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Evaluation of CropSyst Model for Simulating Green Area Index, Soil Water and Yield of Psyllium in Hyper Arid Partially Irrigated Zone of Rajasthan

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Abstract: Cropping systems model (CropSyst) was calibrated using the experimental data of crop parameters, soil profile data and observed daily weather data of experimental site for 2012-13 and validated the experimental data of crop growth, yield parameters and soil moisture for 2013-14 for psyllium crop grown at farmer's field in IGNP stage-II of Bikaner. The results of the present study showed that the CropSyst model calibrated seed yield, above ground biomass and soil moisture reasonably well. The simulated seed yield of psyllium (429 kg ha^{-1}) matched well with the observed yield (462 kg ha^{-1}) with relative error of 7.1%. The observed above ground biomass (AGB) at harvest (1085 kg ha^{-1}) also matched with simulated AGB (997 kg ha^{-1}) with relative error of 8.1%. During validation of the model during 2013-14, prediction of simulated seed yield (597 kg ha$^{-1)}$ was very good and matched well with the observed seed yield (557 kg ha^{-1}) with relative errors of 7.3%. However, the simulated AGB (1894 kg ha^{-1}) of psyllium was over predicted as compared to observed AGB (1395 kg ha^{-1}) with relative errors of 35.8%. The simulated green area index (GAI) was not properly captured by the model. The simulated N-uptake (34.0 kg ha^{-1}) was moderately higher than observed N-uptake (26.0 kg ha^{-1}). Simulated soil moisture was well predicted and excellent matched with observed values in most of the layers. About half of total water applied lost by deep drainage with water productivity of 0.17 kg m^{-3}.

Key words: CropSyst model, calibration, validation, psyllium, IGNP stage-II.

Water is one of the most critical inputs to agriculture. However, the level of water use differs significantly across regions, farming systems, canal command areas and even farm plots (Molden *et al.*, 2001, 2003). Globally, agriculture accounts for 80-90% of all freshwater withdrawals by humans and most of it is used for food production (Shiklomanov, 2000; Wallace, 2000; Morison *et al.*, 2008). Still, water is the main factor of abiotic stress limiting crop production in several regions of the world (Araus *et al.*, 2002; Ali and Talukder, 2008). It is projected that 47% of the world population will be living in areas of high water stress by 2030 (WWAP, 2009). Even where water for irrigation is currently plentiful, there are increasing concerns about future availability (Falkenmark, 1997). Since it is hardly possible to withdraw more water from natural resources, future food production must focus on the improvement of crop water productivity i.e. ´more crop per drop' (IWMI, 2000) and crop diversification. Indira Gandhi Nahar Pariyojana (IGNP) is considered as the life line of *Thar* Desert. It occupies the north-western and far western parts of the Thar Desert in Rajasthan through its expansion in stage I and stage II. The stage I is almost stabilized but stage II is still in quasi-equilibrium with respect to choice of crops and management practices. At present, the crops grown in IGNP stage-II are high water requiring and farmers use excess irrigation for growing the crops. Hence, technological interventions are required to improve water productivity of the area by promoting low water requiring, high value crops with efficient water management practices.

Simulation models are an important tool to understand soil-plant interactions on water balance components and their effects on yield and water productivity. The use of crop simulation models to evaluate crop responses to a wide range of management and

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Table 1. Soil physical and chemical properties of experimental site (pooled over two year)

Soil depth (m)	Soil parameters												
	Sand (%)	Silt (%)	Clay (%)	SOM (%)	pH_2	EC (dS m^{-1})	FC (m^3 m^{-3})	PWP (m^3 m^{-3})	Water content (m^3 m^{-3})	NO_3^--N (kg N ha^{-1})	NH_4^+-N (kg N ha^{-1})	BD (Mg m^{-3})	CEC [c mol (P^+) kg^{-1}]
0-0.15	86.5	7.8	5.7	0.13	7.6	0.18	0.153	0.077	0.067	13.15	33.43	1.55	4.2
0.15-0.25	85.4	8.4	6.2	0.07	7.8	0.11	0.157	0.079	0.069	11.09	29.12	1.53	4.5
0.25-0.50	85.3	8.6	6.0	0.08	7.9	0.12	0.164	0.082	0.069	11.49	28.45	1.53	4.5
0.50-0.75	84.4	9.0	6.5	0.12	7.9	0.15	0.168	0.083	0.076	11.01	26.97	1.54	4.8
0.75-1.00	84.1	9.3	6.5	0.11	8.0	0.1	0.167	0.086	0.074	9.13	22.51	1.52	5.0

environmental scenarios can give more timely answers to many management questions at a fraction of the cost of conducting extensive field experiments. They can assist field experimentation because direct measurement of all elements of the water balance (evaporation, transpiration, drainage, run off and profile water content) is often not possible. However, their accuracy to predict the accumulation of biomass with crop phenological stages viz. timing of flowering and physiological maturity must be ensured. Furthermore, accumulation of yield and crop water use is also needed to predict evapotranspiration and the extraction of soil water by crop roots, accurately (Richter and Semenov, 2005). CropSyst is a multi-year, multi-crop cropping systems model, which takes into account the effects of management practices on crop yield. It has been widely used for cereals and other cropping systems (Stockle *et al.,* 1994). It is credited with the capability to simulate the growth of many crops from a uniform structure and a common set of parameters. As the information pertaining to water productivity of psyllium and use of simulation models are non-existent for IGNP stage II. Hence, the present study was planned to evaluate the CropSyst model for simulating green area index, soil water, yield and N uptake of psyllium in hyper arid partially irrigated zone of Rajasthan.

Materials and Methods

Site description

A field experiment was conducted on farmer's field during rabi 2012-13 and 2013-14 at village Bajju (72°47'79"E longitude and 28°14'23"N latitude and 234.7 m above mean sea level) in Bikaner district of Rajasthan. Soil physical (texture and bulk density) and chemical (pH, electrical conductivity, cation exchange capacity, ammonical-nitrogen and nitrate - nitrogen) properties of experimental field were determined up to 1.0 m soil depth following the standard procedures (Table 1). The sand, silt and clay contents were determined with Hydrometer method (Bouyoucos, 1962), bulk density with core method (Blake and Hartge, 1986), electrical conductivity (EC) with conductivity meter, pH with pH meter (Richards, 1954), soil organic carbon by wet digestion method (Walkley and Black, 1934). ammonical nitrogen by Nessler's method (Peech *et al.*, 1947) and nitrate nitrogen by Phenoldisulphonic acid method (Harper, 1924; Prince, 1945). The field capacity was determined in the field by covering the fully saturated soil surface with a polythene sheet and measuring the moisture content after 24 hours. Soil moisture upto 1 meter depth (at an interval of 0-10 cm) was determined with a TDR-probe at regular interval during cropping season. In order to check the variability of field for soil properties, soil samples were collected from different spots of the experimental field. Daily weather data on maximum and minimum temperature, relative humidity (RH), evapotranspiration (ET) and rainfall during the crop growth period were recorded at meteorological observatory situated at CAZRI, RRS, Bikaner (Table 2).

Crop management

A pre-sowing irrigation of 100 mm was applied on 11th December, 2012 and 7th December, 2013 during first year and second year, respectively. When water content in surface soil dried to field capacity, field was prepared with disking, followed by harrowing and planking. Psyllium cultivar GI-2 with 8 kg ha^{-1} seed rate was sown on 13th December during the first year and on 9th December during the second year. The crop was sown at a spacing of 20 cm x 10 cm distance with seed drill. Nitrogen @ 40 kg ha^{-1} and P_2O_5 @

Table 2. Meteorological data during cropping season

Month	Temperature (°C)				Relative humidity (%)				Total rainfall (mm)		Evaporation (mm)		Solar Radiation (MJ m^{-2} d^{-1})	
	Maximum		Minimum		Maximum		Minimum							
	Y_1	Y_2	Y_1	Y_2	Y_1	Y_2	Y_1	Y_2	Y_1	Y_2	Y_1	Y_2	Y_1	Y_2
November	31.5	28.9	13.0	10.6	64.9	62.0	29.8	24.3	0.0	0.0	170.6	170.0	14.9	14.9
December	26.0	24.4	8.8	10.7	81.7	65.0	56.8	30.5	0.0	0.0	120.3	77.5	13.0	13.8
January	22.1	20.3	5.4	4.9	72.6	70.2	25.5	37.9	1.0	0.0	72.5	43.5	13.9	13.9
February	24.1	24.6	9.4	9.1	78.9	66.6	33.4	32.3	12.4	1.0	86.5	116.0	15.9	16.1
March	32.1	29.9	13.1	14.6	66.2	68.0	18.9	37.7	5.4	0.0	165.5	203.0	19.2	19.6
April	37.5	37.6	18.1	19.9	57.9	58.3	31.5	29.1	1.4	14.9	233.0	291.8	21.2	23.8

* Y_1 = Year 2012-13, Y_2 = Year 2013-14.

25 kg ha^{-1} were applied to the crop. Half dose of nitrogen and entire phosphorus was applied at the time of sowing and remaining half dose of nitrogen was applied at 30 days after crop sowing. Disease and insect-pest control were practiced as required.

Crop growth and yield data

Plant samples were taken at frequent intervals (during crop growth) and at harvest of crop for estimation of crop-based phenological growth and yield parameters viz. leaf area, rooting depth, above-ground biomass (dry weight at 70°C) and total plant nitrogen content. Grain yield was computed from crop cutting of 1 m × 1 m area at five different locations in the field and is converted in kg ha^{-1}.

Model setting

CropSyst crop model (Stockle *et al.,* 2003) version 4.15.24 was used to simulate seed yield, above ground biomass, water balance, N-uptake and water productivity of psyllium. The CropSyst model was calibrated using the observed data on phenological parameters/ stages (emergence, flowering, pod formation and physiological maturity) and harvest index from the experiment conducted during 2012-13 in the crop file of the model. The other parameters for the crop file were taken as default with slight adjustments. These adjustments were made within the range so that the periodic crop growth like phenological stages, periodic biomass and final seed yield were matched with the experimentally observed values. The crop parameters used in the model are given in Table 3. During the first step of calibrating the CropSyst model, simulated phenological stages (degree days) were calculated from the observed weather data, soil characteristics and the base temperature of the crops. Morphological parameters observed from the experiment and extracted from the literature were also adjusted in the CropSyst model. Harvest index (HI) was calculated from the observed data. The calibrated model was validated for grain yield, above-ground biomass (AGB), N uptake and soil moisture content using the observed data on crop parameters, weather and management practices in 2013-14 by comparing simulation outputs with observed data. Statistical test was used to calculate the percentage of difference between measured and predicted values of the crop in each growing season.

Results and Discussion

Soil characteristics

The physical and chemical characteristics of the soil of the experimental site are given in Table 1. The soil was loamy sand (87.7% sand, 7.5% silt and 5.5% clay) with low soil organic carbon, alkaline in reaction and non-saline in nature. The bulk density (BD), Cation exchange capacity (CEC), pH, permanent wilting point (PWP) and field capacity (FC) ranged between 1.51 to 1.55 Mg m^{-3}, 4.1 to 5.1 cmol (p^+) kg^{-1}, 7.5 to 8.0, 0.076 to 0.086 m^3 m^{-3} and 0.152 to 0.168 m^3 m^{-3}, respectively. The CEC, pH, PWP, FC and soil water content increased with increase in soil depth whereas, BD, NO_3-N, NH_4-N, soil organic matter and EC decreased with increase in soil depth. The initial soil water content, NO_3^--N, NH_4^+-N, soil organic carbon and electrical conductivity ranged between 0.061 to 0.073 and 0.072 to 0.079 m^3 m^{-3}, 9.12 to 14.37 and 9.13 to 11.92 kg ha^{-1}, 25.09 to 37.28 and 19.92 to 29.57 kg ha^{-1}, 0.06 to 0.13 and 0.07 to 0.12% and 0.09 to 0.17 and 0.11 to 0.18 d Sm^{-1}, respectively during 2012-13 and 2013-14.

Table 3. Crop parameters used for calibration of psyllium

Parameters	Value	Units
Thermal time accumulation		
Base temperature	5	(°C)
Cutoff temperature	30	(°C)
Phenology		
Degree days emergence		°C day
Degree days maximum rooting depth	200	°C day
Degree days end of vegetative growth	225	°C day
Degree days begin flowering	250	°C day
Degree days begin filling (°C day)	325	°C day
Degree days physiological maturity (°C day)	435	°C day
Canopy growth		
Initial green leaf area index	0.011	$m^2\ m^{-2}$
Minimum Green LAI for regrowth	0.011	$m^2\ m^{-2}$
Maximum expected LAI	4.0	$m^2\ m^{-2}$
Specific leaf area, SLA	23	$m^2\ kg^{-1}$
Fraction of maximum LAI at physiological maturity	0.9	
Leaf/stem partition coefficient, SLP	2	
Leaf water potential that begins reduction of canopy expansion	-800	$J\ kg^{-1}$
Leaf water potential that stops canopy expansion	-1200	$J\ kg^{-1}$
Transpiration		
Canopy extinction coefficient	0.50	
Evapotranspiration crop coefficient at fully canopy	1.15	
Maximum water uptake	10	$mm\ d^{-1}$
Leaf water potential at the onset of stomatal closure	-1500	$J\ kg^{-1}$
Wilting leaf water potential	-2500	$J\ kg^{-1}$
PAR use efficiency	5	$g\ MJ^{-1}$
Mean daily temperature that limits early growth	8	°C
Transpiration use efficiency when VPD is at 1 kPa	5.50	$g\ BM\ kg^{-1}\ H_20$
Scaling coefficient of TUE regression (power function)	0.45	
Harvest		
Unstressed harvest index (HI)	0.42	
Sensitivity to water and N stress during flowering (0.5-1.5)	1.50	
Sensitivity to temperature stress during flowering (0.5-1.5)	1.50	
Biomass translocation to grain fraction (max)	0.40	
Root		
Maximum rooting depth	1.3	m
Root length per unit root mass	120	$km\ kg^{-1}$
Maximum surface root density at full rooting depth	4	$cm\ cm^{-3}$
Curvature of root density distribution	2.5	

Model calibration

CropSyst calibration started with optimizing the base and cutoff temperature, while constantly updating growing degree days so that simulated phenological stages would always match observations. The base and cutoff temperatures determine the onset and speed of accumulation of growing degree days. Optimal simulation results were gained with a base temperature of 5°C and a cutoff temperature of 30°C. The other optimization values of

Table 4. Observed and simulated green area index (GAI) of psyllium

Measurement date	GAI ($m^2 m^{-2}$)	
	Observed	Simulated
2012-13		
12 Jan, 2013	0.0483	0.0402
15 Feb, 2013	0.6740	0.5323
16 March, 2013	0.1587	0.4150
RMSE	0.1690	
2013-14		
10 Jan, 2014	0.125	0.0483
02 Feb, 2014	0.726	0.4230
27 Feb, 2014	1.394	1.6534
16 March, 2014	0.155	0.0157
RMSE	0.2150	

physiological parameters viz. growing degree days, leaf/stem partition coefficient, radiation use efficiency and the biomass-transpiration coefficient etc. has been presented in Table 3. Model calibration was conducted following the procedure outlined by Hu *et al.* (2006). The calibrated model was implemented to generate data on periodic biomass, green area index (GAI), seed yield and N-uptake of the psyllium and used to compare with the observed field data during 2012-13. The simulated GAI, seed yield, above ground biomass and N-uptake were in good agreement to their observed values (Table 4). The maximum GAI of 0.67 was observed at 65-70 DAS which was very closer to simulated GAI (0.53 $m^2 m^{-2}$) with RMSE of 0.1690. The simulated seed yield of psyllium (429 kg ha^{-1}) matched well with the observed yield (462 kg ha^{-1}) with relative error of 7.1% (Table 5). Simulation of AGB development of psyllium also matched with the observed data.

Table 5. Quantitative measures of model performance for yield, AGB and N-uptake of psyllium for calibration and validation

Particular	Seed yield (kg ha^{-1})	AGB (kg ha^{-1})	N-uptake (kg ha^{-1})
2012-13			
Observed	462	1085	13
Simulated	429	997	20
Relative error (%)	7.1	8.1	53.8
2013-14			
Observed	557	1395	26
Simulated	597	1894	34
Relative error (%)	7.3	35.8	30.8

The observed AGB at harvest (1085 kg ha^{-1}) was well matched with simulated AGB (997 kg ha^{-1}) with relative error of 8.1%. Similarly, simulation of N-uptake by psyllium matched moderately with the observed data. The simulated N-uptake (13.0 kg ha^{-1}) was lower than observed N-uptake (20.0 kg ha^{-1}) which shows that N-uptake is under estimated by the model. Data presented in Table 6 show the root mean square error (RMSE), correlation coefficient and index of agreement values for soil moisture content. The RMSE values for soil moisture ranged from 0.0139 to 0.0785, in the different soil layers, while for 0-100 cm soil depth the RMSE value was of the order of 0.0607. Simulated value of soil moisture content was a good match with observed values in most of the layers up to 100 cm (Fig. 1). There was good correlation between observed and simulated soil moisture content except lower layers. Nash-Sutcliffe efficiency of different depth ranged between 0.92-0.99 which shows that model is good predictor of soil moisture.

The total water applied in psyllium was 332.8 mm out of this 84.5 mm may consume in ET. Thus, ET constituted 25.4% of total water applied and deep drainage constituted 56.8% and rest 23.7% stored as residual soil moisture. Results showed that about half of total water applied lost by deep drainage (Table 7) with water productivity of 0.13 kg m^{-3}.

Model validation

After calibration of the model for psyllium in 2012-13, it was validated for the next year crop of 2013-14. Comparison of observed and simulated results with respect to GAI, seed yield and AGB are shown in the Tables 4 and 5. During validation of the model in 2013-14, the simulated values for GAI of psyllium at different growth stages are in poor agreement with observed GAI with RMSE of 0.2150. Prediction of simulated seed yield (597 kg ha^{-1}) was very good and matched well with the observed seed yield (557 kg ha^{-1}) with relative errors of 7.3%. However, the simulated AGB 1894 kg ha^{-1} of psyllium was over predicted as compared to observed AGB of 1395 kg ha^{-1} with relative errors of 35.8%. The above ground biomass of the psyllium at maturity was not properly captured by the model. As it was set for optimal conditions, CropSyst could not properly simulate the late season plant stress

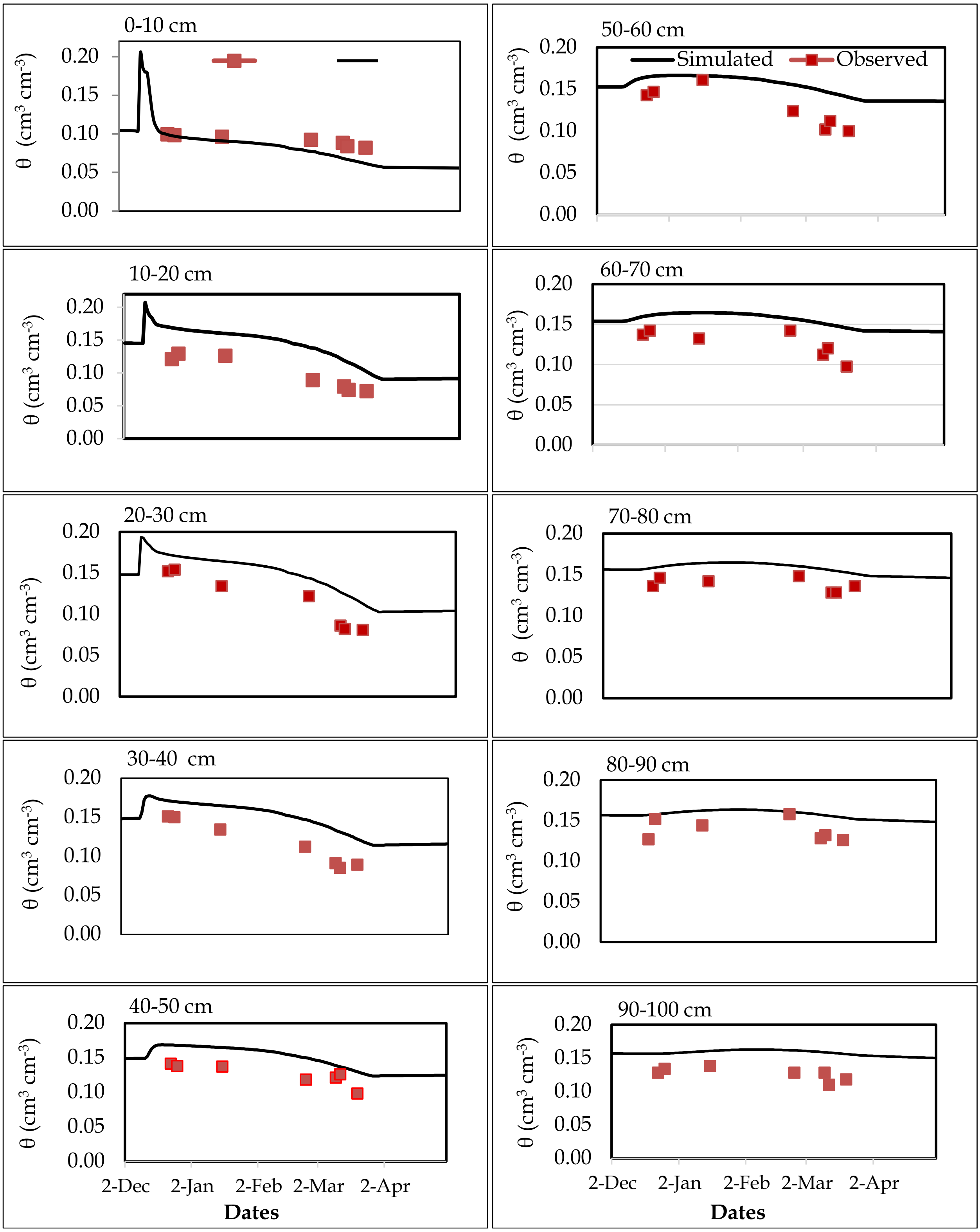

Fig. 1. Observed (squares field) and simulated (thick line) soil moisture (θ) during calibration year in 2012-13 of the psyllium field.

that impaired growth on these sites. Thus, the model is potentially more accurate at predicting grain yield than biomass (Singh *et al.*, 2013; Kumar *et al.*, 2016). Further, the simulated N-uptake of 34.0 kg ha^{-1} was moderately higher than observed N-uptake 26.0 kg ha^{-1}

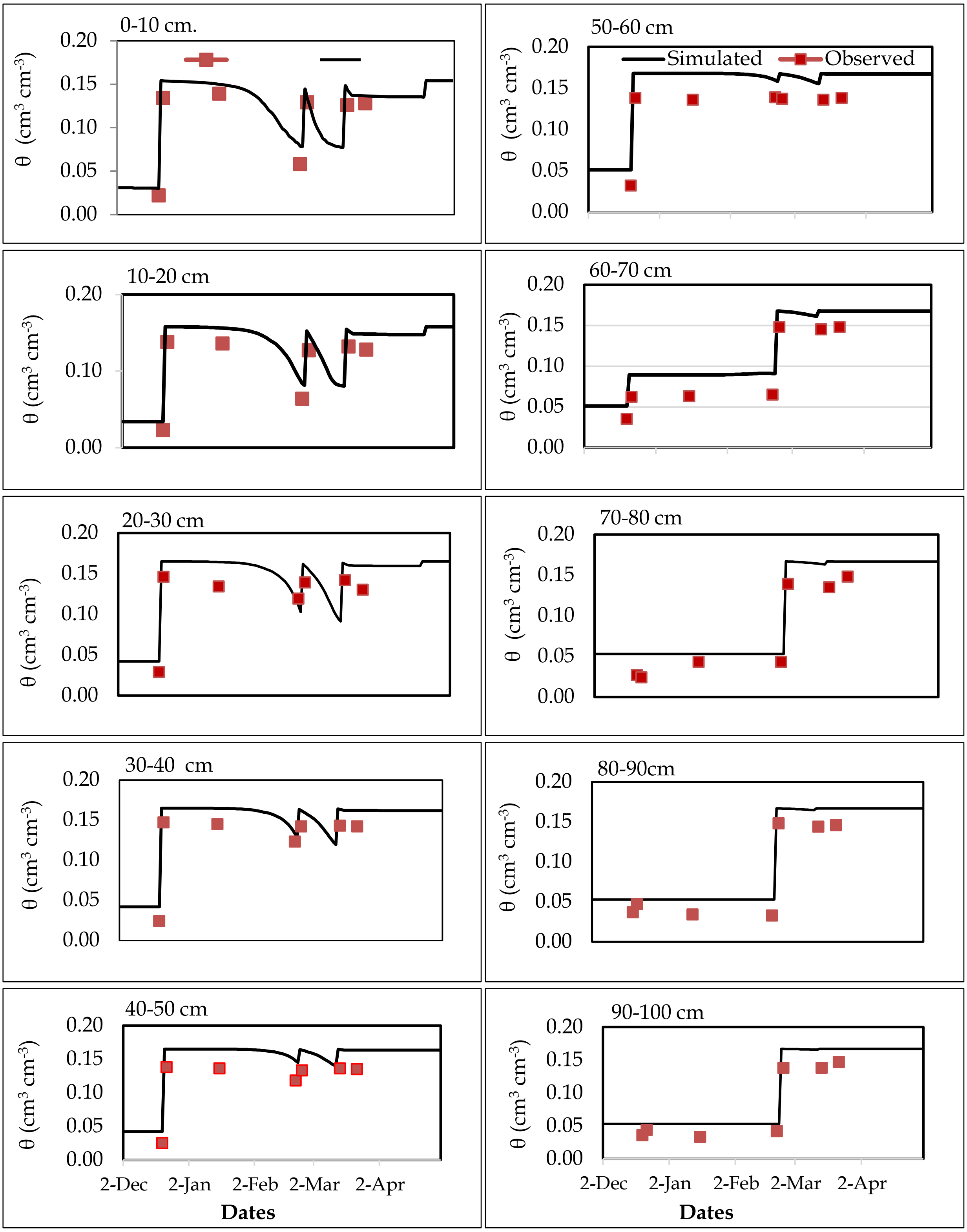

Fig. 2. Observed (squares field) and simulated (thick line) soil moisture (θ) during validation year in 2013-14 of the psyllium field.

with relative error of 30.8%. Increased uptake of N seems to be due to the fact that uptake of nutrient is a product of biomass accumulated by particular part and its nutrient content (Singh *et al.*, 2011). Data presented in Table 6 show the RMSE, correlation coefficient, index of

Table 6. Quantitative measures of model performance for soil moisture under psyllium

Soil layer	RMSE	Correlation coefficient	Index of agreement	Nash-sutcliffe efficiency
2012-13				
0-10	0.0139	0.979	0.65	0.998
10-20	0.0529	0.934	0.38	0.965
20-30	0.0420	0.847	0.66	0.981
30-40	0.0485	0.701	0.60	0.975
40-50	0.0575	0.829	0.52	0.962
50-60	0.0605	0.819	0.44	0.958
60-70	0.0717	0.574	0.39	0.936
70-80	0.0753	0.359	0.36	0.928
80-90	0.0785	0.061	0.29	0.919
90-100	0.0765	0.343	0.30	0.925
2013-14				
0-10	0.0143	0.991	0.97	0.998
10-20	0.0192	0.999	0.95	0.996
20-30	0.0214	0.961	0.93	0.996
30-40	0.0183	0.997	0.95	0.997
40-50	0.0274	0.999	0.90	0.993
50-60	0.0280	0.996	0.88	0.993
60-70	0.0228	0.996	0.94	0.994
70-80	0.0274	0.990	0.94	0.989
80-90	0.0184	0.997	0.97	0.996
90-100	0.0206	0.996	0.96	0.994

agreement and Nash-Sutcliffe for soil moisture content. The RMSE for moisture content ranged from 0.0143 to 0.0280, in the different soil layers, while for 0-100 cm soil depth the RMSE was 0.0222. Simulated soil moisture content was well predicted and excellent matched with observed values in most of the layers up to 100 cm (Fig. 2) with 0.95 index of agreement in entire soil depth of 0-100 cm. The low magnitude of RMSE and higher index of agreement revealed that soil moisture was well predicted by CropSyst at the field level. Nash-Sutcliffe efficiency of different depth also shows that model is very good predictor of soil moisture. Although the above situation provides only a limited evaluation of the model, it should be further tested for more data with varied treatments in different locations and years.

The total water applied in psyllium during validation period was 312 mm, out of this 90.5 mm may consume in ET. Thus, ET constituted 29.0% of total water applied and deep drainage constituted 48.7% and rest 22.6% stored as residual soil moisture. Results showed that about half of total water applied lost by deep drainage (Table 7) with water productivity of 0.17 kg m^{-3}. Water loss measured in other crops revealed ranges from 800 to 1000 mm for cotton (Aujla *et al.*, 1991) and 400 to 450 mm for wheat (Arora *et al.*, 1997). It is significant to note that there was net depletion of soil water storage in long duration crops like cotton and wheat.

Table 7. Soil water balance components, yield and water productivity of psyllium

Component	Year	
	2012-13	2013-14
Inputs		
Irrigation (mm)	332.8	312.0
Rainfall (mm)	20.2	1.0
Total (mm)	353.0	313.0
Losses		
ET (mm)	84.5	90.5
Drainage (mm)	189.4	152.0
Stored soil moisture (mm)	79.1	70.5
Yield and water productivity		
Seed yield (kg ha^{-1})	462	557
Water productivity (kg m^{-3})	0.13	0.17

*ET= Evapo-transpiration.

These results show trends and magnitudes of soil water depletion similar to field observations (Jalota *et al.,* 1985, 2006). In our study, deep drainage constitutes maximum water loss of applied irrigation water, so it can be checked by reducing depth of irrigation. For this separate experiments are needed on irrigation depth and intervals for checking deep drainage losses and improving water productivity.

Conclusions

It is obvious from the simulation results of CropSyst model that it can be used as an important tool for prediction of yield and water productivity of psyllium under arid conditions. The model simulates yield more accurately as compared to above ground biomass and nitrogen uptake. Hence more accurate information on field data and fine tuning of the model with respect to physiological parameters and cultural practices are required to validate the model.

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References

Ali, M.H. and Talukder, M.S.U. 2008. Increasing water productivity in crop production. *Agricultural Water Management* 95: 1201-1213.

Araus, J.L., Slafer, G.A., Reynolds, M.P. and Royo, C. 2002. Plant breeding and water relations in C_3 cereals: What should we breed for? *Annals of Botany* 89: 925-940.

Arora, V.K., Singh, C. and Singh, K. 1997. Comparative assessment of soil water balance under wheat in a sub-tropical environment with simplified models. *Journal of Agricultural Science* 128: 461-468.

Aujla, M.S., Singh, C.J., Vashist, K.K. and Sandhu, B.S. 1991. Evaluation of methods for irrigation of cotton (*Gossypium hirsutam*) in a canal irrigated area of south west Punjab, India. *Arid Soil Research and Rehabilitation 5*: 225-234.

Blake, G.R. and Hartge, K.H. 1986. Bulk density. In *Methods of Soil Analysis. Part 1 - Physical and Mineralogical Methods* (Ed A. Klute). Second Edition. American Society of Agronomy, Madison WI.

Bouyoucos, H.J. 1962. Hydrometer method improved for making particle size analysis of soils. *Agronomy Journal* 54: 464.

Falkenmark, M. 1997. Meeting water requirements of an expanding world population. *Philosophical Transactions of the Royal Society* 352: 929-936.

Harper, H.J. 1924. The accurate determination of nitrates in soils. *Industrial and Engineering Chemistry* 16: 180-183.

Hu, C., Saseendran, S.A., Green, T.R., Ma, L., Li, X. and Ahuja, L.R. 2006. Evaluating Nitrogen and Water Management in a Double-Cropping System Using RZWQM. *Vadose Zone Journal,* 5: 493-405.

IWMI 2000. Water issues for 2025. A research perspective. Research contribution to the World Water Vision. International Water Management Institute, Colombo, Sri Lanka, pp.50.

Jalota, S.K., Parihar, S.S. and Gajri, P.R. 1985. Drainage loss under different irrigation schedules and stage sensitivity of wheat to water stress. *Indian Journal of Agricultural Sciences* 55: 574-581.

Jalota, S.K., Sood, A., Chahal, G.B.S. and Choudhary B.U. 2006. Crop water productivity of cotton (*Gossypium hirsutum* L.) – wheat (*Triticum aestivum* L.) system as influenced by deficit irrigation, soil texture and precipitation. *Agricultural Water Management* 84: 137-146.

Kumar, R., Yadav, R.S., Yadava, N.D., Kumawat, A., Nangia, V., Glazirina, M., Rathore, V.S., Soni, M.L. and Birbal 2016. Evaluation of CropSyst model for clusterbean under hot arid condition. *Legume Research* 39(5): 774-779.

Molden, D., Murray-Rust, H., Sakthivadivel, R. and Makin, I. 2001. A water productivity framework for understanding and action. *Workshop on Water Productivity*. Wadduwa, Sri Lanka, November 12 and 13. ageconsearch.umn.edu/bitstream/127978/2/25.pdf.

Molden, D.C., Plaks, J.E. and Dweck, C.S. 2003. *A Meaning Systems Approach to Social Inference*. Symposium: Annual meeting of the Society for Personality and Social Psychology, Los Angeles, CA.

Morison, J.I.L., Baker, N.R., Mullineaux and Davies, W.J. 2008. Improving water use in crop production. *Philosophical Transactions of the Royal Society of London B. Biological Sciences* 363: 639-658.

Peech, M., Alexander, L.T., Dean, L.A. and Reed, J.F. 1947. Methods of Soil Analysis for Soil-Fertility Investigations. *U.S. Department Agricultural Circular* 25: 757.

Prince, A.L. 1945. Determination of total nitrogen, ammonia, nitrates, and nitrites in soils. *Soil Science* 59: 47-52.

Richards, L.A. 1954. Diagnosis and improvement of saline and alkali soils. *USDA Hand Book No. 60.* Oxford and IBH Pub. Co., New Delhi.

Richter, G.M. and Semenov, M.A. 2005. Modelling impacts of climate change on wheat yields in England and Wales: Assessing drought risks. *Agricultural Systems* 84(1): 77-97.

Shiklomanov, I.A. 2000. Appraisal and assessment of world water resources. *International Water Management Institute,* Colombo 25(1): 11-32.

Singh, A.K., Goyal, V., Mishra, A.K. and Parihar, S.S. 2013. Validation of CropSyst simulation model for direct seeded rice–wheat cropping system. *Current Science* 104(10): 145-153.

Singh, R.P., Yesh, P. and Singh, H. 2011. Effect of organic and inorganic sources of nutrients on growth, yield and quality of Indian mustard (*Brassica juncea* L.) under late sown condition. *Pantnagar Journal of Research 9*(2): 308-310.

Stockle, C.O., Martin, S.A. and Campbell, G.S. 1994. CropSyst a cropping system simulation model: Water/nitrogen budgets and crop yield. *Agricultural Systems* 46: 335-359.

Stockle, C.O., Ddonattelli, M. and Nelson, R. 2003. CropSyst, a cropping system simulation model. *European Journal of Agronomy* 18: 289-307.

Walkley, A. and Black, I.A. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* 37: 29-32.

Wallace, J.S. 2000. Increasing agricultural water use efficiency to meet future food production. *Agriculture, Ecosystems and Environment* 82: 105-119.

WWAP 2009. World Water Assessment Programme. The United Nations world water development report 3, Water in a changing world, Paris, UNESCO, and London, Earthscan.

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