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Validation and application of WOFOST model for yield gap analysis in selected soils of Maharashtra

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Abstract : The average productivity of cotton, sorghum and soybean in Maharashtra is considerably lower than their potential. There is also a large temporal and spatial variability in their productivity due to the spatial distribution of soils and its interaction with the rainfall pattern. WOFOST model-version 7.1 was validated and used for quantification of yield gaps under different rainfall patterns for cotton, sorghum and soybean on five soil series of Maharashtra. The validation results indicate that the model performed well with RMSE less than 20% and simulated the yields with Model efficiency (ME) values 0.73, 0.88 and 0.89 for cotton, sorghum and soybean, respectively. Between soil series, the variability in the mean simulated yield among years experiencing normal rainfall was higher for cotton (CV = 53.9%) than for sorghum (CV = 27.6%) or soybean (CY = 20.1%) as soil parameters significantly affected the cotton yields. There was significant correlation between simulated yield with soil depth (r = 0.91) and extractable soil moisture (r = 0.96) for cotton; but not for sorghum and soybean. It is concluded that the WOFOST model could capture the effects of spatial distribution of soil and rainfall pattern on the yields of cotton, sorghum and soybean and can compliment other techniques in suggesting alternative crop options for aberrant rainfall situations.

Additional key words: *Standardized precipitation index, soil series*

Introduction

Cotton, sorghum and soybean are the principal agricultural crops of Maharashtra, together occupying 54 per cent of its net sown area. They are predominantly grown under rainfed conditions on a variety of soils – Vertisols, Inceptisols and Entisols which are spread over 289 lakh ha (94% of the geographical area) (Challa *et al.* 1995). Although Vertisols and Inceptisols have high agricultural productivity potential (Alagarswamy *et al.* 2000), the average productivity of these crops in the state (330 kg lint ha^{-1} for cotton, 1482 kg ha^{-1} for *kharif* sorghum and 737 kg ha^{-1} for *rabi* sorghum, and 1493 kg ha^{-1} for soybean) is considerably lower than their potential. Moreover, large temporal and spatial variability exist in their productivity, which could be attributed to the spatial distribution of soils and its interaction with the rainfall pattern. Diagnosing the extent and causes of yield gaps is a pre-requisite for improving their performance.

Crop simulation models are being used to understand the complex soil-climate-crop interactions (Staggenborg and Vanderlip 2005), quantify yield gaps (Mathews *et al.* 2002) and diagnose its causes (Kalra *et al.* 2007). However, before application, these models have to be validated (Greenland *et al.* 1994; Rinaldi *et* *al.* 2003) wherein, model outputs are compared with measured or observed values using statistical estimates of bias like Root Mean Square Error (RMSE) and Model Efficiency (ME) (Loage and Green 1991). This paper describes the validation of WOFOST model-version 7.1 (Boogard *et al.* 1998) for cotton, sorghum and soybean and its application to quantify yield gaps on selected soils of Maharashtra (Challa *et al.* 1999) under different rainfall patterns.

Materials and Methods

Model Validation: The datasets used for validating WOFOST (Table 1) were collected from trials conducted at the research farm of the Central Institute for Cotton Research (CICR) for 8 years and on-farm trials conducted at Kokarda village for 2 years, both located in Nagpur district, Maharashtra. Daily weather data recorded at CICR was used for simulation. The crop files of WOFOST were modified using some of the coefficients developed for Indian cultivars in INFOCROP model (Aggarwal *et al.* 2006). The model was validated using RMSE and Model Efficiency (ME)

$$RMSE = \sqrt{\sum_{i-1}^{n}(O_i - S_i)^2/_n * \frac{100}{\tilde{O}}}$$

$$ME = \frac{\left[\sum_{i=1}^{n}\left(O_i - \tilde{O}\right)^2 - \sum_{i=1}^{n}(S_i - O_i)^2\right]}{\sum_{i=1}^{n}\left(O_i - \tilde{O}\right)^2}$$

Where O_i and S_i are observed and simulated yields and $\tilde{O}$ is the mean observed yield.

Model application : Details of the five selected soils (Challa *et al.* 1999) are presented in Table 2. Long-term (17-34 years) weekly data on rainfall for Nagpur, Yavatmal, Parbhani, Aurangabad and Washim districts which have sizeable area under Katol, Phulwari, Jintur, Vaijapur and Mangrulpir series, respectively were analyzed. Characteristics of the rainfall at different soil-site are presented in Table 3. Using Standardized Precipitation Index (Mckee *et al.* 1993), the rainfall patterns were classified into excess (wet), normal or deficit (dry) categories. The dry years were further categorized into initial dry, mid dry or late dry years based on the period of aggregation of negative values of SPI during the monsoon season. Years experiencing combinations of initial dry and mid dry, mid dry and

Table 1. Experimental details of data sets used for validation of WOFOST model

Crop	Period	Crop season	Sowing period	Treatment details	Reference
Cotton	1989-2000	Mid June to Mid Feb	Last week of June-first week of July	Long tem fertilizer trial on cotton using 90:45:45 (NPK) and recommended crop husbandry at CICR, Nagpur	Venugopalan *et al.* (2003)
Sorghum	1986-2000	Mid June to first week of November	Last week of June-first week of July	Long tem fertilizer trial at on sorghum-cotton rotation using 90:45:45 (NPK) and recommended crop husbandry at CICR, Nagpur	Blaise *et al.* (2003)
	2001-2002			On-farm seed priming trial on medium and deep soils at Kokarda village, Nagpur	Ramamurthy *et al.* (2006)
Soybean	2000-2002	Mid June to last week of October	Last week of June-first week of July	Evaluation of soybean productivity on different soils (Entisols, Inceptisols and Vertisols) under recommended crop husbandry on research farms at CICR, Nagpur and farmers' fields at Kokarda, Nagpur	NBSS 2002 and Ramamurthy *et al.* (2006)

Table 2. Soil and site characteristics of the benchmark soils

Series and location	Classification	Spread		Depth (cm)	Maximum extractable water (mm)	Mean annual rainfall (mm)	Growing period (met weeks)
		Area (00ha)	Districts				
Katol V: Mendki T: Katol D:Nagpur	Fine, smectitic, hyperthermic Typic Haplusterts	1372	Nagpur, Wardha, Amravati	146	220	1113	23-44
Phulwari V: Phulwari T: Kinwat D:Nanded	Clayey, mixed, iso-hyperthermic Lithic Ustorthents	627	Nanded, Yavatmal	18	19	1088	24-40
Jintur V: Wadachiwadi T: Jintur D:Parbhani	Fine, smectitic, iso-hyperthermic Typic Haplusterts	3820	Parbhani, Nanded, Latur, Beed, Yavatmal	137	246	737	25-44
Vaijapur V: Satana T: Vaijapur D:Aurangabad	Fine, smectitic, iso-hyperthermic Vertic Haplustepts	1356	Aurangabad, Ahmadnagar, Akola, Nashik, Latur, Yavatmal	65	109	731	27-44
Mangrulpir V: Chandhai T: Mangrulpir D:Washim	Clayey, smectitic, hyperthermic Lithic Haplustepts	1054	Akola, Washim, Nanded, Wardha, Yavatmal	41	73	832	25-43

late dry or initial and late dry were excluded for simulation.

Soils from benchmark locations were collected through field survey and analyzed for physical and chemical parameters necessary for preparing soil files of WOFOST. Daily rainfall data (9 years for Nagpur, 14 years for Yavatmal, 20 years for Parbhani, 10 years for Aurangabad and 20 years for Washim) was used for simulation. During survey, information on crops/cultivars grown, sowing and harvesting time, seed rate, nutrients used and yields obtained were collected by interviewing a group of farmers at each benchmark location. For normal, mid dry and late dry years, the date of sowing for cotton, soybean and sorghum was 25th June at Nagpur, 22nd June for Yavatmal and Washim, 20th June for Aurangabad and Parbhani. For initial dry years, a variable sowing date based on the actual rainfall pattern was selected. Potential yields of cotton, sorghum and soybean were simulated for each benchmark soil, using WOFOST model (version 7.1). Water limited yield (considering both water and oxygen stress) was estimated for each year using the "Read daily rainfall from separate file option". The water limited yields were reclassified into yield obtained during normal, initial dry, mid dry and late dry years obtained through SPI.

Results and Discussion

The relationship between observed and simulated yields indicates a good fit for sorghum (Fig.1b) and soybean (Fig.1c) and a slight overestimation in the simulated seed cotton yield (Fig.1a). Consequently, the R^2 value (Table 4) though significant, was lower for

Table 3. Rainfall characteristics at different locations

Location	No. of years	Minimum (mm)	Maximum (mm)	Mean (mm)	CV (%)
Nagpur	14	680.8	1238.2	959.7	4.6
Yavatmal	29	447.4	1506.7	976.5	27.6
Washim	35	518.2	2067.1	958.1	5.2
Parbhani	10	575.7	1333.0	901.0	8.1
Aurangabad	9	341.0	787.6	561.7	9.6

cotton. This could be due to inherent inability of the models to accurately account for the loss in fruiting forms due to pest damage and the compensatory mechanisms of the plants. Nevertheless, the simulated yields for all the three crops were within the experimental data variability (Table 4). The model also simulated yields with positive values of ME, which was closer to unity for sorghum and soybean than for cotton (Table 4). RMSE was less than 20 for all the crops indicating that the simulation could be rated 'good' (Jamieson *et al.* 1991).

Model application : Soil characteristics and climatic features of the benchmark locations are presented in Table 5. Katol site experiences hot, dry sub-humid climate (AESR 10.2) whereas the others experience semi-arid climate (AESR 6.2 and 6.3). Soils of Katol and Jintur series are Vertisols, that of Phulwari series is Entisol and those of Vaijapur and Mangrulpir series are Inceptisols. All the soils are clayey in texture but depth varies considerably from 18 to 146 cm (Table 5). The variation in length of growing period from 17 to 22 weeks is due to the difference in mean annual rainfall and soil depth.

Potential yields of cotton, sorghum and soybean for different locations, simulated through WOFOST varied within a narrow range (Fig. 2). In WOFOST, the potential yield of a cultivar is dependent upon radiation and temperature (Boogard *et al.* 1998). Since these sites are located within a narrow latitudinal range (19'34' N for Jintur to 21'21' N for Katol), the radiation and thermal regimes is not expected to vary considerably to result in differences in potential yield. The range in potential yield observed was comparable with the simulated potential yield with INFOCROP for

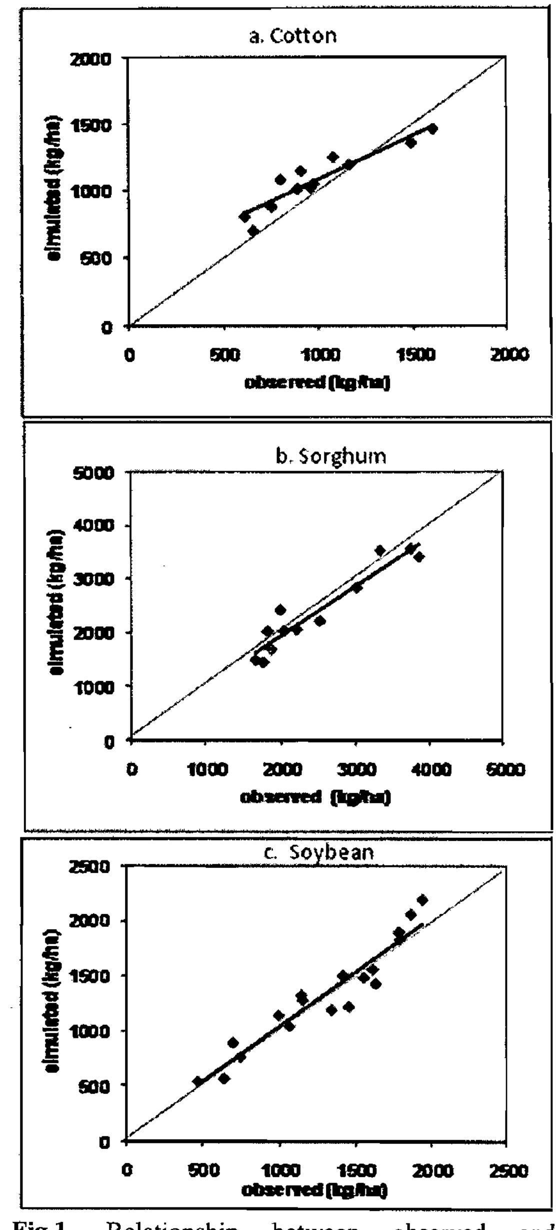

Fig.1. Relationship between observed and simulated yields for a) cotton, b) sorghum and c) soybean, the regression line and the 1:1 (Perfect accordance) line.

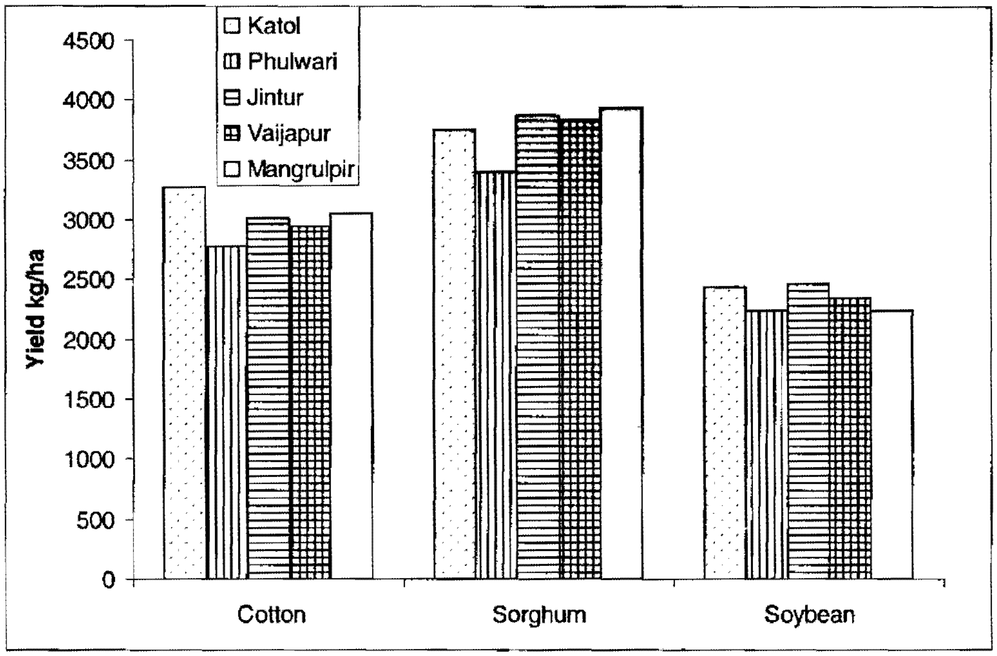

Fig. 2. Simulated potential yield of cotton, sorghum and soybean on benchmark soils

Table 4. Results and statistical indices of observed and simulated data

Crop	No. of observations	Observed yield (kg/ha)		Simulated yield (kg/ha)		R^2	RMSE (% of mean observed)	Model efficiency (ME)
		Mean	Std Dev	Mean	Std Dev			
Cotton	12	989	306.3	1077	220.1	0.78	15.6	0.73
Sorghum	12	2499	793.0	2392	771.0	0.89	10.5	0.88
Soybean	17	1300	455.3	1332	474.9	0.90	11.0	0.89

cotton (Hebbar *et al.* 2004), with DSSAT for soybean (Singh *et al.* 2002) and with CERES sorghum for sorghum (Singh and Thornton 1992).

Within series, the temporal variation in the simulated water limited yield (Table 5) could be attributed to the differences in the annual quantum and distribution of rainfall. Between series, the variability in the mean simulated yield among years experiencing normal rainfall was higher for cotton (CV = 53.9%) than for sorghum (CV = 27.6%) or soybean (CV = 20.1%) indicating that the role of soil parameters in governing the yields was more profound in the former. Cotton being a long duration crop, its productivity under rainfed conditions is strongly related to soil depth and plant extractable soil moisture (Kadu *et al.* 2003). Our study also indicates significant correlations between simulated yield with soil depth (r = 0.91) and extractable soil moisture (r = 0.96) for cotton; but not for sorghum and soybean. Deep soils (>100 cm) with high extractable water capacity (>200 mm) are most suitable for rainfed cotton (Sehgal and Yadav 1995) and soils of Jintur and Katol series fulfilled these criteria (Table 4) and were more productive than those of Mangrulpir and Phulwari series. Further, where rainfall is low (Jintur and Vaijapur), soil depth and extractable water capacity become more limiting for cotton (a long duration crop and deep rooted) than short duration crops viz. sorghum and soybean. Such soil - rainfall interactions are seldom captured by conventional soil-site suitability criteria, and hence

Table 5. WOFOST simulated yields, relative yield ratio and farm yield on benchmark soils

Series Range normal year	Range	Mean normal years	Relative yield ratio (mean dry year yield/ mean normal year yield)			Reported farm yield (kg-ha)
	Yield (kg ha^{-1}) lin		Initial dry year	Mid dry year	Late dry year	
			Cotton			
Katol	146-3014	1310	0.48	1.00	0.30	870
Phulwari	0-292	163	0.50	0.82	0.42	140
Jintur	142-2873	1526	0.25	1.00	0.22	1160
Vaijapur	101-2648	912	0.41	0.51	0.31	1800*
Mangrulpir	55-2730	835	0.66	0.79	0.48	650
Mean		**969**	**0.46**	**0.83**	**0.34**	730**
			Sorghum			
Katol	512-3467	1890	0.43	0.76	0.64	1500
Phulwari	110-1490	1008	0.31	0.37	0.57	950
Jintur	477-1782	1668	0.65	0.44	0.95	1250
Vaijapur	157-3077	2013	0.72	0.35	0.59	1380
Mangrulpir	248-3072	2328	0.64	0.65	0.88	1550
Mean		1781	**0.55**	**0.51**	**0.72**	1286
			Soybean			
Katol	67-1849	970	1.17	0.45	0.73	750
Phulwari	85-1345	759	0.36	0.96	0.43	640
Jintur	184-1317	1003	0.22	1.00	0.47	1060
Vaijapur	165-1044	812	0.72	0.57	0.90	NR
Mangrulpir	179-1714	1250	0.65	0.40	0.76	950
Mean		**958**	**0.65**	**0.68**	**0.66**	825

***** *with supplemental irrigation* ** *excluding Jintur NR- Not recorded*

simulation models (WOFOST) are more useful for their evaluation in a quantitative manner.

Soybean being a shallow rooted crop was less sensitive to soil variations and its productivity was more dependent upon seasonal rainfall. All the soils except that of Phulwari series (which was extremely shallow, 18 cm) were suitable for soybean. Alagarswamy *et al.* (2000) earlier reported that Vertisols and Vertic Inceptisols with more than 37 cm depth are equally productive but on soils with less than 37 cm depth, the productivity decreases whenever the rainfall is below normal.

Yield gap analysis (through relative yield ratio) indicated that, the reduction in the simulated yield for cotton was maximum, if dry period occurs during early stages and hence alternate crops viz. sorghum and soybean may be a better alternative whenever the onset of monsoon is delayed. However, cotton was least affected by mid season drought conditions, whereas sorghum and soybean were more sensitive and suffered greater yield losses. Generally, this period coincides with the grain (sorghum) and pod (soybean) development phases, which are physiologically critical for moisture stress. On the other hand, cotton is benefited by cloud-free conditions during this phase, which induces more flowering and prevents shedding of bolls. Cotton yields are adversely affected by late dry conditions (early withdrawal of monsoon) and hence the relative yield ratio was low. The simulation also ended 10-15 days earlier than the stipulated 190 days for cotton. For rainfed cotton, this phase coincides with the boll development phase which is the most critical period (de Kock *et al.* 1993). Soybean is equally sensitive to moisture deficit in all the three stages.

The average productivity reported by farmers was 75, 72 and 86 percent of the simulated yields (during normal years) for cotton, sorghum and soybean, respectively. Our survey further indicated that delayed sowing, inadequate plant population and sub-optimal plant protection measures were largely responsible for this yield gap.

To sum up, the RMSE and ME values indicated the satisfactory performance of WOFOST (version 7.1) in predicting yield of rainfed cotton, sorghum and soybean. Under each soil series, there are large gaps between potential, water limited and on-farm yields. A calibrated and validated crop simulation model can be successfully used for the estimation of potential as well as water limited yields under different rainfall patterns on diverse swell-shrink soils. Further, the model can compliment other techniques in suggesting alternative crop options for aberrant rainfall situations.

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