



Assessing Aquacrop model for pearl millet (*Pennisetum glaucum*) under *in-situ* water conservation in a rainfed semi-arid environment

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Received: 27 March 2018; Accepted: 06 February 2019

ABSTRACT

AquaCrop (v4. 0) model has been commonly used to simulate the crop yield under irrigated environments, but this model has not yet been calibrated and validated for simulating the yield of pearl millet (*Pennisetum glaucum* (L.) R. Br.) under *in-situ* water conservation. Thus, a three year (2011–13) field experiment was conducted at ICAR-Indian Agricultural Research Institute, New Delhi with six *in-situ* water conservation treatments, viz. trench-cum-bund (TCB: 20 cm depth of trench, 20 cm height of bund), bund (30 cm height), ridge-and-furrow (R&F: 15 cm height), skip-row (SR: 3:1) planting, basin-tillage (BT: 45 cm × 45 cm) and control (no-water conservation). Calibration of AquaCrop (v 4. 0) model for pearl millet grain yield and total soil moisture content was done using experimental data of 2011 and validated separately for 2012 (deficit rainfall year) and 2013 (excess rainfall year) data. For the year (2012), absolute prediction errors of grain yield were 1.7, 8.7, 14.1, 14.9, 3.3 and 7.3% for BT, R&F, TCB, bunds, SR and control, respectively, whereas Nash Sutcliffe Efficiency, root mean square error and coefficient of determination were 0.95, 0.07 and 0.96, respectively during calibration period and 0.73, 0.15 and 0.93 during validation period of deficit year. Thus, model predictions were satisfactory for less rainfall (<600 mm) year. Coefficient of determination R^2 (0.4 to 1.0) was better for soil moisture simulation during dry-spell periods and for BT practice. The validated AquaCrop model can be used for prediction of pearl millet yield and soil moisture under different water conservation practices in a semi-arid environment.

Key words: AquaCrop, *In-situ* water conservation, Pearl millet yield, Simulation, Soil moisture dynamics

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is predominately grown in arid and semi-arid regions of India under rainfed conditions. Farmers cultivating pearl millet suffer heavy yield-and income-losses due to erratic rainfall and low market price for its grain. The demand for pearl millet grain will rise with its increasing use as poultry-and animal-feed (Rockstrom *et al.* 2003, Rockström and Baron 2007). Storage of adequate moisture in crop root zone soil is very important in rainfed agriculture and *in-situ* water conservation could help to enhance crop yield (Sudhishri and Dass 2012, Sudhishri *et al.* 2014). However, measuring layer-wise soil water content within effective root zone on daily basis is cumbersome and time consuming.

Simulation modeling approach can be alternative means to predict moisture in crop root-zone depth. At the field level, soil water balance models can conveniently estimate soil moisture content (Panigrahi *et al.* 2003, Sudhishri and Patnaik 2004, Sudhishri *et al.* 2007, Sudhishri and Dass 2014). Moreover, accurate modeling of crop response to water plays an important role in optimizing crop water productivity (Hsiao *et al.* 2009). Several models are available that simulate the growth and development of maize, rice, wheat and other cereals under irrigated or rainfed conditions (Jones *et al.* 1986, Stockle *et al.* 2003, Steduto *et al.* 2009, Raes *et al.* 2009, Todorovic *et al.* 2009 and Dass *et al.* 2012), but not in pearl millet.

AquaCrop can be used for modelling crop yield and soil moisture (FAO 2009). Although AquaCrop required less input information than CropSyst and WorldFoodStudies (WOFOST) crop growth models, it performed equally well in simulating biomass and yield (Todorovic *et al.* 2009). Hamid *et al.* (2009), Bitri *et al.* (2014), Paredes *et al.* (2014) and Mohammad *et al.* (2018) used AquaCrop model in simulation of cotton, potato, maize, and direct seeded rice yields, respectively and model predicted with acceptable accuracy. Meager information is available on

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use of AquaCrop model under different water conservation practices in rainfed systems. Hence current investigation was conducted to determine the effect of different *in-situ* water conservation practices on pearl millet yield and simulate the soil moisture, grain and stover yields using AquaCrop model.

MATERIALS AND METHODS

The experiment was carried out with pearl millet (var. Pusa composite 443) as test crop during rainy seasons (June–Oct) of 2011–2013 at ICAR-IARI, New Delhi (28°38' 23"N, 77° 09' 27" E and 228.6 m above msl). Soil of the study site was sandy loam with a neutral pH (7.2), low in organic C (0.44%), available N, P and K (64.1, 15.9, 115 kg/ha, respectively). Field capacity, permanent wilting point, porosity and average hydraulic conductivity of soil were 19.5%, 7.5%, 25% and 1.4 cm/hr, respectively. The experiment was laid-out in a three-time replicated randomized complete block design, on a land having 2.5% uniform slope. The field was ploughed during 2011 only; during 2012 and 2013 all experimental plots were maintained under zero-tillage. The treatments consisted of six engineering water conservation practice treatments, viz. trench-cum-bund (20 cm depth of trench and 20 cm height of bund), bund (30 cm height), ridge-and-furrow (15 cm height), skip-row planting (3:1), basin tillage (length 45 cm × width 45 cm × depth 20 cm) (squared pit) and control (no moisture conservation practice). Size of each experimental plot was 20 m × 3 m. Trench-cum-bund and bunds were placed at 10 m horizontal interval, whereas the distance

between ridge-to-ridge in ridge and furrow method was 45 cm. In basin-tillage, pit-to-pit distance was 45 cm and placed in a staggered manner. Pearl millet was sown in 3rd week of June and harvested during first week of October in all study years. The crop was planted at a spacing interval of 45 cm × 15 cm in all the treatments barring basin-tillage where five plants were maintained in each pit. A buffer-strip of 1 m width was maintained between two consecutive plots, to avoid border effect. The crop was fertilized with recommended dose of fertilizers (N 40 kg/ha, P₂O₅ 25 kg/ha, and K₂O 25 kg/ha). Nitrogen was applied in two equal splits, 1st at the time of sowing and another at 30 days after sowing (DAS). Entire amount of P and K was applied at the time of sowing. Two hand weeding were done at 21–25 DAS and at 40–45 DAS to control weeds. Crop matured in 105–110 days. On occurrence of different phenological events, viz. emergence, tillering, jointing, heading, flowering, grain filling and maturity were demarcated. When 50% of plants reached that particular event, that day was taken into consideration to denote that event. Grain, stover and biomass yields were recorded plot-wise at harvest. For modelling of soil moisture, soil moisture measurements were done by gravimetric method, for 0–15, 15–30, 30–60 and 60–90 cm soil depths at 21, 65, 75, 85, and 95 DAS and at harvest. These dates of moisture measurement were selected to present important phenological stages and water deficit conditions in the soil.

The weather data required by AquaCrop model were collected from Agrometeorological Observatory, ICAR-

Table 1 Crop input parameters for AquaCrop Model

Crop parameter	Description	Basin tillage	Control	Skip row	Ridge & furrow	Trench cum bund	Bund
Plant density	Plants/ha	70000	140000	90000	140000	120000	120000
CCo	CCo	0.35	0.6	0.45	0.7	0.6	0.6
Emergence	Days to 90% emergence (calendar) (days)	7	6	6	6	7	6
CGC	Canopy growth coefficient CGC (%)	1.359	0.931	1.316	1.105	1.268	1.297
CDC	Canopy decline coefficient CDC (%)	0.521	0.542	0.516	0.532	0.04	0.628
	Canopy decline (days)	34	29	35	29	37	28
CCx	Maximum canopy cover (%)	85	90	85	90	85	90
Zr (min)	Min effective rooting depth (m)	0.3	0.3	0.3	0.3	0.3	0.3
Zr (max)	Max effective rooting depth (m)	0.9	0.9	0.9	0.9	0.9	0.9
Kc _u	Coefficient for transpiration	0.95	0.75	0.8	0.75	0.8	0.85
	Green canopy cover (%)	60	60	60	60	60	60
	Reduction with age (% /day)	0.15	0.15	0.15	0.15	0.15	0.15
Water productivity	Normalized Water productivity (g/ m ²)	32	32	32	32	32	32
Canopy stress	Ks p(upper)	0.3	0.35	0.25	0.35	0.3	0.3
	Ks p(lower)	0.6	0.7	0.6	0.7	0.65	0.65
	Shape factor	3	2.5	3	2.5	3	2.5
Stomatal stress	Ks p(upper)	0.7	0.75	0.65	0.75	0.7	0.68
Canopy senescence	Ks p(upper)	0.75	0.8	0.65	0.8	0.75	0.76
T base	Base temperature (°C)	10	10	10	10	10	10
T upper	Upper temperature (°C)	35	35	35	35	35	35

IARI, New Delhi. Rainfall amount of 470 mm, 412 mm and 1162 mm i. e. 13% less and 23. 7% less i. e. deficit, 115. 2% more (i. e. 2. 15 times) i. e. excess, respectively compared to normal growing season rainfall (i. e. 540 mm) were recorded during 2011, 2012 and 2013, respectively. Crop evapotranspiration (ET_c) was estimated using ET_c calculator. AquaCrop model requires six parameters that determine the development of canopy cover, viz. canopy growth coefficient (CGC), canopy decline coefficient (CDC), maximum canopy cover, days to emergence, days to senescence, and days to full maturity. These parameter values were determined by trial and error approach during simulation. Biomass and grain yields were compared with the measured data using the normalized water productivity and the transpiration crop coefficient. Other crop-specific but non-location-specific parameters for major agricultural crops including pearl millet have been determined and validated in varying locations by the FAO, so taken as default values in the model. Calibration was done by adjusting certain model parameters to make the model match (Table 1). Simulation periods were linked to the growing cycle starting with the initial soil water content measured in the field. Default values were selected for some parameters i. e. conservative parameters, canopy cover (CC) per seedling, water extraction pattern and average root zone expansion that were not measured during the experimental studies. Calibration was performed with the datasets of the field studies for pearl millet under rainfed conditions.

Data recorded during the crop growing season of 2011 were used for the calibration of the model, but separate validation was done for two different years (i) deficit year of 2012 when seasonal rainfall amounted <600 mm, and (ii) excess rainfall year 2013, to know the effect of water conservation practices and then predicting soil moisture, grain and stover yields as well performance of the model w. r. t. two contrast years. The predicted values were compared with the observed values of the experiment and the model validation performance statistics were analysed. The calibration process of AquaCrop described by Steduto *et al.* (2009) and Raes *et al.* (2009) was followed. Different observed parameters like climate, crop, management (i. e. rainfed and field management) and soil properties were incorporated as input in the model. Inputs for the crop development parameters, such as plant density, days to 90% emergence, time to recover, maximum canopy cover and time to harvest were from observations taken during the field studies while parameters, such as canopy growth and canopy decline coefficients were generated by the model from the observed values. Calibration of the model was started with the green crop canopy (CC) development and during this process, the importance of the coefficient of transpiration ($K_{c_{tr}}$) was observed as it is proportional to CC. Simulations were run and the $K_{c_{tr}}$ was reduced until a good fit was achieved for the CC of each crop under irrigated and rainfed treatments. The prediction error (Pe) and mean absolute error (MAE) were used as the error statistics to evaluate both calibration and validation results

of the model. The model efficiency (E) (Nash and Sutcliffe 1970) shows efficiency of the model in simulation of the parameters and coefficient of determination (R^2) shows the discrepancy between simulated and observed values. These error statistics were used to evaluate the predictive power of the model. In this study, the model output in terms of prediction for grain yield, stover yield and soil moisture in root-zone was considered for evaluation of the model. Model efficiency (CE) and R^2 approaching one and Pe and MAE close to zero are indicators for better model performance. Following equations were used to evaluate model (Sudhishri *et al.* 2016):

$$CE = \left\{ 1 - \frac{\sum_{j=1}^n (y_j - \hat{y}_j)^2}{\sum_{j=1}^n (y_j - \bar{y})^2} \right\} \times 100 \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{j=1}^n (y_j - \hat{y}_j)^2}{n}} \quad (2)$$

$$R^2 = \frac{\left[\sum_{j=1}^n (y_j - \bar{y}) \left(\hat{y}_j - \bar{\hat{y}} \right) \right]^2}{\left\{ \sum_{j=1}^n (y_j - \bar{y})^2 \sum_{j=1}^n (\hat{y}_j - \bar{\hat{y}})^2 \right\}^{1/2}} \quad (3)$$

Where, y_j and \hat{y}_j are observed and predicted values, \bar{y} and $\bar{\hat{y}}$ are mean of observed and predicted values, respectively; n is the number of observations and j is an integer varying from 1 to n. Prediction error (Pe) and mean absolute error (MAE) were calculated by using following equations:

$$Pe = \left[\left\{ \frac{\hat{y}_j - y_j}{y_j} \right\} \times 100 \right] \quad (4)$$

$$MAE = \sqrt{\sum_{i=1}^n \frac{(\hat{y}_j - y_j)}{n}} \quad (5)$$

RESULTS AND DISCUSSION

Observed and model simulated grain yield and stover yield are shown in Fig. 1 and 2, both for calibration and validation results and soil moisture in Fig. 3. It was observed that the grain yield varied from 1.17–2.11 t/ha during calibration and 1.38 –2.35 t/ha during deficit year 2012 and 1.71–2.47 t/ha during excess rainfall year 2013 (i. e. validation periods) under different water conservation practices. It was observed that the grain yield prediction

Table 2 Performance evaluation indicators of grain and stover yields simulation during calibration and validations periods, and soil moisture simulation at different dates of observations

Year/DAS	Pe (%)	MAE	RMSE	CE	R ²
<i>Grain yield</i>					
2011 (calibration)	-4 to 8	0.05	0.07	0.95	0.9615
2012 (validation)	2 to 15	0.15	0.17	0.73	0.9321
2013 (validation)	-21 to 9	0.17	0.19	0.44	0.9147
<i>Stover yield</i>					
2011 (calibration)	-23 to 39	1.61	1.67	-0.59	0.1139
2012 (validation)	-38 to 6	1.50	1.91	0.05	0.2057
2013 (validation)	-43 to 4	1.51	1.84	-9.12	0.1858
<i>Soil moisture</i>					
DAS					
21	-2 to 17	0.87	1.01	1.00	0.9997
65	43 to 64	11.42	11.48	-86.80	0.0899
75	-37 to -30	10.16	10.22	-98.16	0.0003
85	-1 to 18	1.21	1.44	0.07	0.6795
95	0.3 to 42	2.44	2.84	-1.37	0.3811
Harvest	15 to 74	4.96	5.26	-8.06	0.0018

DAS, Days after sowing

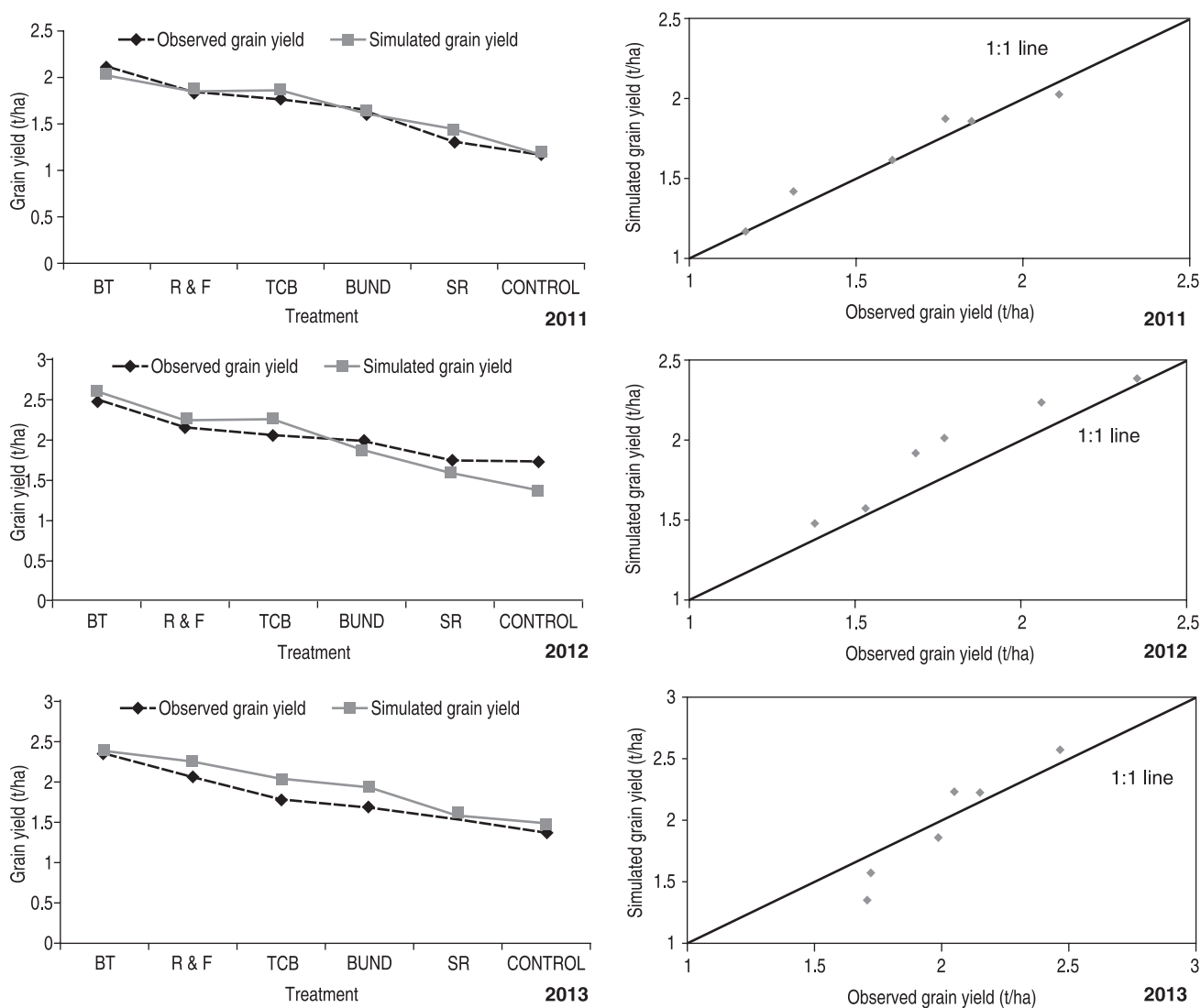


Fig 1 Grain yield simulation for 2011, 2012 and 2013 (observed and simulated).

when compared with data sets of deficit year 2012 and calibrated for 2011 resulted in absolute prediction error of 1.70, 8.74, 14.12, 14.88, 3.27 and 7.25% for BT, R&F, TCB, bunds, SR and control, respectively (Table 2). Similarly, for the data set of excess rainfall year 2013, the absolute prediction errors of 4.45, 3.72, 9.27, 6.53, 8.14 and 21.05, respectively were found. Prediction error (-21 to 9%) was more during the validation period as less variation occurred in grain yield due to high rainfall during 2013 compared to 2011 and 2012 (Table 2). Nash Sutcliffe Efficiency (CE), RMSE and coefficient of determination were better during calibration period (i. e. 0.95, 0.07 and 0.96, respectively) and validation period of 2012 (i.e. 0.73, 0.15 and 0.93, respectively), but during 2013 it was 0.44, 0.17 and 0.91, respectively (Table 2). These results show that the model was predicting satisfactorily during less rainfall year of <600 mm, whereas it was not predicting well for excess rainfall year, i.e. 2013.

Stover yield varied between 4.96 – 8.25, 5.02 – 10.39 and 7.54 – 9.16 t/ha during 2011, 2012 and 2013,

respectively. Basin-tillage *in-situ* water conservation measure showed highest yield compared to other. Stover yield prediction during validation period resulted in prediction error of -43 to 4% (Table 2). It was observed that the stover yield prediction when compared with validation data set of 2012 and calibrated using the 2011 data set, resulted in absolute prediction error of 37.63, 14.06, 9.91, 5.61, 19.19 and 37.05% for BT, R&F, TCB, bunds, SR and control, respectively. Similarly for the data set of 2013, the absolute prediction error of 22.16, 3.86, 20, 22.7, 43.03 and 1.86%, respectively were found. Nash Sutcliffe Efficiency (CE), RMSE and coefficient of determination were found to be 0.05, 1.91 and 0.21, respectively during validation period of 2012, and -9.12, 1.84 and 0.19, respectively during validation period of 2013 (Table 2). This shows there was no trend in stover yield estimation during deficit or excess rainfall year w. r. t. different water conservation practices.

It was observed that the AquaCrop model predicted the soil moisture due to the effect of water conservation measures very well. During validation period of soil moisture

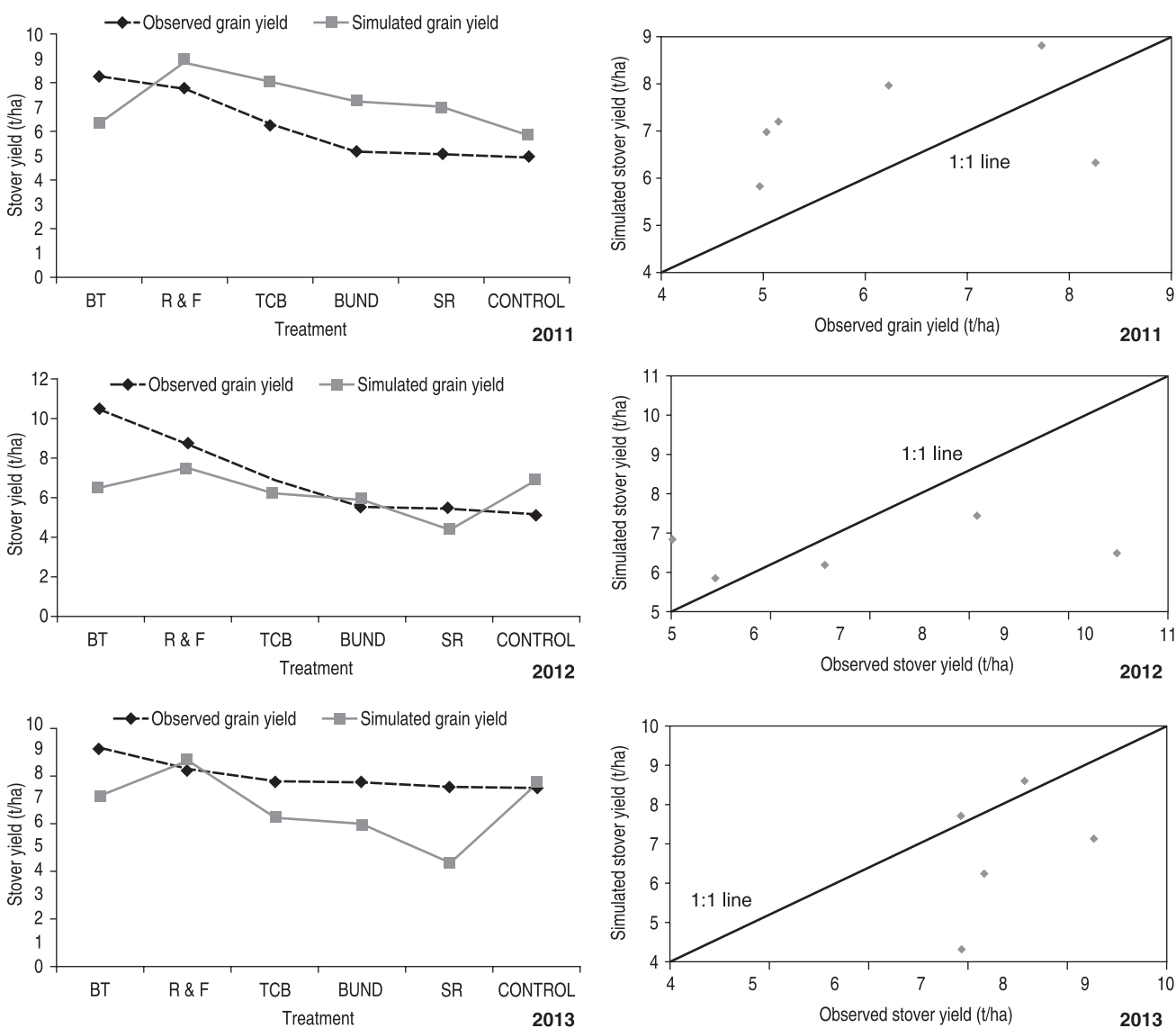


Fig 2 Stover yield simulation for 2011, 2012 and 2013 (observed and simulated).

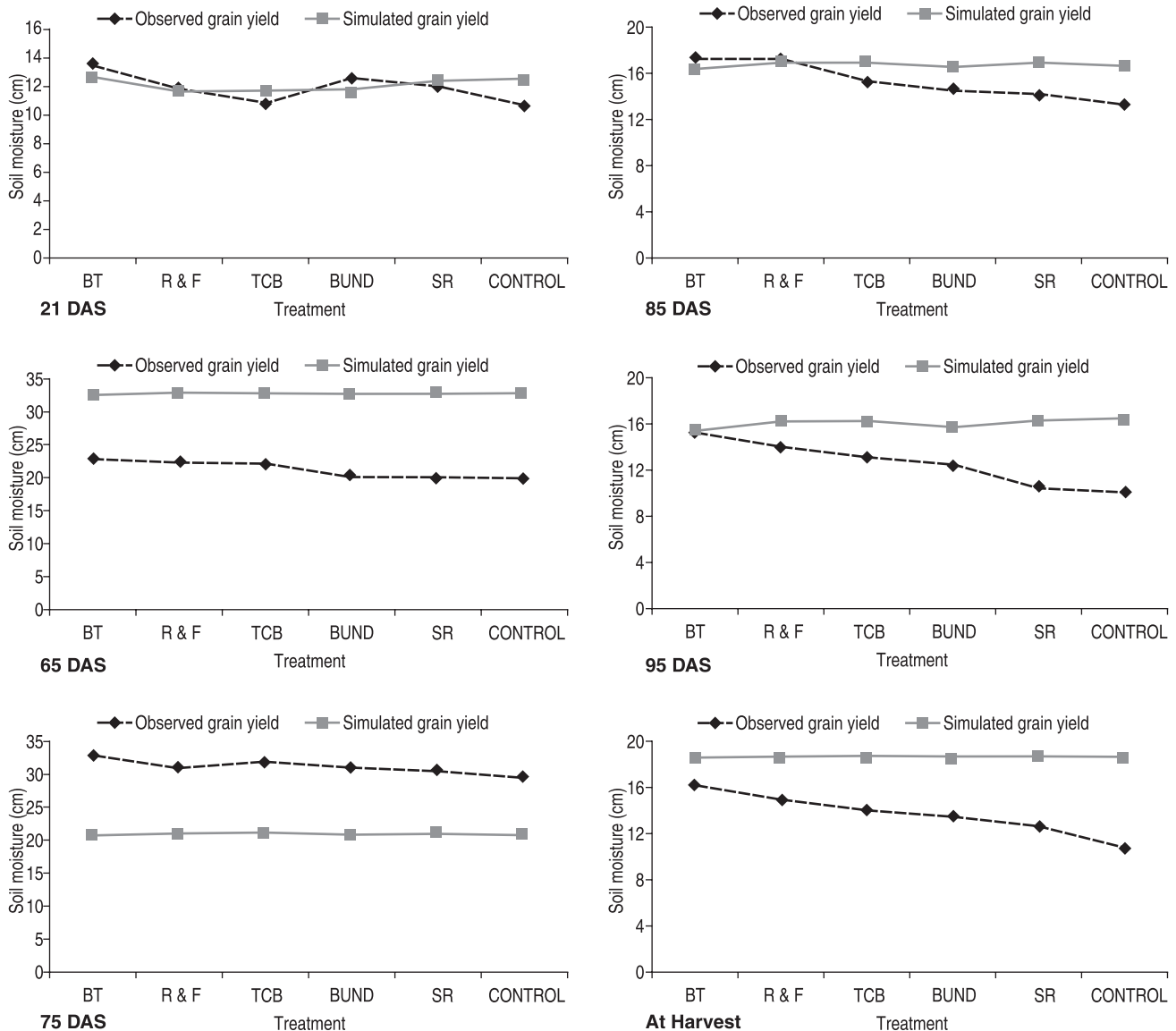


Fig 3 Soil moisture simulation at different dates of observation (observed and simulated) during 2013.

simulation, absolute prediction errors, MAE, RMSE were less and R^2 was higher during 21, 85 and 95 DAS (Table 2). This shows the model was predicting very well during the dry- spell period. During 21 DAS and 85 DAS, there were dry-spell periods, effect of soil water conservation through different measures was reflected through higher R^2 i. e. 1.0 and 0.68, respectively. During 95 DAS due to severe deficit of soil moisture, there was comparatively lower R^2 value i. e. 0.4. But, there was a little variation in soil moisture (predicted and observed) under basin-tillage method of water conservation measure (Fig 3). However, at 65, 75 DAS and at harvest, there was rainfall, so not much variation in the soil moisture due to different water conservation practices was observed due to which CE and R^2 values were very low (Table 4). This shows the positive effect of water conservation practices under dry-spell conditions and during excess and extreme deficit conditions, variation in impact of moisture conservation practices became negligible.

Statistical parameters (Fig 3) showed that the model was predicting well and basin-tillage (BT) method is better water conservation practice compared to others. Since basin-tillage method harvests the rainwater uniformly and the soil-water-plant environment is congenial for enhancing the vegetative growth and grain yield. The model was validated for simulating the grain yield for all moisture conservation measures with R^2 value of >0.91 , both for calibration and validation periods. However, the model did not predict stover yield satisfactorily, which corroborated with research done by Zeleke *et al.* (2011), Simba *et al.* (2013) and Paredes *et al.* (2014). Similarly, R^2 (0.38-0.9997) was better for moisture simulation during 21, 85 and 95 DAS, i.e. dry-spell periods. Difference in grain yield for different *in-situ* water conservation practices was due to moisture conserved during this deficit period of 85–95 DAS, i.e. panicle development and grain-filling stages. Since the total moisture harvested in BT is highest therefore, yield was also observed highest among different water conservation practices. Overall, the

model was overestimating for soil moisture prediction (Fig. 3). Bitri *et al.* (2014) and Paredes *et al.* (2014) also found slightly overestimation in canopy cover, biomass and water productivity when tried the AquaCrop model in potato and maize crop, respectively under deficit irrigation.

Pearlmillet grain and stover yields were significantly affected by different *in-situ* water conservation measures. AquaCrop model simulated soil moisture and yield during both calibration and validation processes indicated basin-tillage water conservation practices as the best method, though this model performed well for prediction of grain yield for all the moisture conservation practices also. Soil moisture prediction was better during dry-spell periods and also difference in soil moisture contents were observed during the panicle development and grain-filling stages, which were very well reflected in yield variations under different moisture conservation practices. Thus, the validated AquaCrop model can be used for prediction of pearlmillet yield with acceptable accuracy under different water conservation practices in a semi-arid environment.

ACKNOWLEDGMENTS

The authors wish to thank the Project Director, Water Technology Centre, and Dean, and Director, ICAR-Indian Agricultural Research Institute (IARI), New Delhi for providing necessary facilities to undertake and complete the research work.

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