 m above from the crop canopy with oblique measurements at 30–45° from the horizon to minimize soil background in FOV.

Since, the maximum root zone depth for wheat crop was considered to be 100 cm, gypsum block moisture sensors (200SS Watermark, Irrrometer Company, Riverside CA, USA) were installed at 20 cm interval up to 100 cm soil depth for recording soil moisture at every half hour time interval in all experimental plots. Gypsum block moisture sensors measured the soil moisture resistance which was converted to soil water potential (centibar) using standard equation developed through experimentation by Pramanik *et al.* (2017). Field measurements of leaf area index (LAI) were carried out by plant canopy analyzer. (LAI-2000, LI-COR, Inc., Lincoln, NE, USA), which was based on 'fish-eye' measurement of diffuse radiation interception by measuring gap fraction at five zenith angles (0–13, 16–28, 32–43, 47–58, 61–74°) simultaneously. Three LAI readings were recorded in each plot and two to three such readings were averaged out to represent the field LAI. Using these LAIs, canopy cover (CC, %) was calculated by the following equation given by Hsiao *et al.* (2009).

Calculation and statistical analyses: Air temperature and Relative humidity measurements were used to calculate the VPD of air as given by Allen *et al.* (1998) and aerodynamic resistance (r_a) was calculated by the equation given by Montith (1973) and Thom and Oliver (1977). The minimum canopy resistance was calculated according to O'Toole and Real (1986) and it was found to be 35 sm^{-1} . Calculation of summary statistics, five statistical indicators and regression analyses were performed using the statistical software SAS 9.3 for window. Unreasonable data of weather parameters and canopy temperatures were excluded before analysis. The performance of different approaches of non-stress baseline were evaluated by root mean square error (RMSE), mean bias error (MBE), the mean absolute error (MAE) and Willmott index of agreement.

RMSE provides a measure (%) of relative difference between the simulated and observed values and MAE is the average over the verification sample of absolute values of the differences between simulated and the corresponding observed values (Chai and Draxler, 2014). R^2 values close to 1 indicate that the model explains well the variance of observations whereas MAE and RMSE values close to zero indicate good model predictions (González *et al.*, 2015). MAE is considered as the most natural and unambiguous measure of average error magnitude (Willmott and Matsuura, 2005). MBE is an indicator of whether the model is under predicting or over predicting the observed values and also gives the uniformity of error distribution. Positive MBE values indicate over prediction, negative values indicate under prediction and a zero value indicates equal distribution between negative and positive values. Willmott index of agreement (d) is a descriptive measure and their values range from 0 to 1 (Willmott, 1982). A value of 1 indicates perfect agreement between the simulated and observed data and 0

indicates no agreement at all.

Results and Discussion

Analysis of historical weather data for the area revealed that the 2009 growing season was one of the coolest in the last decade. During November–April, the mean monthly minimum temperature was lowest in December and highest in April, and the mean monthly maximum temperature was as low as 19.8°C in January and as high as 32.3°C in April. The lower air temperatures and high relative humidity reduced crop evapotranspiration rate, which ultimately reduced crop water uptake and seasonal irrigation requirements.

A total of 8 rainfall events occurred during wheat growing seasons 2008–09 and 2009–10, supplying 75.7 and 67.7 mm of water was not enough to meet the seasonal crop water requirement of wheat. During both the seasons, the crop attained 80–85 % canopy cover after 40 DAS and, thereafter, plant stress indicator (PSI) based irrigation was started to eliminate the effect of soil temperature (Pramanik *et al.*, 2017). Accordingly, required amount of irrigations were calculated based on soil moisture deficit to match crop water requirements for both seasons and applied next morning. During both the cropping seasons, a life-saving irrigation of 50 mm was applied to all treatments irrespective of stress condition at crown root initiation growth stage (23 DAS). No further irrigation was provided to water stressed treatment (T_{cmax}) to maintain crop at maximum water stress condition. No water stressed treatment (T_{cmin}) was given frequent irrigations (280 and 275 mm during 2008–2009 and 2009–2010 seasons, respectively) to ensure no water stress in plant at any growth stages. The results of water applied are in agreement with the previous study of Ranjan *et al.* (2015) who reported 104–156 mm for maximum water stress and 296–314 mm for no water stress in wheat crop.

Table 1: Mean, standard deviation, minimum and maximum values of weather variables at Roorkee during 2009–10 growing season (between 12:00–14:00 hrs)

Variables	Mean $\pm$ SD (Min-Max)
T_c (°C)	24.62 $\pm$ 2.54 (19.75–29.95)
T_a (°C)	25.81 $\pm$ 3.60 (17.90–31.42)
u (m s^{-1})	0.62 $\pm$ 0.43 (0.00–1.78)
VPD (kPa)	1.67 $\pm$ 0.66 (0.40–2.78)
R_n (W m^{-2})	329.94 $\pm$ 51.62 (219.80–449.75)
h (m)	0.81 $\pm$ 0.18 (0.50–1.11)
CC (%)	79.14 $\pm$ 2.71 (72.80–82.50)

^aVariables are canopy temperature (T_c), air temperature (T_a), wind speed (u), vapor pressure deficit (VPD), net solar radiation (R_n), canopy height (h), canopy cover (CC), and n is the number of data points included in the analysis ($n = 1860$) Wind speed was measured at a height of 2.0 m above ground level

Table 2: Non-stress baseline equation for wheat and coefficient of determination (R^2) of different approaches determined at Roorkee during 2009-2010

Approach	Equation*	<i>n</i>	R^2
Idso <i>et al.</i> (1981)	$T_c - T_a = -2.15VPD + 2.2$	912	0.61
Jackson <i>et al.</i> (1981)	$T_c - T_a = 3.056 - 2.77VPD$	912	0.67
Payero and Irmak (2006)	$T_c - T_a = 0.0987 + 0.0085R_h - 1.8279h + 0.0781u - 1.911VPD$	863	0.75
New non-stress baseline (this study)	$T_c - T_a = 20.03 + 0.621u - 1.824VPD + 0.012R_h - 2.649h - 0.261CC$	1860	0.89

*Variables and units are given in Table 1 and *n* is the number of data points included in the analysis

Fig. 1: Performance validation of the observed and predicted $T_c - T_a$ ($^{\circ}\text{C}$) of different approaches on 1:1 line for second year data (2009-2010).

The seasonal evapotranspiration (ET_w) of wheat was 89.7 mm (max. water stress) and 184.2 mm (no water stress) during first year which compare well with seasonal ET_w of 100.2 mm (max. water stress) and 190.2 mm (no water stress) during second year. Tyagi *et al.* (2000) measured crop ET using lysimeter method and reported that total seasonal ET of wheat under semiarid condition at Karnal was 343 mm. This value was 1.80 times higher than values obtained at Roorkee in this study. Crop

ET depends on the aerodynamic variables (Irmak *et al.*, 2015) and climatic condition mainly air temperature, wind speed and VPD (Madugundu *et al.*, 2017). Hence, variation may be due to difference in climatic conditions at two locations. Multiple regression analysis is a powerful technique used for predicting the unknown or dependent value of a variable from the known or independent value of two or more variables. After screening of the outliers, the remaining data were used for multiple regression

baseline analysis. Continuous storing of data at half an interval made it possible to monitor the impact of diurnal variation of climatic parameters on canopy temperature. It was observed that peak canopy temperature reached maximum during 12:00 to 14:00 hrs local time (noon period) in clear sky condition which is in accordance with the earlier findings of Idso *et al.* (1981). Half an hour interval data points ($n=5 \text{ times} \times 62 \text{ days} \times 2 \text{ treatments} \times 3 \text{ replication}=1860$) recorded during noon period were included to analyse the baseline. Based on the energy balance equation and statistical significance, the climatic variables were selected.

The major component of energy balance equation is input (net radiation), output (sensible heat, latent heat) and restore (soil heat flux). It is very important to understand the transformation of energy from one phase to other phase within and above the canopy. The canopy air temperature difference is the function of net solar radiation (R_n , W m^{-2}), wind speed (u , m s^{-1}), vapor pressure deficit (VPD, kPa), canopy height (h , m) and canopy cover (CC, %). The descriptive statistics (mean, standard deviation, minimum and maximum values) of different variables that described the non-stress baseline are given in Table 1. All the variables that could affect the baseline were included in the multiple regression analyses. However, only those variables that were statistically significant ($P < 0.01$) were included for multiple regression equation for non-stress baseline.

The multiple regression analyses for non-stress baseline for different approaches resulted in coefficient of determination (R^2) values ranging from 0.61 to 0.89 (Table 2). Idso *et al.* (1981) and Jackson *et al.* (1981) used only VPD to determine the non-stress baseline had very poor R^2 values. Payero and Irmak (2006) emphasised the inclusion of crop parameters to improve the non stress baseline over the growing period ($R^2=0.75$). Many researchers had reported different non stress baseline for pre and post heading stage of wheat during growing season which implies that a function of crop growth parameter should be incorporated (Idso *et al.*, 1981; Gontia and Tiwari, 2008). Canopy cover is a crop growth parameter determining the amount of light intercepted or absorbed by the canopy, photosynthetic rates and evapo-transpiration. The error associated with natural spatial variability of field crops reduced significantly and R^2 increased to 0.89 from 0.61-0.75, after taking canopy cover into consideration in the development of new non stress baselines.

The non-stressed multiple regression baselines developed in this study were evaluated based on the statistical indicators in term of error and compared with other existing three approaches. The RMSE values varied from 0.55 to 1.03. González *et al.* (2015) found that model performed better when the values were closer to zero. The RMSE value for new baseline approach (this study) was found to be near to zero (0.55) than the other approaches, indicates better model performance. MAE measures the weighted average absolute error and MBE indicates the over (positive value) and under (negative value) estimation of the model performance (Willmott and Matsuura, 2005). MAE of new non-stressed baseline was minimum (0.62)

among other compared approaches whereas the MBE values of all approached were negative value indicating underestimation of the model. Less negative value of MBE of new non-stress baseline (-0.08) indicates less underestimation, *i.e.*, more accurate than other approaches. The performance statistics different approaches are shown in Fig. 1. Index of agreement (d) closer to one indicates better prediction of actual condition (Willmott, 1982). The index of agreement of new non-stressed baseline was 0.95, *i.e.*, closer to one than the other approaches indicated better resemblance to the actual field condition. Thus, based on these statistical indicators, newly developed non-stressed multiple regression baseline has given better agreement between observed and simulated value than other existing approaches for humid sub tropical climate. It should be kept in mind that the baselines were empirically determined for specific range of climatic and crop conditions and, therefore, the equations should only be applied within these ranges. To generalise the equation for wheat crop, more studies are required in similar climatic condition over a longer period.

Acknowledgment

The first author acknowledges the financial support provided by IIT, New Delhi, in the form of a scholarship and contingency grant and IIT, Roorkee for providing all the experimental facility.

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