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Analysis of potential yields and yield gaps of rainfed soybean in India using CROPGRO-Soybean model

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ABSTRACT

To assess the scope for enhancing productivity of soybean (*Glycine max* L. Merr.), the CROPGRO-Soybean model was calibrated and validated for the diverse soybean-growing environments of central and peninsular India. The validated model was used to estimate potential yields (water non-limiting and water limiting) and yield gaps of soybean for 21 locations representing major soybean regions of India. The average water non-limiting potential yield of soybean for the locations was 3020 kg ha^{-1}, while the water limiting potential was 2170 kg ha^{-1} indicating a 28% reduction in yield due to adverse soil moisture conditions. As against this, the actual yields of locations averaged 1000 kg ha^{-1}, which was 2020 and 1170 kg ha^{-1} less than the water non-limiting potential and water limiting potential yields, respectively. Across locations the water non-limiting potential yields were less variable than water limited potential and actual yields, and strongly correlated with solar radiation during the season ($R^2 = 0.83$, $p \leq 0.01$). Both simulated water limiting potential yield ($R^2 = 0.59$, $p \leq 0.01$) and actual yield ($R^2 = 0.33$, $p \leq 0.05$) had significant but positive and curvilinear relationships with crop season rainfall across locations. The gap between water non-limiting and water limiting potential yields was very large at locations with low crop season rainfall and narrowed down at locations with increasing quantity of crop season rainfall. On the other hand, the gap between water limiting potential yield and actual farmers yield was narrow at locations with low crop season rainfall and increased considerably at locations with increasing amounts of rainfall. This yield gap, which reflects the actual yield gap in rainfed environment, is essentially due to non-adoption of improved crop management practices and could be reduced if proper interventions are made. The simulation study suggested that conservation of rainfall and drought resistant varieties in low rainfall regimes; and alleviation of water-logging and use of water-logging tolerant varieties in high rainfall regimes will be the essential components of improved technologies aimed at reducing the yield gaps of soybean. Harvesting of excess rainfall during the season and its subsequent use as supplemental irrigation would further help in increasing crop yields at most locations.

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1. Introduction

Worldwide, there is growing realization that the productivity of rainfed crops needs to be improved if the growing demand of food due to large increase in population is to be met. Rainfed agro-ecosystem constitutes 67% of the net cultivated area in India and accounts for 70% of oilseeds and 90% of pulses production of the country (Abrol et al., 1994). In recent years, soybean has established itself as a major rainy season crop in the rainfed agro-ecosystem of central and peninsular India. The region spread in latitudinal belt of about 15° to 25°N contributes to 98% of the total area under soybean in the country. Starting from just 30,000 ha in 1970, the area under soybean in India has increased to 8.8 million ha in 2007 (SOPA, 2007). The crop is predominantly grown on Vertisols and associated soils with an average crop season rainfall of about 900 mm which varies greatly across locations and years. Introduction of soybean in these areas has led to a shift in the cropping system from rainy season fallow followed by post-rainy season wheat or chickpea (fallow-wheat/chickpea) system to soybean followed by wheat or chickpea (soybean-wheat/chickpea) system. This has resulted in an enhancement in the cropping intensity and resultant increase in the profitability per unit land area. Besides improving the socio-economic conditions of small and marginal farmers of this region, the crop helps in meeting 14% of the total edible oil requirement of the country and earns substantial foreign exchange by exporting de-oiled cake (DOC). Despite its phenomenal growth in area, the average productivity of soybean has remained more or less stagnated at about 1000 kg ha^{-1} due to several abiotic, biotic and socio-economic factors (Paroda, 1999; Joshi and Bhatia, 2003; Bhatnagar and Joshi, 2004).

Several studies have shown that assessment of potential yield and yield gaps can help in identifying the yield limiting factors and in developing suitable strategies to improve the productivity of a crop (Aggarwal and Kalra, 1994; Lansigan et al., 1996; Evenson et al., 1997; Naab et al., 2004). Determination of the potential yield and gaps between potential and actual yields requires a thorough understanding of crop growth and development, which in turn depends on several climatic, edaphic, hydrological, physiological and management factors. Analyzing the effects of some specific factors without consideration of interactions and feedbacks from other controlling elements can often be misleading. For understanding such complex production systems, de Wit proposed four levels of crop production in order of descending productivity (Penning de Vries et al., 1989). In production level one, growth occurs with ample water and nutrient availability throughout the plant life. In such conditions, growth and productivity of a crop/cultivar are primarily determined by solar radiation and temperature. Yields obtained in this production level are also referred as the water non-limiting potential yields and its estimation is important for determining the scope of yield improvement (Aggarwal et al., 1994). At level two, growth is limited by water availability at least for a part of the plant life, thus decreasing crop growth rate and yield. Rainfed or partially irrigated crops with ample nutrients are examples of this production system. At level three, growth is limited by the shortage of nitrogen and water for some part of the plant life. In level four, growth is limited by additional shortage of phosphorus and other minerals. At all these levels, it is assumed that biotic factors are not a constrain to growth; however, biotic factors are obviously a fifth level of limitation. Crop productivity and yield gaps then can be quantified in terms of the differences of water non-limiting yields, water limiting yields, nutrient-limiting yields, and actual yields obtained by the farmers.

Identifying the yields at different production levels and quantifying the yield gaps through field experiments may involve many years of data collection on which to make meaningful inferences. Besides being time consuming and expensive, total elimination of factors other than the ones governing growth and development and their interactions for a given production level may not be possible in these field experiments. In recent years, several process based dynamic crop simulation models have been developed that predict crop growth, development and yield using systems approach that integrate knowledge of the underlying processes and interaction of different components of crop production (Boote et al., 1996). These simulation models are being increasingly used in the yield gap analysis by assessing the water non-limiting potential, water limiting potential or nutrient-limiting potential yields for a particular region with given environmental conditions that characterize the factors that define crop growth and development (Aggarwal and Kalra, 1994; Lansigan et al., 1996; Naab et al., 2004). However, before a model is put to use, it needs to be thoroughly tested and validated for given site/region to establish its credibility (Boote et al., 1996).

The CROPGRO-Soybean is one such model which has been developed to simulate vegetative and reproductive development, growth and yield as function of crop characteristics, climatic factors, soil characteristics and crop management scenarios. It is part of a suite of crop growth models available in the software named Decision Support System for Agrotechnology Transfer (DSSAT) (Boote et al., 1998; Hoogenboom et al., 1999). The model has been evaluated across a wide range of soil and climate conditions and has been used for various applications in temperate regions. However, the evaluation and application of CROPGRO-Soybean in tropical and subtropical regions such as India has been somewhat limited.

The objectives of the present study were (i) to evaluate the CROPGRO-Soybean crop growth model to simulate soybean growth, development, yield and soil water balance under rainfed conditions of central and peninsular India, and (ii) to use the model to estimate water non-limiting potential yield, water limiting potential yield and yield gaps in relation to water availability in the major soybean-growing regions of India.

2. Materials and methods

2.1. *CROPGRO-Soybean model*

Crop growth simulation models which share a common input data and format have been developed and embedded in a software package called Decision Support System for Agrotechnology Transfer (Tsuji et al., 1994). For this study we used CROPGRO-Soybean model v3.5, which is part of the DSSAT v3.5. The major components of the soybean model are vegetative and reproductive development, carbon balance, water balance and nitrogen balance. It simulates soybean growth and development using a daily time step from sowing to maturity and ultimately predicts yield. The physiological processes that are simulated describe the crop's response to major weather factors, including temperature, precipitation, and solar radiation, and include the effect of soil characteristics on water availability for crop growth. Daily photosynthesis is a function of light interception and the pool of carbohydrates available for growth is reduced by daily maintenance and growth respiration. The remaining carbohydrates are partitioned to vegetative and reproductive growth as a function of the development stage (Boote et al., 1998). The soil water balance is a function of precipitation, irrigation, transpiration, soil evaporation, runoff from the soil surface and drainage from the bottom of the soil profile and is calculated on a daily basis. Soil water is distributed among different soil layers with depth increments specified by the user. The water content of any soil layer can decrease by soil evaporation, root absorption, or flow to an adjacent layer (Ritchie, 1998). Actual plant water uptake and transpiration is a function of potential demand and potential supply and is the minimum of either demand or supply. If potential transpiration demand is higher than potential supply by the root system, a water stress factor is calculated. Water stress causes a reduction in photosynthesis and canopy abscission of plant material, depending on the timing and severity of the stress.

2.2. *Experiment details and data collection*

For model calibration, two field experiments and one pot experiment involving soybean cultivar JS 335 were conducted in randomized block design with three replications at Indore (22.7°N, 75.8°E). The cultivar JS 335 is the most popular and predominant cultivar in central and peninsular India (Bhatia et al., 2002). For the first field experiment, planting was done on June 24, 2001 in two separate blocks. One block was kept rainfed, while the other block was well irrigated to avoid any moisture stress. Second experiment was planted on June 29, 2002 under rainfed conditions only. Before planting seeds were treated with recommended fungicides and inoculated with Bradyrhyzobium culture. Recommended dose of fertilizers to supply NPK @ 20:26:17 kg ha^{-1} was applied at the time of planting. Plant population of 45 plants m^{-2} was maintained with a row-spacing of 45 cm. Standard agronomic practices for weed and insect control were uniformly followed to maintain plots free from biotic stresses. To develop genetic coefficients of soybean cultivar JS 335 for day length sensitivity traits and for duration of important life cycle phases, an additional pot experiment involving 14 planting dates between May 2001 and April 2002 was conducted. Plants were grown in 18 cm diameter cement pots containing coarse sand, black clayey soil and farm yard manure mixed in the ratio of 1:2:1. The pots were soaked with tap water 24 h before each planting. Ten seeds of uniform size treated with recommended fungicides and Bradyrhyzobium culture were sown in each pot. A week after germination, thinning was done to two plants per pot. The pots were watered daily and were kept free from biotic stresses.

For model validation, the data from field experiments conducted under rainfed conditions at three diverse locations were used. The experiments were conducted in 2001 at Patancheru (17.5°N, 78.3°E), and in 2003 at Bhopal (23.3°N, 77.4°E) and Indore (22.7°N, 75.8°E). Soybean cultivar JS 335 was planted on June 15 at Patancheru, on July 12 at Bhopal and on June 27 at Indore. All the agronomic practices were the same as described earlier except for plant density, which was maintained at 30 plant m^{-2} with 30 cm row-spacing at Patancheru and Bhopal, while at Indore it was maintained at 45 plants m^{-2} with row-spacing of 45 cm.

Data collection in these experiments was performed according to the experimental procedures for model calibration described by Hoogenboom et al. (1999). Data that were collected from field experiments included plant growth and development, crop management, daily weather conditions and soil water content. In pot experiment, data only on soybean phenology and daily weather conditions were recorded.

Besides the above experiments, data from the large number of field experiments involving varying seasons and management practices conducted with soybean cultivar JS 335 at diverse locations under All India Coordinated Research Project on Soybean (AICRPS) were also used for model evaluation. All the existing relevant data on the available field experiments conducted at five locations viz., Jabalpur (23.2°N, 79.6°E), Indore (22.7°N, 75.8°E), Amravati (20.9°N, 77.8°E), Parbhani (19.1°N, 76.8°E) and Dharwad (15.5°N, 75.0°E) were collected from the annual reports of All India Coordinated Research Project on Soybean (AICRPS, 1989–2003). This database included grain yield, days to flowering and days to maturity along with the relevant information on management practices adopted at each location in the field experiments conducted between 1989 and 2003.

2.3. *Model calibration and validation*

To simulate a crop cultivar, the CROPGRO-Soybean model requires 15 genetic coefficients (Table 1) that describe the growth and development characteristics for each individual cultivar. The genetic coefficients of the cultivar JS 335 were estimated by model iterations until a close match between simulated and observed phenology, growth and yield was obtained. The genetic coefficients determined through model calibration using the identical conditions as in the field experiments for soybean cultivar JS 335 are presented in Table 1. These coefficients were used in the subsequent validation and application.

Soil parameters required to determine soil water balance dynamics such as drained upper limit (DUL) of soil water content ($cm^3\ cm^{-3}$), lower limit (LL) of soil water content ($cm^3\ cm^{-3}$), saturated (SAT) water content ($cm^3\ cm^{-3}$), stage 1 soil evaporation coefficient (*U*, mm), runoff curve number (CN2), whole profile drainage rate coefficients (SWCON), etc. were initially estimated by inputting soil physical properties data such as soil texture (percentage of sand, silt, and clay), soil organic matter content and soil bulk density, etc., into a soil file creation utility programme of the DSSAT software. These estimated characteristics for the soil were further modified to make more specific for the experimental site,

Table 1 – Genetic coefficients of cultivar JS 335 obtained in calibration experiments

Cultivar trait	Acronym	Unit	Genetic coefficients
1. Critical short day length below which reproductive development progresses with no day length effect	CSDL	h	12.35
2. Slope of the relative response of development to photoperiod with time	PPSEN	h^{-1}	0.315
3. Time between plant emergence and flower appearance (R1)	EMFL	Photo thermal day	22.0
4. Time between first flower and first pod (R2)	FLSH	Photo thermal day	6.5
5. Time between first flower and first seed (R5)	FLSD	Photo thermal day	13.0
6. Time between first seed (R5) and physiological maturity (R7)	SDPM	Photo thermal day	32.0
7. Time between first flower (R1) and end of leaf expansion	FLLF	Photo thermal day	18.0
8. Seed filling duration for pod cohort at standard growth conditions	SFDUR	Photo thermal day	22.0
9. Time required for cultivar to reach final pod load under optimal conditions	PODUR	Photo thermal day	7.5
10. Maximum leaf photosynthesis rate at 30 °C, 350 vpm CO_2, and high light	LFMAX	CO_2 m^{-2} s^{-1}	1.03
11. Specific leaf area of cultivar under standard growth conditions	SLAVR	cm^2 g^{-1}	400
12. Maximum size of full leaf (three leaflets)	SIZLF	cm^2	180
13. Maximum fraction of daily growth that is partitioned to seed and shell	XFRT		1.0
14. Maximum weight per seed	WTPSD	g	0.155
15. Average seed per pod under standard growing conditions	SDPDV	Numbers per pod	2.20

following the procedure of Singh et al. (1994). The soils at the three sites are Vertisols and have extractable water capacity of 294 mm at Patancheru, 229 mm at Indore and 210 mm at Bhopal. The estimated value of *U* was 6.0 mm at all the sites. The values of CN2 and SWCON were 70 and 0.70, 70.0 and 0.50 and, 80.0 and 0.50 at Patancheru, Indore and Bhopal, respectively. A SLPF value of 1.0 was assumed for all the sites indicating that soil fertility was not a limiting factor for plant growth. To assess the performance of the CROPGRO-Soybean model, the model validation were made with the data generated from the field experiments carried out at three locations as well as with the data collected from large number of diverse experiments carried out under AICRPS (AICRPS, 1989–2003). The model performance was based on the agreement between simulated and observed data using statistical procedures.

2.4. Statistical evaluation of model performance

To evaluate model performance and accuracy in prediction, statistical indicators of root mean square error (RMSE) (Wallach and Goffinet, 1987) and Willmott (1982) index of agreement (*d* value) were computed from observed and simulated variables (leaf area index, total above ground biomass, seed biomass, days to flowering, days to maturity, grain yield and soil water content). The Willmott's *d* value is a better indicator of model performance, particularly relative to 1:1 line, than a correlation coefficient (r or R^2), and values closer to 1 indicate better prediction, while a *d* value of zero indicates no predictability.

2.5. Simulation for potential yield of soybean

The study was confined to a latitudinal belt of 15°N (Dharwad) to 24°N (Kota) encompassing the states of Madhya Pradesh, Maharashtra, Rajasthan and Karnataka together contributing to 98% of soybean area in India. Long-term simulations for potential yield were carried out for 21 locations (Table 2) under two scenarios i.e. water non-limiting and water limiting. Depending on the availability of weather data, the simulations were carried out for 18 to 30 years. All the locations selected for simulation of potential yields have Vertisols and associated soils representing the major soils on which soybean is grown in India. The data on soil characteristics of each of these locations were collected from the database published by National Bureau of Soil Survey and Land Use Planning (Lal et al., 1994).

For long-term simulation of potential yield and water balance components of soybean, the CROPGRO-Soybean model v3.5 coupled with seasonal analysis program of DSSAT was used. For water non-limiting potential yield the simulated crop was sown on 22 June every year taking into account the recommended optimum planting time for major soybean-growing region of India (Bhatia et al., 1999). The water, nutrient and pest controls switches of the model were kept off. For simulation of water limiting potential yield, only the water balance switch of the model was activated. The model simulations were initiated on 15 May each year and the soil profile was considered to be at the lower limit of water availability (SLL) on that day. The sowing window assumed was 1 June to 30 July considering the spatial and temporal variations in the onset of rainy season and actual farmers' practice in the target region. The simulated crop was sown on the day when the soil moisture content in the top 30 cm soil depth reached at least 40% of the extractable water-holding capacity during the sowing window. The plant population of 35 plants m^{-2} at 30-cm row-spacing was considered throughout the simulation study. A soil fertility factor (SLPF) of 1.0 was used for all sites to simulate the crop yield without any soil fertility limitations.

Table 2 – Geographical details, period of weather data used and soil characteristics of the locations selected for simulation of potential yields of soybean in India

Location	Latitude (°N)	Longitude (°E)	Period	No. of years	Soil depth (cm)	Extractable soil water (EXSW) (mm)
Kota	25.18	75.83	1965–1996	30	188	224
Rajgarh	24.00	76.72	1969–1996	26	140	165
Sagar	23.83	78.72	1969–1996	28	140	165
Vidisha	23.53	77.82	1970–1996	27	140	165
Shajapur	23.50	76.25	1969–1996	26	160	195
Ujjain	23.42	75.50	1969–1996	28	160	195
Ratlam	23.32	75.05	1969–1995	27	160	195
Bhopal	23.27	77.40	1974–2003	30	140	165
Jabalpur	23.17	79.57	1975–1996	22	150	177
Hoshngabad	22.75	77.72	1975–1997	22	140	90
Indore	22.72	75.83	1975–2003	29	160	54
Dhar	22.60	75.30	1973–1996	24	160	195
Betul	21.83	77.83	1975–1996	22	240	283
Raipur	21.23	81.65	1973–1999	27	160	201
Nagpur	21.15	79.10	1969–1996	28	144	160
Amravati	20.93	77.75	1976–1994	19	240	283
Wardha	20.83	78.60	1975–1992	18	150	178
Akola	20.50	77.17	1969–1996	28	240	283
Parbhani	19.13	76.83	1975–2003	29	240	270
Nanded	18.92	77.50	1969–1994	26	240	283
Dharwad	15.47	75.02	1975–2003	29	170	189

2.6. *Actual yields*

The district yields represent the average productivity of the crop in diverse farmers' fields and are the product of climate of the area and management practices adopted by the different farmers. Soybean in all the districts, to which the 21 locations belonged, is grown in rainfed environment. Hence, district yields were used as actual yields and were compared with simulated potential yields to quantify yield gaps of soybean in India. The district yields were calculated from the district wise area and production data published by the Directorate of Oilseeds Research (Damodaram and Hegde, 2002). The district yields of 3 normal years (1995 to 1997) were averaged out for calculating the actual yield for each location for which simulations were carried out. The soybean variety JS 335 was released for cultivation in 1993 and by 1995 was spread over 70% of the total soybean area in central and peninsular India. Also the 3 years period was short enough to meet the criterion of unchanged technology for yield gap analysis.

3. Results and discussion

3.1. *Model validation*

Evaluation of the CROPGRO-Soybean model with the experimental data collected at three locations indicated that the model predicted different growth stages reasonably well. The errors in prediction of days to flowering, pod initiation and seed initiation were in the range of −1 to +3 days, −1 to +4 days and −1 to +2 days, of observed dates, respectively (Table 3). The model prediction for days to physiological maturity ranged from −4 to +10 days at these locations. When the model was evaluated with large number of experimental data that included 35 experimental data sets of different years and management practices conducted at 5 diverse locations under AICRPS revealed that model was able to reasonable predict well the days to flowering and days to maturity (Fig. 1a and b). The average predicted days to flowering and days to maturity in these experiments were 37.1 and 99.4 days as against

Table 3 – Simulated (S) and simulated minus observed (S − O) days after sowing to flowering, pod initiation, seed initiation and physiological maturity of soybean cultivar JS 335 obtained from validation experiments conducted at three locations in India

Location	Planting date	Flowering		Pod initiation		Seed initiation		Physiological maturity	
		S	S − O	S	S − O	S	S − O	S	S − O
Patancheru	15 June, 2001	37	3	47	4	58	1	97	10
Indore	27 June, 2003	37	−1	47	−1	56	−1	94	-4
Bhopal	12 July, 2003	35	2	45	2	53	2	89	1
RMSE			2.1		3.0		3.2		8.0
d value			0.81		0.78		0.88		0.78

d, Willmott index of agreement (Willmott, 1982), ranging from 0 to 1, 1 being perfect agreement.

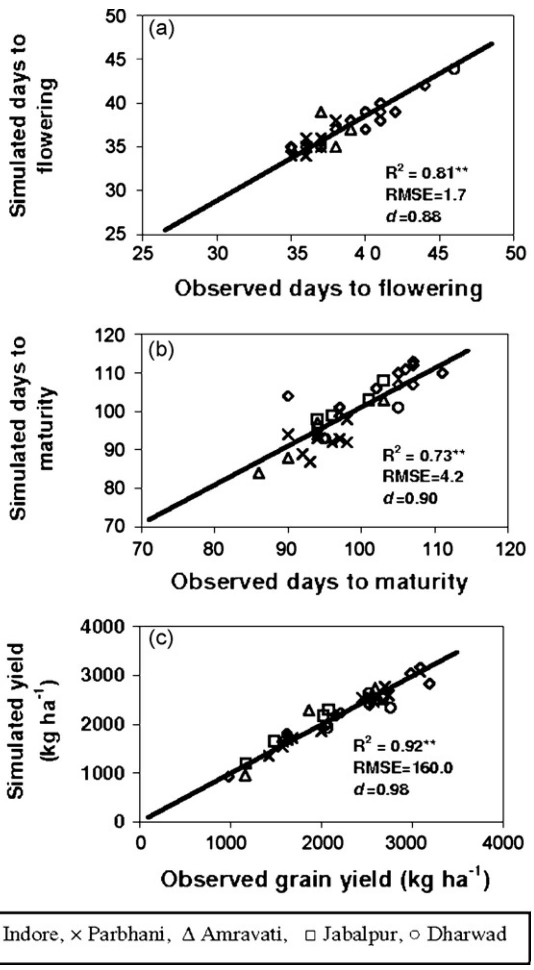

Fig. 1 – Comparison of simulated and measured (a) days to flowering, (b) days to maturity and (c) grain yield at harvest of soybean cultivar JS 335 using AICRPS experimental data sets (n = 35). d, Willmott index of agreement (Willmott, 1982), ranging from 0 to 1, 1 being perfect agreement.

observed values of 38.5 and 98.3, respectively. The value of RMSE for days to flowering and days to maturity were 1.7 and 4.2 days, while d values were 0.88 and 0.90, respectively, indicating a good agreement between the simulated and observed values. The R^2 values for predicted and simulated days to flowering and days to maturity were 0.81 and 0.73, respectively. Hence, it was established that the CROPGRO-Soybean model was able to simulate the observed duration to flowering and maturity reasonably well for most treatments and at all the sites selected from the main soybean-growing region of India.

The evaluation of model for crop growth in terms of leaf area index, total biomass and seed weight at different durations observed at 3 diverse locations indicated that the model also predicted the growth characteristics reasonably well. The observed and simulated leaf area index, crop biomass and grain weight at three locations are presented in Fig. 2. The RMSE and d values for LAI ranged from 0.29 to 0.69 and 0.89 to 0.99, for crop biomass 554 to 774 kg ha^{-1} and 0.96 to 0.98 kg ha^{-1}, and for grain weight from 167 to 570 kg ha^{-1} and 0.81 to 0.99 kg ha^{-1}, respectively. The observed average grain yield at harvest of 35 experimental data sets was 2140 kg ha^{-1} as against simulated average of 2150 kg ha^{-1}. The RMSE and d value for grain yield at harvest were 160 and 0.98 kg ha^{-1} indicating a close agreement between the simulated and observed value of grain yield for these diverse experiments (Fig. 1c).

For simulation of soil water balance under rainfed environment, the model was also validated for soil moisture changes in the soil profile using the soil moisture data collected at Patancheru and Indore. The simulated and observed changes of soil moisture content during the season at various depth of the soil profile at Patancheru and Indore are presented in Fig. 3. At Patancheru, the RMSE and d values for soil moisture content ranged from 0.015 to 0.033 cm^3 cm^{-3} and 0.62 to 0.94 cm^3 cm^{-3}, respectively, indicating a good agreement of observed and simulated values. Similarly, at Indore, the RMSE for soil moisture content ranged from 0.023 to 0.052 cm^3 cm^{-3} and d values were between 0.67 and 0.91. Hence, the model was able to predict moisture content in soil profile of these soils reasonably well.

3.2. *Simulated water non-limiting potential yield of soybean*

Depending on climatic conditions, considerable spatial and temporal variability in simulated water non-limiting potential yield was observed (Table 4). When averaged over locations, the water non-limiting potential yield was 3020 kg ha^{-1} with a coefficient of variation of 11.1%. Among locations, mean simulated potential yield ranged from 2290 kg ha^{-1} (Dharwad) to 3670 kg ha^{-1} (Dhar). Similarly, there was a wide variability in minimum and maximum yields recorded over the simulation period at each location. The coefficient of variation for this temporal variability ranged from 6.2 to 22.7% among these locations. The average minimum yield of these locations (2070 kg ha^{-1}) was 46% less than the average maximum simulated yield (3850 kg ha^{-1}).

Yields obtained in these simulations were governed only by climatic conditions and the data on solar radiation and temperatures are presented in Table 5. The long-term mean solar radiation, minimum and maximum temperatures for crop growth period of these locations ranged from 13.0 to 20.5 MJ m^{-2} day^{-1}, 20.4 to 26.3 °C and 27.6 to 34.7 °C, respectively. As soybean is grown during the rainy season in India, depending upon the monsoon activity over locations and years, large fluctuations are observed in solar radiation. This was also evident in the present study as during the crop period, both spatial and temporal variability in solar radiation was relatively of greater extent as compared to minimum and maximum temperatures. Using measured and simulated data, Spaeth et al. (1987) have reported that high soybean yields in Japan are dependent on high solar radiation and moderately cool temperatures. In our study, the mean simulated water non-limiting potential yields of selected locations showed a significant ($p \leq 0.01$) positive association (R^2 = 0.83) with mean crop season solar radiation (Fig. 4). On the other hand, the maximum and minimum temperatures did not show any significant association with simulated yields indicating that most of the variability in potential yield of these locations in India was accounted by the variability in the solar radiation.

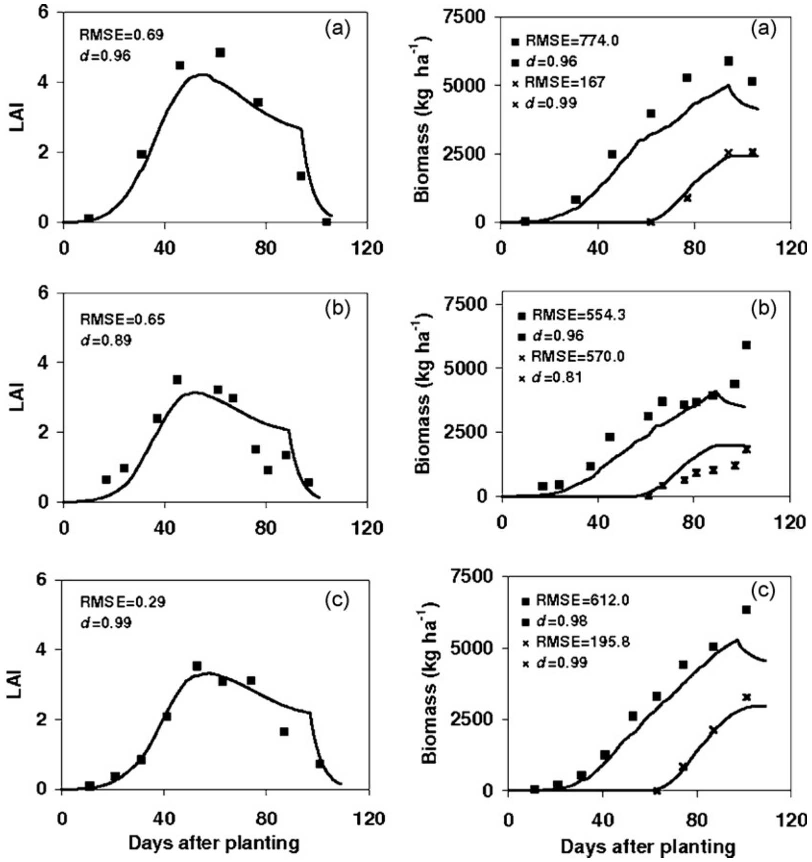

Fig. 2 – Comparison of simulated (lines) and observed (data points) values of leaf area index (LAI), above ground biomass (■) and seed weight (×) of soybean cultivar JS 335 at (a) Indore, (b) Bhopal and (c) Patancheru. *d*, Willmott index of agreement (Willmott, 1982), ranging from 0 to 1, 1 being perfect agreement.

3.3. *Simulated water limiting potential yield of soybean*

Due to rainfed nature, the planting of soybean in India totally depends on the onset of rainy (monsoon) season which varies across years and locations. The normal arrival of monsoon in target region is from 10 June to 25 June. In rainfed trails conducted over years involving 5 planting dates ranging from 20 June to 30 July (Bhatia et al., 1999), the highest average seed yield of soybean irrespective of genetic variability was obtained with 20 June planting and marginally declined as the planting was delayed till 10 July. Beyond 10 July, there was a sharp decline in the soybean yield. However, because of hard (when dry) and sticky (when wet) consistency of the Vertisols, the general practice among the soybean farmers is to plant the crop at the first opportunity after the first monsoon showers. Also being the most remunerative and a cash crop, farmers in the command area of soybean do plant it beyond 10 July in case of delayed arrival of monsoon. Considering these factors, the sowing window for simulation of water limiting potential yield was kept between 1 June and 30 July. The average planting time of the selected locations was 21 June with a coefficient of variation of 1.4% indicating that by and large the crop was planted within an optimum time period. Among these locations, the mean planting time ranged from 15 June to 28 June. The coefficient of variation for temporal variability in planting time at selected locations ranged from 3.9 to 8.2%.

Under water limiting conditions, the average simulated potential yield of soybean was 2170 kg ha^{-1} with a coefficient of variation of 22.6% (Table 4). Among these locations, the water limiting potential of the crop ranged from 1150 kg ha^{-1} (Dharwad) to 3060 kg ha^{-1} (Wardha). There was a wide variability in minimum and maximum yields recorded over the simulation period at each location. The coefficient of variation for this temporal variability ranged from 10.2 to 76.1% at these locations. The average minimum yield of the locations (900 kg ha^{-1}) was 73% less than the average maximum simulated yield (3300 kg ha^{-1}). As productivity at this level was primarily governed by the water availability (rainfall) besides other elements of weather, both the spatial and temporal variability in simulated water limiting potential yield was of very high magnitude as compared to simulated water non-limiting potential yield. Such large variations in simulated water limiting yield explain the degree of fluctuations in soybean productivity under rainfed conditions in India. However, there was only one location (Dharwad) where total failure of the crop in one season (2002) was observed during the simulation period. The failure was due to meager amount of rainfall (41 mm) (Table 6) received during the crop season at this location. The failure of the crop in farmers' fields in the district and also the experimental station located at Dharwad was reported for crop season 2002 (AICRPS, 2003).

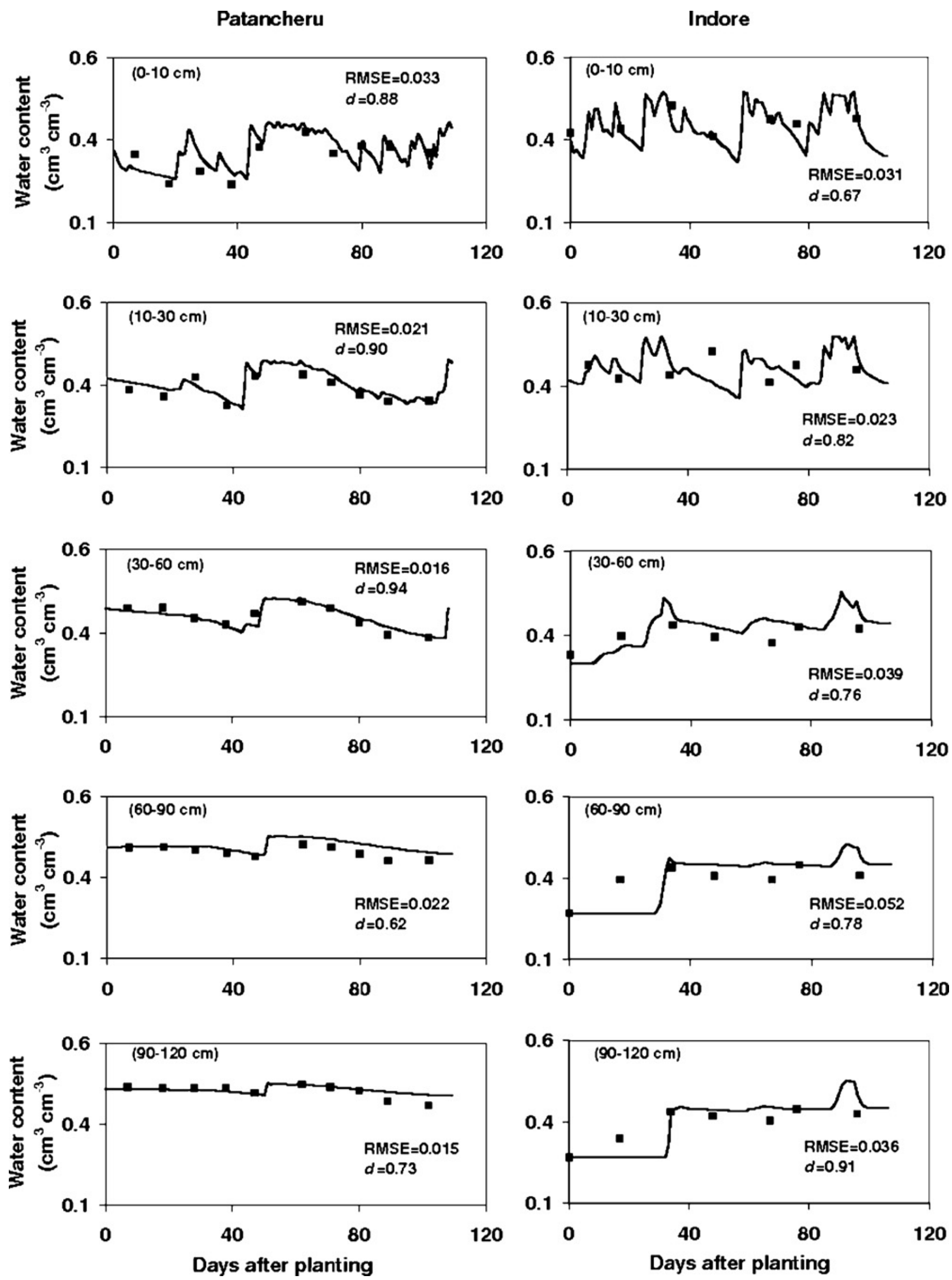

Fig. 3 – Comparison of simulated (lines) and observed (data points) soil moisture content in different soil layers at Patancheru and Indore. *d*, Willmott index of agreement (Willmott, 1982), ranging from 0 to 1, 1 being perfect agreement.

When the mean simulated water limiting potential yield was plotted against the mean crop season rainfall of these locations, a significant ($p \leq 0.01$) positive; but curvilinear relationship ($R^2 = 0.59$) (Fig. 5) was observed. The simulated yields increased with increasing rainfall from 420 to 1240 mm, which was the range of long-term mean crop season rainfall at these locations. However, the rate of increment in yield was of greater extent between 420 and ~800 mm, above which the rate of increase in yield in response to increasing rainfall showed a lesser trend. In contrast to simulated water non-limiting potential yield, no significant association was observed between mean simulated water limiting potential yield and mean crop solar radiation of these locations. This indicated that at this production level the variability in potential yield across the locations was largely governed by the availability of water.

The model simulations of water balance components are presented in Table 6. There was a considerable spatial and temporal variability in the crop season rainfall, total runoff and deep drainage of water at selected locations. The average crop season rainfall was 924 mm which ranged from 423 mm (Dharwad) to 1241 mm (Jabalpur). It was also evident that on an average 283 mm of water, which is 31% of the average rainfall of these locations, is lost as surface runoff. Among the

Table 4 – Simulated yield (water non-limiting and water limiting), actual yield and yield gaps of soybean at selected locations across India

Locations	Simulated potential yield ($kg\,ha^{-1}$)								Actual yield ($kg\,ha^{-1}$) (C)	Yield gap ($kg\,ha^{-1}$)		
	Water non-limiting				Water limiting					Due to water limitation (A–B)	Due to factors other than water availability (B–C)	Total (A–C)
	Minimum	Maximum	Mean (A)	CV[a]	Minimum	Maximum	Mean (B)	CV[a]				
Kota	630	3990	2880	22.7	120	3820	1340	76.1	1140	1540	200	1740
Rajgarh	2300	3750	2990	10.9	490	2950	1880	39.0	970	1110	910	2020
Sagar	2460	3602	3000	10.6	720	3280	2150	30.4	840	850	1310	2160
Vidisha	2190	4620	3170	14.5	1030	3640	2540	23.3	950	630	1590	2220
Shajapur	1660	3280	2820	14.2	820	3550	2070	39.8	1010	750	1060	1810
Ujjain	1560	3880	2960	17.0	780	3010	2080	36.0	1100	880	980	1860
Ratlam	1810	3520	2760	15.9	630	3190	2080	40.8	1250	680	830	1510
Bhopal	2120	3630	2890	13.6	820	3260	2410	26.5	890	480	1520	2000
Jabalpur	2330	3120	2730	6.2	1340	2800	2390	16.6	860	340	1530	1870
Hoshangabad	1940	5400	3180	20.3	1850	3360	2690	17.0	1130	490	1560	2050
Indore	2340	3770	3210	10.0	920	3410	2520	30.5	1150	690	1370	2060
Dhar	2130	4550	3670	15.3	630	4320	2670	36.3	950	1000	1720	2720
Betul	2510	3600	3240	6.3	1080	3290	2420	24.5	760	820	1660	2480
Raipur	2420	3410	2830	9.5	2350	3450	2890	10.2	870	−60	2020	1960
Nagpur	2080	3200	2680	11.1	1010	2770	2050	23.2	900	630	1150	1780
Amravati	2480	4860	3610	15.7	600	3040	1790	41.6	1130	1820	660	2480
Wardha	1990	4430	3330	20.6	2030	3940	3060	19.7	1040	270	2020	2290
Akola	2120	3690	2990	13.6	140	2640	1510	53.1	1250	1480	260	1740
Parbhani	1930	3620	2670	21.6	1160	3260	2040	27.2	1130	630	910	1540
Nanded	2730	4220	3450	10.4	370	3820	1850	56.7	1130	1600	720	2320
Dharwad	1780	2730	2290	10.1	0	2520	1150	66.4	630	1140	520	1660
Average	2070	3850	3020		900	3300	2170		1000	850	1170	2020
CV[a]	21.5	16.5	11.1		67.4	13.7	22.6		16.2	55.8	42.3	16.0

[a] CV, coefficient of variation (%).

Table 5 – Solar radiation and minimum and maximum temperatures during crop period of simulated soybean at selected locations across India

Location	Solar radiation (MJ m^{-2} day^{-1})				Minimum temperature (°C)				Maximum temperature (°C)			
	Minimum	Maximum	Mean	CV[a]	Minimum	Maximum	Mean	CV[a]	Minimum	Maximum	Mean	CV[a]
Kota	10.4	21.3	17.2	13.5	24.0	28.9	26.3	4.6	29.7	36.7	34.7	4.3
Rajgarh	15.3	20.0	18.0	5.9	22.9	25.5	24.2	2.5	31.7	36.0	33.7	3.5
Sagar	12.4	21.2	16.5	9.9	18.5	23.9	22.8	4.6	29.2	34.4	31.8	4.0
Vidisha	15.2	21.5	18.8	6.7	18.6	24.6	22.8	5.5	31.5	35.9	33.3	3.0
Shajapur	13.7	20.6	16.7	8.7	21.9	24.1	23.2	2.6	30.1	34.6	32.3	3.5
Ujjain	12.6	19.3	16.9	10.2	21.2	25.0	22.4	3.5	29.6	34.0	31.8	3.4
Ratlam	12.4	19.1	16.1	10.4	20.0	25.0	22.9	4.6	28.5	33.2	31.6	3.3
Bhopal	13.7	18.9	16.6	6.3	22.2	24.3	23.0	2.2	29.8	34.0	31.9	3.3
Jabalpur	12.9	17.9	16.3	6.7	23.0	24.4	24.0	1.2	29.8	32.9	31.7	2.0
Hoshangabad	13.3	25.6	18.2	18.5	18.0	24.9	23.2	8.3	29.1	34.1	31.9	4.5
Indore	13.8	19.9	17.3	8.5	21.7	24.5	23.2	3.3	29.7	34.0	32.0	4.2
Dhar	15.3	21.5	19.2	9.2	18.6	23.0	21.2	5.5	29.2	33.9	31.8	3.4
Betul	14.6	20.6	17.8	6.7	21.1	22.2	21.7	1.0	28.6	31.8	30.1	2.2
Raipur	12.6	17.9	15.2	9.4	22.4	25.7	23.9	3.5	29.1	33.2	31.7	3.1
Nagpur	14.5	18.7	16.7	6.3	23.1	25.1	23.9	2.0	31.0	34.5	32.9	2.6
Amravati	17.2	24.0	20.5	8.5	20.7	25.5	24.5	4.7	31.3	36.3	34.5	2.9
Wardha	12.0	23.1	18.8	13.9	21.2	23.9	23.1	2.9	29.8	34.9	32.0	4.2
Akola	17.7	19.5	17.5	7.5	21.9	25.3	23.5	2.6	30.9	34.6	33.2	3.0
Parbhani	10.9	19.4	14.5	18.8	19.7	23.5	22.5	3.7	30.1	35.0	32.5	3.3
Nanded	16.8	21.3	19.0	5.9	19.7	24.2	22.4	3.7	31.5	35.0	33.2	2.6
Dharwad	10.6	15.2	13.0	10.3	19.2	21.4	20.4	2.3	26.2	29.1	27.6	2.3
Average	13.7	20.3	17.2		20.9	24.5	23.1		29.8	34.2	32.2	
CV[a]	15.0	11.1	9.9		8.3	6.0	5.3		4.3	4.8	4.6	

[a] CV, coefficient of variation (%).

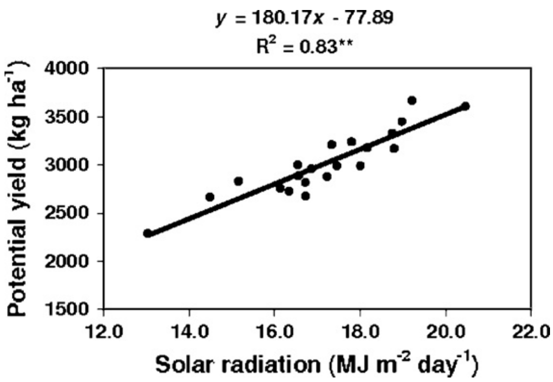

Fig. 4 – Association of long-term mean simulated water non-limiting potential yield with mean crop season solar radiation among selected locations across India.

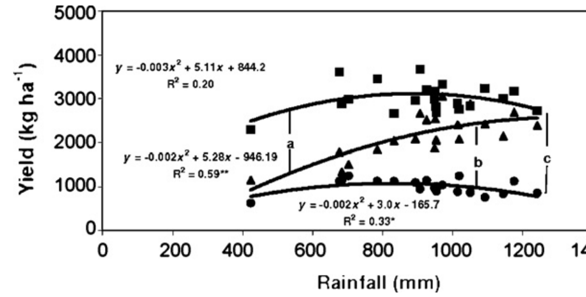

Fig. 5 – Association of long-term mean simulated water non-limiting potential yield (■), mean simulated water limiting potential yield (▲) and actual yield (●) with mean crop season rainfall among selected locations across India. (a, yield gap between simulated water non-limiting and water limiting yield, b, yield gap between simulated water limiting and actual yield and, and c, yield gap between simulated water non-limiting and actual yield or total yield gap).

locations, the loss of water through surface runoff ranged from 16 to 37% of the total rainfall received.

3.4. *Actual yield of soybean*

The actual yields (district average yields) were very low and ranged from 630 kg ha^{-1} (Dharwad) to 1250 kg ha^{-1} (Akola and Ratlam) with an average value of 1000 kg ha^{-1} as compared to simulated water non-limiting (3020 kg ha^{-1}) and water limiting potential yield (2170 kg ha^{-1}) (Table 4). Actual yield also showed a significant ($p \leq 0.05$) positive and curvilinear relationship with the mean crop season rainfall ($R^2 = 0.33$) (Fig. 5) at these locations. The spread of yield data around the fitted regression line indicated the effect of rainfall distribution and soil properties on the yield of soybean and explains the variability in actual farmers' yield among the locations. However, compared to simulated water limited yield, the rate of increment in actual yield in response to increase in rainfall was very low. Also the observed marginal increase in actual yield in response to increasing rainfall was only up to ~700 mm and between ~700 and ~900 mm of rainfall there was no substantial change in the yield. An increase in rainfall beyond 900 mm resulted in a negative impact on the actual yield. The negative impact of rainfall beyond ~900 mm could be due to poor drainage conditions and resultant water-logging in the farmers' fields, indicating the need for adoption of management practices to overcome the problem of poor drainage and water-logging. On the other hand, yield response between ~400 and 900 mm brings out the importance of the factors other than the water availability which limit the realization of rainfed potential of the crop. Besides suboptimal availability of water, the crop management factors such as suboptimal use of nutrients, suboptimal planting time, poor plant population, and infestation with weeds, pests and diseases that limit the productivity of rainfed soybean in India have been reported by several workers (Paroda, 1999; Joshi and Bhatia, 2003; Bhatnagar and Joshi, 2004).

3.5. *Yield gaps of soybean*

The simulation of water non-limiting and water limiting yields across a large number of locations in major soybean-growing region of India clearly indicated that there is high yield potential of the crop, which is not presently realized by the farmers. The average actual yield of the farmers at these locations (1000 kg ha^{-1}) was 2020 and 1170 kg ha^{-1} less than the average simulated water non-limiting and water limiting potential yields indicating a 67 and 54% reduction in actual yield as compared to water non-limiting and water limiting potentials, respectively. It is important to appreciate that the model accurately predicted yields in the evaluation trials at various research stations in India. Total yield gap (water non-limiting minus actual yields) ranged from 1510 to 2720 kg ha^{-1} (Table 4) and was more or less unaffected by the quantity of rainfall received at these locations (Fig. 5).

The magnitude of yield loss due to suboptimal water availability was 850 kg ha^{-1} (Table 4) and varied considerably from location to location (0–1820 kg ha^{-1}) depending on the magnitude of rainfall received. The gap in yields was very large at locations with low rainfall and it narrowed considerably with the increase in rainfall (Fig. 5). At about 850 mm of rainfall, the yield gap because of water deficiency was almost the same that caused by other factors limiting crop yield. Hence, water deficiency appears to be the main cause for reduction in yield up to ~850 mm of rainfall. As soybean in India is mainly cultivated under rainfed conditions, reducing yield losses due to suboptimal water availability may not be possible unless rainfall conservation technologies and cultivars tolerant to drought conditions are developed and adopted.

On the other hand, the gap between actual and water limited yields which ranged from 260 to 2020 kg ha^{-1}, were narrow at locations with low rainfall and increased considerably as the quantity of rainfall increased among the locations. This gap in yield (which reflects the actual yield gap in a rainfed environment) is mainly caused by non-adoption of improved crop management practices (improved cultivars, nutrient, pest and disease management, optimum plant density and planting time, etc.) and can easily be reduced if proper interventions are made. Also, higher gains in produc-

Table 6 – Water balance components of simulated soybean at selected locations across India

Location	Rainfall (mm)				Runoff (mm)				Deep drainage (mm)			
	Minimum	Maximum	Mean	CV[a]	Minimum	Maximum	Mean	CV[a]	Minimum	Maximum	Mean	CV[a]
Kota	300	1475	683	39.3	24	656	212	69.5	0	183	39	145.6
Rajgarh	423	1701	948	30.1	71	826	328	54.8	0	439	152	70.4
Sagar	442	2047	1144	30.6	84	891	396	53.1	0	592	267	53.2
Vidisha	562	1627	950	25.3	90	680	245	65.3	0	444	150	71.6
Shajapur	589	1751	952	24.9	77	842	320	54.6	0	447	113	87.1
Ujjain	454	1821	893	32.7	98	930	315	57.3	0	404	90	117.8
Ratlam	582	1851	1018	30.2	146	890	378	48.7	17	399	153	72.5
Bhopal	462	1684	1014	27.2	72	761	337	47.9	0	455	191	61.0
Jabalpur	592	1986	1241	24.3	124	1000	368	63.2	0	576	343	44.3
Hoshangabad	572	1975	1175	26.1	123	901	400	47.0	3	635	263	57.3
Indore	449	1447	925	26.1	77	824	325	49.3	0	294	79	91.3
Dhar	596	1492	906	24.4	75	648	255	55.5	0	317	84	115.5
Betul	574	1544	1092	22.5	138	691	367	42.0	0	306	120	77.9
Raipur	628	1636	1050	25.2	92	460	234	45.3	0	595	256	57.8
Nagpur	553	1463	953	23.5	83	673	298	44.1	0	321	135	64.6
Amravati	496	1151	767	25.9	41	453	212	54.1	0	50	9	195.6
Wardha	564	1568	970	23.4	87	719	293	47.9	0	333	125	77.8
Akola	278	1191	702	30.2	37	444	199	49.1	0	109	7	354.8
Parbhani	470	1548	832	36.4	69	500	209	60.8	0	425	68	177.6
Nanded	309	1509	784	31.6	32	600	190	71.3	0	98	6	356.0
Dharwad	41	776	423	38.5	0	177	71	62.7	0	47	2	511.8
Average	473	1583	924		78	694	283		1	356	126	
CV[a]	30.2	18.8	20.1		47.6	29.3	29.5		392.1	50.2	75.7	

[a] CV, coefficient of variation (%).

tivity would be possible with improved management practices in areas with higher rainfall/soil moisture availability as compared to low rainfall areas. Large surface runoff of water (Table 6) which on an average accounted for 31% of the total rainfall received at these locations, indicated that efficient use of water through adoption of improved watershed management incorporating conservation tillage (broadbed-and-furrow, ridge-and-furrow, reduced tillage, residue recycling and mulching) and water harvesting technologies (Wani et al., 2003; Teklu et al., 2006) could help in reducing the yield gaps of soybean grown largely on Verisols and associated soils in India. These technologies will not only help in improving the productivity in areas with suboptimal rainfall; but could also be helpful in areas with high rainfall by improving the land surface drainage and adopting water-logging resistant crop varieties to reduce the risks of water-logging conditions.

A large number of 'On-farm Demonstrations' are being conducted in India to demonstrate the improved production technology and simultaneously to assess the yield constraints in soybean under real farm conditions involving huge amount of money and time. The results of these on-farm trails conducted from 1989 till 2002 show an average rainfed potential yield of about 2000 kg ha^{-1} (Bhatnagar and Joshi, 2004; Billore et al., 2004) as against 2170 kg ha^{-1} observed during the simulations in this study. The reported average yield gap between potential rainfed yield and national average yield is about 1000 kg ha^{-1} as compared to 1170 kg ha^{-1} obtained between simulated water limited and district average yields in the present study. The close values of rainfed potential and yield gap of soybean obtained in on-farm trials and through simulations in the present study thus indicated that the CROPGRO-Soybean simulation model can be a useful tool in quantifying the potential yields and yield gaps of soybean. As the model predicts the crop growth, development and yield using a systems approach involving integrated knowledge of the underlying processes and interaction of different components of crop production (Boote et al., 1996), it can very well supplement the above trials in understanding the underlying constraints to productivity of soybean with respect to specific location as well as at the national level.

3.6. *Conclusions*

The results for model calibration and evaluation showed that simulated growth and development of soybean were in good agreement with their corresponding observed values. Thus, the CROPGRO-Soybean model can be successfully used for simulating growth and yield for soybean for major soybean-growing region in India. The model simulations showed that the average water non-limiting potential of the soybean crop across locations was 3020 kg ha^{-1}, while water limiting potential was 2170 kg ha^{-1} indicating a 28% reduction in yield due to adverse soil moisture conditions. On the other hand, the actual yield was just 1000 kg ha^{-1} which was 2020 and 1170 kg ha^{-1} less than the water non-limiting potential and water limiting potential of soybean in India, respectively.

Across locations the water non-limiting potential yields were less variable than water limited potential and actual yields, and strongly correlated with solar radiation during the season ($R^2 = 0.83$, $p \leq 0.01$). Both simulated water limiting potential yield ($R^2 = 0.59$, $p \leq 0.01$) and actual yield ($R^2 = 0.33$, $p \leq 0.05$) had significant; but positive and curvilinear relationships with crop season rainfall across locations. However, lower rate of increment in actual yield with increasing rainfall as compared to simulated yield clearly indicated the limits to productivity caused by factors related to non-adoption of improved crop management practices in real farm situations. Total yield gap (water non-limiting minus actual yields) did not vary much with crop season rainfall. The gap between water non-limiting and water limiting potential yields was very large at locations with low crop season rainfall and it narrowed down at locations with increasing quantity of crop season rainfall. On the other hand, the gap between water limiting potential yield and actual farmers' yield was narrow at locations with low crop season rainfall and increased considerably at locations with increasing amounts of rainfall. This yield gap, which reflects the actual yield gap in rainfed environment, is essentially due to non-adoption of improved crop management practices and could be reduced if proper interventions are made.

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