Estimation of crop coefficients and water productivity of mustard (*Brassica juncea*) under semi-arid conditions

A. Gupta[1,*], A. Sarangi[2] and D. K. Singh[1]

[1]Division of Agricultural Engineering, and [2]Water Technology Centre, ICAR-Indian Agricultural Research Institute, New Delhi 110 012, India

Experiment was conducted using weighing-type field lysimeters to determine single and dual crop coefficients (K_c) and to estimate water productivity of mustard (*Brassica juncea*) cultivar, Pusa Vijay (NPJ-93) during *rabi* 2013–14 and 2014–15. It was observed that the single crop coefficient (K_c) during *rabi* 2013–14 was 0.39, 0.72, 1.02 and 0.5 for initial, development, mid and late stages respectively. While in dual K_c the value of K_{cb} (basal crop coefficient) was 0.19, 0.55, 0.91 and 0.24 for the four stages, respectively. During *rabi* 2014–15, the single K_c was 0.36, 0.63, 1.04 and 0.44 and for dual K_c the value of K_{cb} was 0.17, 0.46, 0.91 and 0.23 for four stages respectively. Relationship between K_{cb} and leaf area index as well as between K_{cb} and growing degree days was also established. Water productivity was estimated to be 14.9 kg/ha-mm corresponding to grain yield of 2.34 t ha^{-1} with 157 mm of total irrigation water applied during *rabi* 2013–14. Whereas during *rabi* 2014–15, water productivity was 15.4 kg/ha-mm with grain yield of 2.89 t ha^{-1} with 187 mm depth of applied irrigation. Nonetheless, the estimated crop coefficients of mustard can be used for judicious irrigation scheduling in order to enhance water productivity in semi-arid environment.

Keywords: *Brassica juncea*, crop coefficient, evapotranspiration, leaf area index, water productivity.

AGRICULTURE sector is the major consumer of water resources in India. Supplemental irrigation in semi-arid environment with limited and irregular rainfall is necessary for enhancing crop production and productivity. Knowledge of crop-water requirements is crucial for management and planning of water resources in order to improve water productivity[1,2]. Scheduling the time and quantity of irrigation water application is primarily governed by the crop evapotranspiration. Therefore, determination of daily crop evapotranspiration (ET) and computation of crop coefficients (K_c) at different crop growth stages help in judicious irrigation scheduling and agricultural water management[3–6].

*For correspondence. (e-mail: ajitagupta2012@gmail.com)

The concept of K_c was first introduced by Jensen[7] and then further developed by other researchers[8–11]. K_c which is the ratio of actual crop evapotranspiration (ET_c) to reference evapotranspiration (ET_0) can be estimated using either the single or the dual crop coefficient approaches. In single crop coefficient approach, the effect of both crop transpiration and soil evaporation is integrated into a single crop coefficient[11]. Whereas in dual crop coefficient approach, the basal crop coefficient (K_{cb}) and soil evaporation coefficient (K_e) are estimated separately. Dual crop coefficients are preferred over single crop coefficients for crops with incomplete soil cover and for high frequency irrigation[12,13].

India is one of the largest mustard-growing countries in the world, and occupies the first position in terms of area of cultivation and second position in production after China. Mustard (*Brassica juncea*) is the second most important edible oilseed crop in India after groundnut. India's share in mustard is about 19.3% of area with about 11% of global production[14]. Crop water requirement of Indian mustard (*B. juncea*) varies from 250 to 350 mm (refs 15 to 17). Moreover, it was observed that plant height and long growing season influence the crop coefficient[18]. However, there are limited studies on the estimation of dual crop coefficient for field crops, including oilseed crops because of the complexity involved in the computation process, which requires weighing-type field lysimeters, daily meteorological data and different soil-specific parameters. A weighing-type field lysimeter with crop is generally used directly to estimate ET_c by considering the dynamic mass balance of water concept, in contrast to a non-weighing-type lysimeter which indirectly determines ET_c using the volume balance approach[19]. Crop coefficient values for a number of crops grown under different climatic conditions have been suggested by different authors[9,20,21]. Moreover, a database of crop coefficients of different crops in varying agro-climatic regions of India is not available and K_c values given by FAO are being used for irrigation scheduling of different crops. Therefore, it is necessary to generate region-specific crop coefficients under the given climatic conditions[3,4]. Moreover, significant difference between ET_c values calculated and those estimated using FAO K_c values is reported by different researchers[16,18].

Table 1. Soil physical and chemical properties of the experimental field

	Soil depth (cm)				
Soil properties	0–15	15–30	30–45	45–60	60–90
Sand (%)	52.4	53.7	44	39	38
Silt (%)	21	19	23	25	27
Clay (%)	26.6	27.3	33	36	34
Soil texture	Sandy loam	Sandy loam	Loam	Loam	Clay loam
θ_{fc} (w/w)	20.45	22.02	30.59	32.8	33
θ_{pwp} (w/w)	9.5	10.2	13.7	14.7	15
Ks (cm d^{-1})	27.4	26.2	18.6	19.1	19.5
Bd (g cm^{-3})	1.66	1.7	1.88	1.67	1.83
EC (dS m^{-1})	0.24	0.25	0.35	0.37	0.38
pH	7.7	8.1	8.01	8.05	8.5
Organic matter (%)	0.56	0.50	0.40	0.37	0.38
N (ppm)	179	159	130	123	126
P (ppm)	3.3	3.7	129.6	4.3	4.1
K (ppm)	172.4	177.7	182.5	188.1	191.2

Bd, Bulk density; Ks, Saturated hydraulic conductivity; θ_{fc}, Field capacity; θ_{pwp}, Permanent wilting point; EC, Electrical conductivity.

Figure 1. View of the experiment with three lysimeters (***a–c***) located at the Water Technology Centre farm, ICAR-IARI, New Delhi.

The present study was undertaken to estimate the crop coefficients, water requirement and water productivity of mustard using weighing-type lysimeters in semi-arid climatic conditions prevailing in the Water Technology Centre (WTC) research farm of ICAR-IARI, New Delhi.

Materials and methods

Site description

The experiment was conducted in 0.1 ha (50 m × 20 m) area enclosing three weighing-type field lysimeters at the WTC research farm located between 28°37′22″–28°39′00″N and 77°8′45″–77°10′24″E, with an average elevation of 230 m amsl. The meteorological observations during mustard growth period used in the data analysis were acquired from the WTC observatory, located at a distance of 100 m from the experimental site. Soil texture of the experimental field was sandy loam up to 30 cm soil depth. Table 1 presents the soil physical and chemical parameters of the experimental site.

Lysimeters and experimental details

Three weighing-type field lysimeters (ASIA-brand dormant-type steelyard, model-DS) located at 3 m distance from each other were used in the present study (Figure 1). They comprised of two rectangular tanks, the dimensions of the inner tanks were 1.2 m × 1.2 m × 1 m and of the outer tank were 1.25 m × 1.25 m × 1.25 m, with effective surface area of 1.44 sq. m. The total capacity of the lysimeter, including weight of tank, soil and water was about 2000 kg and resolution was 200 g.

Two-year field experiment was conducted with mustard cultivar Pusa Vijay (NPJ-93) cropped from 22 November 2013 to 28 March 2014 during *rabi* 2013–14, and from 14 November 2014 to 20 March 2015 during *rabi* 2014–15 to measure the daily evapotranspiration. The first lysimeter was kept bare to correlate calculated K_e values using FAO-56 methodology with bare soil evaporation, whereas the second and third lysimeters were sown with mustard. The adjoining areas surrounding the lysimeters were sown with similar variety of mustard under non-limiting water condition. Crop parameters, viz. plant height, root depth and leaf area index (LAI) were recorded at 15 days interval. Grain and biomass yields were estimated after harvesting of the crop. LAI was measured using Decagon's AccuPAR model LP-80 PAR.

Irrigation scheduling

Soil moisture inside the lysimeter and of the adjoining field was recorded every alternate day using a TDR (time domain reflectometer) sensor for irrigation scheduling. In the lysimeters irrigation was applied to replace cumulative crop evapotranspiration (weight loss), thus maintaining non-limiting soil water condition. Soil moisture deficit was calculated as follows:

$$\mathrm{SMD} = (\theta_{Fc} - \theta_i) \times D \times Bd \times f, \tag{1}$$

where SMD is the soil moisture deficit (mm), θ_{Fc} the soil water content at field capacity (F_c), θ_i the soil water content before irrigation (weight per cent basis), D the root zone depth (mm), Bd the bulk density of a particular soil layer (g cm^{-3}) and f is the coefficient for irrigation treatment levels. The coefficient of treatment $f = 1$ (full irrigation up to FC without any deficit).

Estimation of reference evapotranspiration

Reference evapotranspiration (ET_0) is defined as the evapotranspiration from reference crops such as alfa–alfa grass with an assumed height of 0.12 m, surface resistance of 70 S m^{-1} and an albedo of 0.23, actively growing in large areas with adequate water supply (FAO-56). ET_0 was estimated using CROPWAT software version 4.2 developed by FAO. Penman–Monteith equation was used for the estimation of ET_0, which utilizes daily sunshine hours, air temperature (maximum and minimum), relative humidity and wind speed at 2 m height.

$$\mathrm{ET}_0 = \frac{0.408\Delta(R_\mathrm{n} - G) + \gamma \dfrac{900}{T+273} U_2 \; (e_\mathrm{a} - e_\mathrm{d})}{\Delta + \gamma(1 + 0.34U_2)}, \tag{2}$$

where ET_0 is the reference evapotranspiration (mm day^{-1}), R_n the net radiation at the crop surface (MJ m^{-2} day^{-1}), G the soil heat flux density (MJ m^{-2} day^{-1}), T the mean daily air temperature at 2 m height (°C), U_2 the wind speed at 2 m height (m s^{-1}), e_a the saturation vapour pressure (kPa), e_d the actual vapour pressure (kPa), $(e_a - e_d)$ the saturation vapour pressure deficit (kPa), Δ the slope vapour pressure curve (kPa °C^{-1}) and γ is the psychometric constant (kPa °C^{-1}).

Estimation of single crop coefficient

For determining the crop coefficients, crop development has been basically partitioned into four stages, viz. initial stage (1–30 days after sowing (DAS)), crop development stage (31–70 DAS), mid-season stage (71–110 DAS) and late season stage (111–130 DAS) based on the phenology of the crop as described in the FAO-56 methodology[11].

Evapotranspiration rates were obtained from the change in weight of the lysimeter divided by lysimeter area on a daily basis using the following water balance equation:

ET = Rainfall + irrigation – percolation ± change in soil moisture.

Further, K_c values were calculated using eq. (3)

$$K_c = \frac{\mathrm{ET}_c}{\mathrm{ET}_0}. \tag{3}$$

Estimation of dual crop coefficient

In dual crop coefficient approach, the basal crop coefficient (K_{cb}) and soil evaporation coefficient (K_e) were estimated separately. Multiplication of K_{cb} with ET_0 represents primarily the transpiration component of ET_c, whereas K_e represents the evaporation component of ET_c. In dual crop coefficient approach, K_c is the sum of K_{cb} and K_e given by:

$$K_\mathrm{c} = K_\mathrm{s} K_\mathrm{cb} + K_\mathrm{e}, \tag{4}$$

where K_s is the water stress coefficient.

Under standard conditions where the soil is not under water stress, K_s is taken as 1. The present study was performed under standard condition.

The values of K_{cb} were estimated with the standard FAO-56 dual crop coefficient approach[11]. K_{cb} was calculated from the lysimeter K_c values minus the estimated evaporation component K_e values were calculated using FAO-56 methodology. Table 2 shows the main parameters used to calculate K_e.

The values of K_{cmax}, daily evaporation reduction coefficient (K_r) using water balance equation and exposed and wetted soil fraction (f_{ew}) were calculated using the FAO-56 methodology[11].

Table 2. Value of parameters used for the calculation of K_e

Parameters	Value
Field capacity (m^3/m^3)	0.27
Permanent wilting point (m^3/m^3)	0.12
Total evaporable water (mm)	21
Readily evaporable water (mm)	10
Depth of the surface soil layer (m)	0.1
Fraction of soil surface wetted	1.0 (basin irrigation) 1.0 (rainfall)

Results and discussion

Variation of evapotranspiration, transpiration and soil evaporation components of mustard during cropping seasons

Mean values of daily crop evapotranspiration (ET_c) were 1.23 and 1.08 mm/day during *rabi* 2013–14 and 2014–15 respectively. The total ET_c values during the mustard growth period were 153.3 and 153.8 mm and the reference evapotranspiration values (ET_0) were 217.33 and 207.9 mm during the same seasons respectively. The maximum value of daily crop evapotranspiration was estimated as 2.81 and 2.76 mm/day at 102 and 101 DAS during *rabi* 2013–14 and 2014–15 respectively. Figures 2 and 3 show the variation of daily evapotranspiration, evaporation and transpiration components during *rabi* 2013–14 and 2014–15 respectively. Table 3 presents rainfall, effective rainfall, irrigation depth, reference evapotranspiration and crop evapotranspiration values of mustard during *rabi* 2013–14 and 2014–15. The ratio of transpiration to evapotranspiration was observed to be 0.75, which implies that the soil evaporation component is only 25% whereas the transpiration component is 75%. A similar result for canola (*Brassica napus* L.) has been reported[22] for which the ratio of transpiration to evapotranspiration varied from 75% to 80%. It was observed that the actual crop evapotranspiration exceeded the reference evapotranspiration from 60 to 90 DAS during both years, which was during the mid-season stage of crop growth. Thus it can be interpreted from this result that the crop water demand was high during the mid-season stage due to flowering, grains formation and filling. Therefore, presence of adequate soil moisture during mid-season stage needs to be ensured to avoid stress in plants and create an environment for enhancing grain yield.

Single and dual crop coefficients of mustard

The crop growth period of mustard under different growth stages during both years of the experiment was 30, 40, 40 and 20 days for initial, crop development, mid-season and late season stages respectively, with a total growing period of 130 days. K_{cb} was calculated from the lysimeter K_c values minus the estimated K_e values calculated using FAO-56 methodology. Table 2 shows the values used to calculate K_e. In the single crop coefficient approach, K_c for mustard cultivar Pusa Vijay (NPJ-93) during *rabi* 2013–14 was estimated to be 0.39, 0.72, 1.02 and 0.5 for initial, development, mid-season and late season stages respectively. In the dual crop coefficient approach, the value of basal crop coefficient was 0.19, 0.55, 0.91 and 0.24 for initial, development, mid-season and late season stages respectively (Figure 4). Similarly, during *rabi* 2014–15, K_c was estimated to be 0.36, 0.63, 1.04 and 0.44 and K_{cb} was 0.17, 0.46, 0.91 and 0.23 for initial, development, mid-season and late season stages respectively (Figure 5). Moreover, the single K_c values obtained were observed to increase from the initial to development stages; they reached a maximum at the end

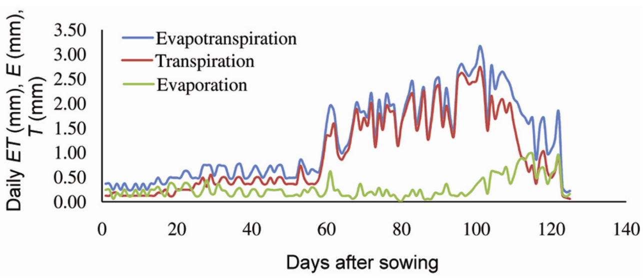

Figure 2. Variation of daily evapotranspiration (ET), evaporation (E) and transpiration (T) components during *rabi* 2013–14.

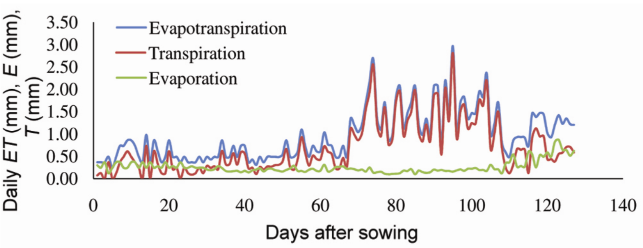

Figure 3. Variation of daily evapotranspiration, evaporation and transpiration components during *rabi* 2014–15.

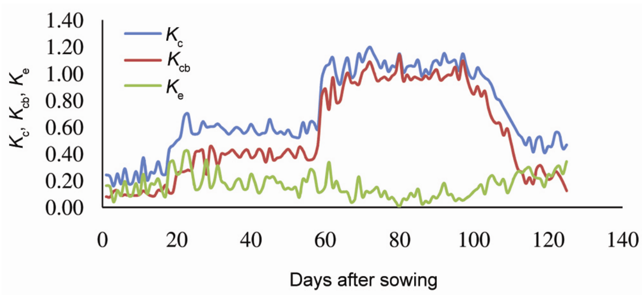

Figure 4. Variation of crop coefficient (K_c), basal crop coefficient (K_{cb}) and evaporation component of crop coefficient (K_e) during *rabi* 2013–14.

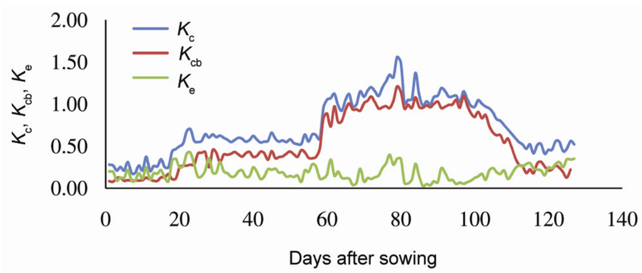

Figure 5. Variation of crop coefficient (K_c), basal crop coefficient (K_{cb}) and evaporation component of crop coefficient (K_e) during *rabi* 2014–15.

Table 3. Rainfall, effective rainfall, irrigation depth, reference evapotranspiration (ET_0) and crop evapotranspiration (ET_c) of mustard during *rabi* 2013–14 and 2014–15

Growth stage	Rainfall (mm)	Effective rainfall (mm)	Irrigation (mm)	ET_0 (mm) Average daily	ET_0 (mm) Growth stage	ET_c (mm) Average daily	ET_c (mm) Growth stage
Rabi 2013–14							
Initial (1–30 DAS)	0.76	0.76	30 (28 DAS)	1.21	36.25	0.35	7.32
Development (31–70 DAS)	20.07	17.8	30 (46 DAS)	1.19	47.52	0.65	25.46
Mid-season (71–110 DAS)	73.16	69.2	0	2.18	87.05	1.99	87.51
Late season (111–130 DAS)	9.65	9.1	0	3.10	46.51	1.58	33.26
Total	103.64	96.86	60		217.33		153.55
Rabi 2014–15							
Initial (1–30 DAS)	0	0	0	1.47	44.07	0.53	15.85
Development (31–70 DAS)	42.8	23.4	0	0.97	39.08	0.63	25.36
Mid-season (71–110 DAS)	15.4	15	30 (83 DAS) 30 (96 DAS) 15 (105 DAS)	1.65	66.06	1.55	60.36
Late season (111–130 DAS)	175.8	73.8	0	2.61	44.38	1.22	20.14
Total	234	112.2	75		207.90		153.8

DAS, Days after sowing.

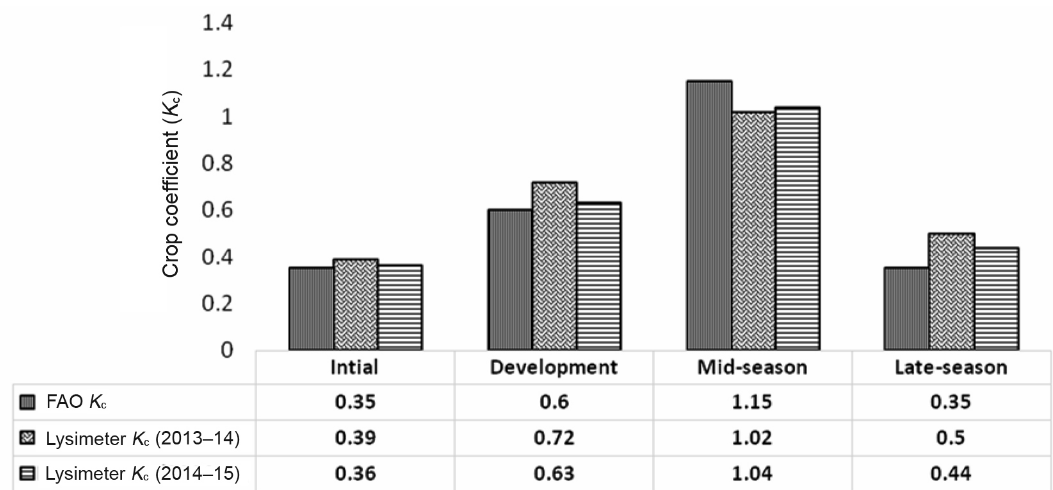

Figure 6. Comparison of single crop coefficient (K_c) of mustard during *rabi* 2013–14 and 2014–15 with FAO reported K_c values.

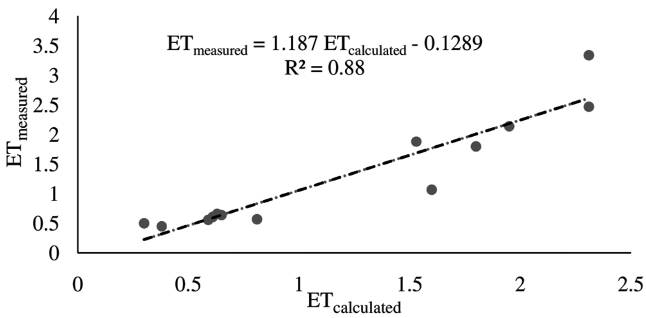

Figure 7. Comparison between lysimeter measured and FAO-56 calculated evapotranspiration during *rabi* 2013–14.

of the development stage and remained almost constant up to the mid-season stage; then there was a rapid decline in K_c values during the late season stage. However, in case of the dual K_c of mustard, the soil evaporation component exceeded the plant transpiration during initial growth stages of the crop up to 28 and 27 DAS during 2013–14 and 2014–15 respectively. Thereafter, the plant transpiration component was more than the soil evaporation component and the difference between these two components increased up to maximum LAI value, i.e. up to 82 and 89 DAS during *rabi* 2013–14 and 2014–15 respectively.

Comparison of estimated regional K_c with FAO reported values for mustard

The estimated crop coefficient values at different growth stages of mustard during two growing seasons were compared with the K_c values reported by FAO[11]. The FAO reported K_c values for mustard crop were 0.35, 0.6, 1.15 and 0.35 during initial (0–30 DAS), development (31–70), mid (71–110) and late stages (111–130) respectively. It was observed that measured K_c values exceeded the FAO values by about 10%, 17% and 30% during *rabi* 2013–14 and by 3%, 5% and 21% during *rabi* 2014–15 (Figure 6) during initial, development and late-season stages respectively. However, K_c value corresponding to mid-season growth stage was observed to be less than that value given by FAO-56 by about 11% and 9% during *rabi* 2013–14 and 2014–15 respectively (Figure 6). Overall, it was observed that there was an overestimation of K_c values during the entire growing season, excluding the mid-season stage for the study region by about 19% and 10% compared to FAO reported K_c values during *rabi* 2013–14 and 2014–15 respectively. Results showed a linear relationship between the FAO measured and experimental values with coefficient of determination of the fitted regression equation being 0.88 and 0.82 during *rabi* 2013–14 and 2014–15 respectively (Figures 7 and 8). Similar results pertaining to the relationship between the measured and estimated ET_c of mustard have been reported[16].

Variation of different crop growth parameters

Figures 9 and 10 present the variation in plant height, root depth and LAI for mustard for *rabi* 2013–14 and 2014–15 respectively. It was observed that during *rabi* 2013–14, LAI increased up to 82 DAS, i.e. the fully developed stage and thereafter it decreased gradually. Maximum value of LAI was obtained as 3.88 during mid-season stage. Whereas during 2014–15, LAI increased up to 89 DAS with maximum value being 4.14 during mid-season stage. Similar to LAI, plant height also increased consistently from initial to the development and mid-season stages, which were attained at 31–70 DAS and 71–110 DAS respectively. Moreover, at the late-season stage of plant development, LAI started to decrease gradually, whereas plant height remained relatively constant for the rest of the growing period up to harvest of the crop. To facilitate extrapolation of the results pertaining to estimation of K_{cb} from LAI for other regions having similar climatic conditions, LAI values were plotted against the basal crop coefficient and a regression equation was fitted which depicted a linear relationship with

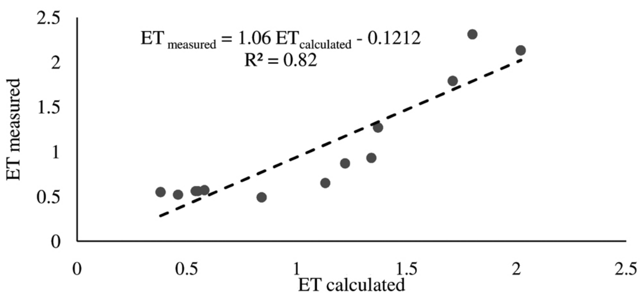

Figure 8. Comparison between lysimeter measured and FAO-56 calculated evapotranspiration during *rabi* 2014–15.

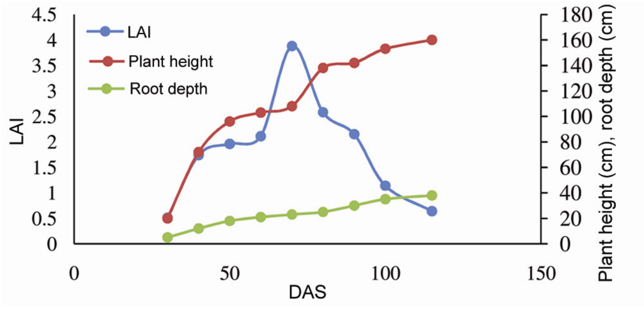

Figure 9. Variation of leaf area index (LAI), plant height and root depth at different days after sowing (DAS) during *rabi* 2013–14.

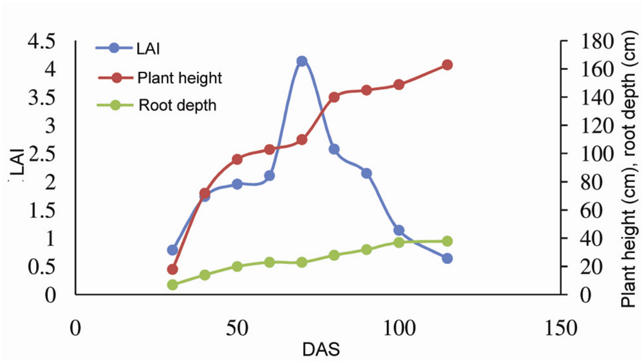

Figure 10. Variation of LAI, plant height and root depth at different DAS during *rabi* 2014–15.

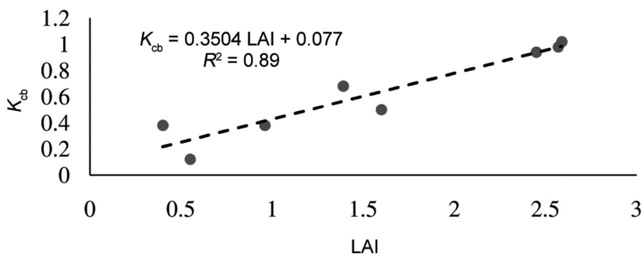

Figure 11. Relationship between the LAI and basal crop coefficient (K_{cb}) of mustard during *rabi* 2013–14.

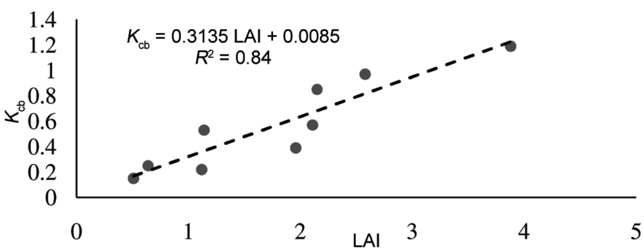

Figure 12. Relationship between the leaf area index (LAI) and basal crop coefficient (K_{cb}) of mustard during *rabi* 2014–15.

Table 4. Grain yield, biomass yield, water productivity (WP) and harvest index (HI) of mustard during *rabi* 2013–14 and 2014–15

Irrigation	Grain yield ($t\ ha^{-1}$)	Biomass yield ($t\ ha^{-1}$)	HI (%)	Total water applied (mm)	WP (kg/ha-mm)
Rabi 2013–14					
Full irrigation (lysimeter-3)	2.34	7.77	23	157	14.9
Deficit irrigation (50%; lysimeter-2)	1.85	7.45	20	127	14.6
Rabi 2014–15					
Full irrigation (lysimeter-3)	2.89	9.05	24	187	15.4
Deficit irrigation (50%; lysimeter-2)	2.77	10.92	20	150	18.5

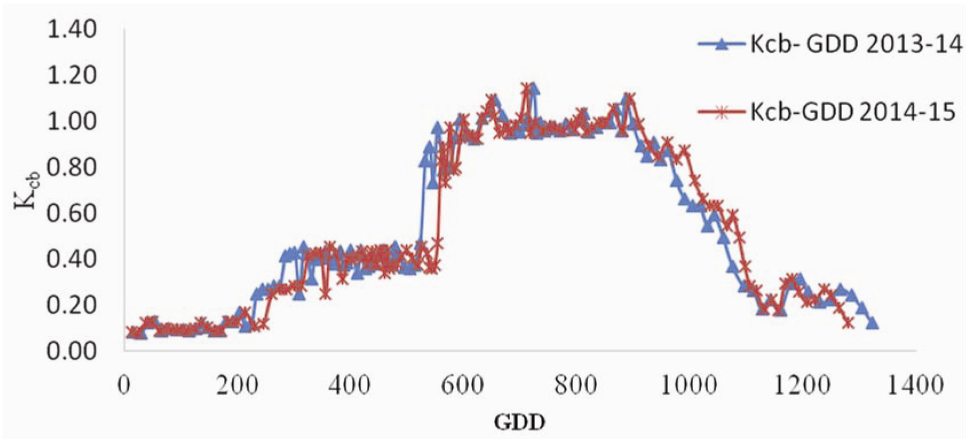

Figure 13. Variation of basal crop coefficient (K_{cb}) with growing degree days (GDD) during *rabi* 2013–14 and 2014–15.

coefficient of determination (R^2) value of 0.89 and 0.84 during *rabi* 2013–14 and 2014–15 respectively (Figures 11 and 12). Similar trend of K_{cb} and its correlation with LAI were also reported for other crops[3,22–24]. Such relationship would facilitate extrapolation of the results pertaining to the estimation of K_{cb} from LAI for other regions having similar climatic conditions.

Variation of K_{cb} with growing degree days

To account for the climatic differences which would affect the transpiration rate, K_{cb} values were plotted as a function of growing degree days (GDD) during both years of the experiment (Figure 13). GDD is a measure of the amount of heat required by the plants during their growth period and can be calculated using eq. (5) below

$$\mathrm{GDD} = \frac{T_{\mathrm{Max}} - T_{\mathrm{Min}}}{2} - T_{\mathrm{Base}}, \tag{5}$$

where T_{Max} and T_{Min} are the maximum and minimum temperatures (°C) of a day and T_{Base} is the base temperature taken as 5°C for mustard[17,25]. For *rabi* 2013–14, K_{cb} reached a maximum value of 1.14 after about 724 GDD, whereas for *rabi* 2014–15 the maximum value of K_{cb} (1.21) was attained after 701 GDD. The K_{cb} values then decreased to a minimum during harvest of the crop at 1322 and 1307 GDD during *rabi* 2013–14 and 2014–15 respectively (Figure 13). It was observed that during *rabi* 2014–15, K_{cb} was higher by 0.07 and was attained before 23 GDD compared to *rabi* 2013–14. Such difference in K_{cb} and GDD might have resulted in higher grain yield during *rabi* 2014–15.

Grain yield and biomass yield of mustard

Grain yield was measured as weight of harvested grain with 15% grain moisture content in each lysimeter and the adjoining field and converted to $kg\ ha^{-1}$ unit. Biomass yield was determined by taking the weight of above-ground plant parts without grain. Total water applied (187 mm) during *rabi* 2014–15 was more than the actual crop evapotranspiration (154 mm) by 33 mm. However, this difference may be attributable to the effective rainfall of 73.8 mm estimated from total rainfall depth of 175.8 mm, which occurred during the crop harvesting stage in March 2015. Therefore, this excess rainfall might not have been taken up by the mustard crop to meet evapotranspiration demand. Table 4 presents the estimated grain yield, biomass yield, water productivity and harvest index values.

Conclusion

It can be concluded that estimation of single crop coefficient was easier and less cumbersome than that of basal crop coefficient and soil evaporation components in dual crop coefficient approach. Empirical relationship between LAI and basal crop coefficient of mustard developed in this study can be used for calculating transpiration rate from LAI values in regions similar to the study area for estimation of basal crop coefficient without having the lysimeter facility. It was observed that the single and dual crop coefficient values estimated in the study region were different than the FAO reported values at different growth stages. Therefore, it has been corroborated through this study that the regional crop coefficient values need to be estimated regionally and can be used for more accurate irrigation scheduling compared to the FAO reported values. Database on actual crop evapotranspiration besides the segregated values of transpiration and evaporation generated in this study would be useful for researchers and policy makers in proper irrigation scheduling of mustard for enhancing the water productivity.

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