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Simulating soybean–wheat cropping system: APSIM model parameterization and validation

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ABSTRACT

In recent years, nutrient management of soybean–wheat systems in central India has become a cause for concern because of stagnation of grain yields of soybean and wheat. The reduction in grain yield was mainly attributed to a suboptimal supply of nutrients to both the crops, use of poor quality farmyard manures and erratic distribution of rainfall during soybean's growing season and unavailability of irrigation water during wheat season. In this connection, the crop growth simulation models are handy in identifying the constraints to yield and recommending appropriate management practices to optimize the productivity of soybean–wheat system. To achieve this, the APSIM model was parameterized and validated for soybean and wheat crop of subtropical central India.

Independent data set was used to parameterize soybean cultivar (JS 335) and wheat cultivar (Sujata) to be used for APSIM simulation. Genetic coefficient generated from this study was used for subsequent model validation. The data on water use, N uptake, grain yield and soil organic C from an ongoing long-term experiment was used for validation purpose. Three nutrient treatments, viz., control (no nutrient), inorganic (recommended rate) and FYM (8 t ha^{-1} to soybean and 16 t ha^{-1} to wheat) were used to validate the APSIM model. For organic treatments, we simulated N management using the FYM as the source of plant available N under field condition. The model was parameterized by specifying the N mineralized from the manure in the laboratory incubation. The model predicted successfully grain yield and N uptake under FYM treatments in soybean and wheat. For other treatments, model prediction was satisfactory in most of the cases in simulating water and organic carbon, grain yield and N uptake by both the crops. The discrepancy observed between the observed and predicted yield in the control under soybean was due to the P limiting condition of the treatment rather than the model. The predicted variability of crop yield was also due to the variation of weather during soybean growing season and amount of irrigation and N used during wheat growing season. Therefore, this APSIM simulation study can satisfactorily be used to make appropriate management decisions to provide farmers and others with alternative options for nutrient management for soybean–wheat cropping systems.

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1. Introduction

Soybean [*Glycine max* (L.) Merrill] has emerged as one of the major rainy season cash crops in central India. The state of Madhya Pradesh has been identified as a 'Soya State' on account of its share in area (77%) and production (72%) of soybean in India (SOPA,

2007). The area sown to the crop has increased from 30,000 ha in 1980 to over 8.8 million ha in 2007. The crop is predominantly grown on Vertisols and associated soils with an average crop season rainfall of about 900 mm, but varying 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 (*Triticum aestivum*, L.) or chickpea (*Cicer aeritinum* L.) (fallow-wheat/chickpea) to soybean followed by wheat or chickpea (soybean–wheat/chickpea). Soybean–wheat production is the dominant cropping system of central India (Mandal et al., 2002). This has resulted in an increase in the cropping intensity and resultant increase in the profitability per unit land area. Despite its

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phenomenal growth in area, the average productivity of soybean has remained more or less at 1000 kg ha^{-1} due to several abiotic, biotic and socio-economic factors (Bhatnagar and Joshi, 2004). These include crop management factors such as suboptimal use of nutrients, suboptimal planting time, poor plant population, and infestation with weeds, pests and diseases that limit productivity (Bhatnagar and Joshi, 2004; Paroda, 1999). The average yield of wheat in Madhya Pradesh is 35–40% lower than national average. Proper management of inputs particularly nitrogen (N) and irrigation water using modern technology is essential for maximizing production and for providing high returns to farmers. With efficient use of available resources, farmers can harvest 10–40% additional yield (Reddy and Sen, 2004).

In cropping systems, either inorganic fertilizers or organic manures alone may not sustain crop productivity. So, judicious use of organic manures and inorganic fertilizers are essential to safeguard soil health and augment productivity and nutrient use efficiency. The positive effect of integrated use of farmyard manure (FYM) and inorganic fertilizers on productivity of soybean–wheat system has been reported by many workers (Ghosh et al., 2004; Bhattacharyya et al., 2008). Transfer of such site- and season-specific findings to other locations and evaluation of alternative management strategies is possible using systems simulation models. Alagarswamy and Virmani (1996) reported that long-term simulation analysis gives a clear indication of the risks associated with alternative N fertilizer application strategies. Since long-term experimental evaluation of conditional and/or alternative management strategies is not possible, crop simulation models suggest alternative management strategies to evaluate the risks associated with crop production.

Simulation models with demonstrated accuracy and reliability provide an alternative method of investigating both short and long-term agricultural practices with low time requirements and cost (Farage et al., 2007; Malone et al., 2007). Evaluation of a crop simulation model involves establishing confidence in its capability to predict outcomes experienced in the real world. Models that can simulate nutrient release patterns according to the resource quality, soil conditions, and climate would provide a means of making initial nutrient recommendations to optimize the use of different resources depending upon their availability.

The APSIM modeling framework (Keating et al., 2003; website www.apsim.info) was selected because it is one of the most appropriate models for use in tropical and subtropical soil and crop management conditions, and its ability to simulate the effect of application of FYM on N availability to crops (Probert et al., 2005; Mohanty et al., 2011). The APSIM model has been reported to simulate realistically the observed yields of soybean, wheat and several other crops and cropping systems (Singh et al., 1999; Chikowo et al., 2008; Chen et al., 2010; Asseng et al., 2011). The model has been used successfully for simulating efficient production, improved risk management, crop adaptation, and sustainable production. Through the linking of crop growth with soil processes, the APSIM model is particularly suited for assessing the impacts of alternative management practices on the soil properties and crop productivity.

To present the applicability of the APSIM model, it is necessary that the model be tested in different geographical conditions, for different crops and soil fertility management, including supply of nutrient from organic and inorganic sources. Moreover, this model provides not only the short time-step essential for simulating effects of management on nutrient availability and crop growth, but also incorporates longer-term effects of changes in soil organic matter content and hence N mineralization. The APSIM model has been used to predict N release from different organic sources (feed and faecal materials of animals) (Probert et al., 2005) and from the Indian FYM (Mohanty et al., 2011). The ability to simulate crop growth in response to application of organic and inorganic

sources of N is to test the capability of the model in simulating the soybean–wheat cropping system. The model output of N uptake and plant growth will assist in better understanding of interactions between water and N to optimize plant growth and yield in a cropping system. To achieve this, the following objectives were set:

(i) To determine the genetic coefficients of local soybean and wheat cultivars for parameterization of the APSIM model.
(ii) To validate the model for different N management practices (organic and inorganic sources) under soybean–wheat cropping systems.
(iii) To evaluate the model in predicting soil water content, grain yields and N uptake by soybean and wheat crops using results from an ongoing long-term soybean–wheat experiment.

2. Materials and methods

2.1. Model description

APSIM is a crop growth model that combines biophysical and management modules to simulate cropping systems (Keating et al., 2003). It simulates crop growth in a given environment, including temperature, solar radiation, water and N supply, but does not consider pest and diseases. In this study, APSIM (version 6.0) was configured with the soybean and wheat modules, the soil water module SOILWAT, and the soil N module SOILN, Surface OM and Manager.

2.2. Parameterization of the APSIM model

The APSIM model was parameterized for soybean and wheat crops grown during the year 2003–2005 in field experiments conducted at the research farm of the Indian Institute of Soil Science, Bhopal (23.28°N, 77.48°E).

2.2.1. Parameterization of crop cultivars in the model

Cultivars used in the experiment were soybean, JS 335 (medium maturing, 100–110 days duration), the most popular and predominant cultivar in central and peninsular India, and wheat cultivar Sujata (long maturing, 140–150 days duration), one of the widely grown cultivars in Madhya Pradesh, India.

Soybean was sown on July 15, 2005 under rainfed condition. Fertilizer to supply 20 kg ha^{-1} N; 26 kg ha^{-1} P and 17 kg ha^{-1} K was applied at the time of sowing. A plant population of 50 plants m^{-2} was maintained with a row-spacing of 30 cm. Standard agronomic practices for weed and insect control were followed to maintain the plots free from biotic stresses. The crop data collected for the parameterization of the soybean was based on the procedure of Fehr et al. (1971). Minimum crop data sets required for parameterizing the model included dates of emergence, anthesis, maturity, pod initiation and full pod, grain yield, above-ground biomass, grain density and weight.

Wheat was sown on November 17, 2003 under irrigated conditions. Fertilizers to supply 100 kg ha^{-1} N; 26 kg ha^{-1} P and 33 kg ha^{-1} K was applied at the time of sowing. Plant population of 120 plants m^{-2} was achieved with a row-spacing of 22.5 cm. Standard agronomic practices for weed and insect control were uniformly followed to maintain plots free from biotic stresses. The crop data collected for the parameterization of wheat was based on the procedure of Zadoks et al. (1974).

To simulate a crop cultivar, the APSIM-soybean and wheat modules require genetic coefficients that describe the growth and development characteristics for each individual cultivar (Table 1). Based on the observations made and weather records from the location, the thermal time between various growth stages of soybean

Table 1
Parameterization of crop genotype used in the model for soybean and wheat simulation.

Parameters or variables	Acronym	Value	Units
Cultivar name	JS335		
Phenology			
Emergence: end of juvenile	TT_EMERG_TO_ENDJUV	60	°C days
End of juvenile: floral initiation	TT_ENDJUV_TO_INIT	480	°C days
Floral initiation: flowering	TT_INIT_TO_FLOWER	60	°C days
Flowering: start grain filling	TT_FLOWER_TO_SATRT_GRAIN	400	°C days
Start grain filling: end grain	TT_START_TO_END_GRAIN	610	°C days
End grain: maturity	TT_END_GRAIN_TO_MATURITY	60	°C days
Maturity: harvest ripe	TT_MATURITY_TO_RIPE	5	°C days
Radiation and water use			
Radiation use efficiency	RUE	0.88[a]	$g\,MJ^{-1}\,day^{-1}$
Transpiration use efficiency coefficient	TRANSP_EFF_CF	0.005	kPa
Soybean water lower limit	LL	0.2	$m^3\,m^{-3}$
Rate of soil water extraction	KL	0.1	–
Cultivar name	Sujata		
Phenology			
Emergence: end of juvenile	TT_EMERG_TO_ENDJUV	800	°C days
End of juvenile: floral initiation	TT_ENDJUV_TO_INIT	50	°C days
Floral initiation: flowering	TT_INIT_TO_FLOWER	450	°C days
Flowering: start grain filling	TT_FLOWER_TO_SATRT_GRAIN	120	°C days
Start grain filling: end grain	TT_START_TO_END_GRAIN	380	°C days
End grain: maturity	TT_END_GRAIN_TO_MATURITY	50	°C days
Maturity: harvest ripe	TT_MATURITY_TO_RIPE	1	°C days
Genetic			
Potential grain growth rate during grain filling	POTENTIAL_GRAIN_FILLING_RATE	0.002	$g\,grain^{-1}\,day^{-1}$
Potential grain growth flowering to grain filling	POTENTIAL_GRAIN_GROWTH_RATE	0.001	$g\,grain^{-1}\,day^{-1}$
Leaf development	PHYLLOCHRON	105	
Vernalization sensitivity	VERN_SENS	1.85	
Photoperiod sensitivity	PHOTO_SENS	3.0	
Radiation and water use			
Radiation use efficiency	RUE	1.24	$g\,MJ^{-1}\,day^{-1}$
Transpiration use efficiency coefficient	TRANSP_EFF_CF	0.006	kPa
Wheat water lower limit	LL	0.2	$m^3\,m^{-3}$
Rate of soil water extraction	KL	0.06	–
Soil surface			
Soil albedo	SALB	0.13	–
Stage-1 soil evaporation coefficient	U	6	mm
Stage-2 soil evaporation coefficient	CONA	3.5	–
Bare soil runoff curve number	CN2_BARE	73	
Reduction in CN2_BARE due to cover	CN_RED	20	
Each soil layer[b]			
Layer drainage rate coefficient	SWCON	0.3	
Inert fraction of organic C	FINERT	0.4	
Non-inert fraction of microbial C	FBIOM	0.04	
Soil C/N ratio	SOIL_CN	12	

[a] 0.88 from emergence to end of grain filling and 0.44 thereafter.
[b] Provided in Table 2 for other soil layers

and wheat could be estimated. Genetic coefficient were determined after obtaining a close match between observed and predicted values for leaf area index (LAI), total biomass, grain yield, time to reach 50% flowering, physiological maturity, etc. These coefficients were used in the subsequent model validation.

2.2.2. Soil parameterization

For the soil water balance module the inputs include soil bulk density, saturated soil water content, soil water at field capacity and wilting point in the soil layers that make up the profile, and two parameters (U and CONA) which determine first and second stage of soil evaporation. There are also crop specific parameters that determine rate of root extension and crop's lower limit of water extraction. Soil water characteristics used to specify the model for the experimental site are given in Table 2.

The input parameters for SOILN include pH, organic C, Finert (inert C fraction) and Fbiom (microbial biomass fraction). The soil parameters used for simulation are given in Table 2. Lower limit, drained upper limit, saturation, bulk density, organic C, pH and NH_4- and NO_3-N are determined under laboratory condition using standard procedures and some parameters like Fbiom and Finert

used for parameterization are collected from literature for Vertisols of central India.

2.2.3. Parameterization of N released from farmyard manure

The SOILN module of APSIM was used to specify N released from FYM following the procedure of Probert et al. (2005) and Mohanty et al. (2011). Briefly, crop residues added to the soil and roots, are designated fresh organic matter (FOM) and are considered to comprise three pools (FPOOLs), sometimes referred to as the carbohydrate-like (FPOOL1), cellulose-like (FPOOL2) and lignin-like (FPOOL3) fractions of the residue. Each FPOOL has its own rate of decomposition, which is modified by functions to allow for the effects of soil temperature and soil moisture.

It is assumed that the same FPOOLs also constitute organic C and N in FYM, but earlier studies (Probert et al., 2005; Mohanty et al., 2011) have shown that the prediction of N mineralization from FYMs was improved where the proportion of C and N in these FPOOLs differ from the default values used for crop residues and roots. To specify the model, FPOOL1 which decomposes most rapidly has been equated with water soluble C and N, whilst FPOOL3 which is slowest to decompose was equated with lignin-C.

Table 2

Soil parameterization of Vertisol at IISS, Bhopal experimental farm to specify APSIM simulations. LL, lower limit; DUL, drained upper limit; SAT, saturated volumetric water content; BD, bulk density; OC, organic carbon; Fbiom, non-inert fraction of microbial C; and Finert, inert fraction of organic C.

Soil layer (cm)	LL ($m^3\,m^{-3}$)	DUL ($m^3\,m^{-3}$)	SAT ($m^3\,m^{-3}$)	BD ($Mg\,m^{-3}$)	OC (%)	pH	NH_4-N ($mg\,kg^{-1}$)	NO_3-N ($mg\,kg^{-1}$)	Fbiom	Finert
0–15	0.24	0.39	0.51	1.28	0.49	7.8	15	1.6	0.04	0.4
15–30	0.27	0.38	0.49	1.34	0.47	8.0	12	1.9	0.02	0.6
30–60	0.27	0.39	0.47	1.35	0.46	7.9	8	1.5	0.02	0.8
60–90	0.28	0.40	0.45	1.40	0.43	7.9	4.5	1.5	0.02	1
90–120	0.28	0.41	0.45	1.45	0.41	8.0	3.5	0.5	0.01	1

For the FYMs applied each year in the field experiment, the total C and N were measured, but water soluble- and lignin-C were not. We have assumed that the distribution of C and N between the FPOOLs is always the same and have used the values that Mohanty et al. (2011) used to describe N mineralization in incubation studies. Full details of the specification of C and N in the different FYM used are given in Table 3.

2.3. Validation of the APSIM model

The well parameterized APSIM model was validated to simulate soil water content, grain N uptake and yield of soybean and wheat against the experimental data (2002–2006) from a long-term fertility trial carried out at the experimental farm of the Indian Institute of Soil Science, Bhopal (Anon., 2004–2005). The experiment was initiated in the year 2002 to evaluate different on-farm and off-farm resource based integrated plant nutrient supply modules for sustainable productivity of soybean–wheat system in a Vertisol. The genetic coefficients developed and presented in Table 1 for both the cultivars of soybean and wheat were used for validation purpose. The weather data, soil properties and management practices used for validation purpose that are different from the parameterization procedure are given below.

2.3.1. Weather

The input weather data required to run the APSIM included daily maximum and minimum temperature, solar radiation and rainfall. The weather data collected during the year 2002–2006 from an automatic weather station located 150 m away from the experimental site was used for validation of the model against the long-term dataset. The total rainfall recorded in an automatic weather station was 763, 1113, 863 and 917 mm for 2002, 2003, 2004 and 2005. There was year to year variation in rainfall during soybean and wheat growing seasons.

Table 3

Parameterization for C, N, C/N ratio pools of FYM applied before sowing of the soybean and wheat crops.

Year	Crop	% C	% N	C/N ratio
2002	Soybean	29.00	1.10	26
	Wheat	32.94	1.22	27
2003	Soybean	29.90	1.15	26
	Wheat	31.25	1.25	25
2004	Soybean	28.71	0.99	29
	Wheat	28.50	0.95	30
2005	Soybean	24.70	0.95	26
	Wheat	29.41	1.11	26.5

Partioning of C and N between FPOOLs

	FPOOL1[a]	FPOOL2	FPOOL3
Fraction C[a]	0.09	0.73	0.18
Fraction N	0.054	0.50	0.446

[a] Based on the incubation experiment.

2.3.2. Soil

The soil of the long-term experimental site is predominantly semectitic, an Entic Chromustert (Soil Taxonomy, 1974), having 52% clay, 30% silt, 18% sand, pH 7.8, 49 cmol (p+) kg^{-1} cation exchange capacity and 4.9 g kg^{-1} organic C in the 0–15 cm layer. The inorganic N (NH_4-N + NO_3-N) measured in the 0–15 cm soil layer at the beginning of the experiment in 2002 was 22 mg kg^{-1}. The initial plant-available P as measured by the conventional soil test using 0.5 M $NaHCO_3$ extractant (Olsen P) was 4 mg kg^{-1}. The other soil properties used for parameterization of the model remained unchanged for validation as mentioned in Table 2.

2.3.3. Treatments

Three treatments were selected out of the thirteen treatments from the long-term fertility experiment for the simulation study to provide a contrast in nutrient management (Anon., 2004–2005). The treatments were (i) control (no nutrient added), (ii) inorganic (applied fertilizer for soybean was 20 kg ha^{-1} N, 26 kg ha^{-1} P and 11 kg ha^{-1} K and that of wheat was 100 kg N, 22 kg P and 17 kg K), and (iii) organic (8 t FYM ha^{-1} to soybean and 16 t FYM ha^{-1} to wheat). In the organic treatment, the manure was incorporated to a depth of 5 cm in soil approximately one month before sowing. For soybean all fertilizer was applied pre-sowing as urea, single superphosphate and muriate of potash; for wheat 50% N (as urea), P and K were applied pre-sowing whilst remaining 50% of N (as urea) was applied at crown root initiation (CRI) which was 25 days after sowing. In the year 2002–2003, the wheat crop was grown only with one pre-sowing irrigation due to irrigation water shortage. For the other years, there was one pre-sowing irrigation and three in-crop irrigations; each irrigation supplied 80 mm water. The FYM was from a local farm, and varied slightly in quality from year to year (Table 3).

2.3.4. Crop management

Soybean seeds were sown in 30-cm rows. Seedlings emerged approximately 5 days after sowing, and the plants were thinned to a final plant population of 50 plants m^{-2}. Regular plant protection measures were followed to maintain pest-free conditions. For wheat plant population of 120 plants m^{-2} and row spacing of 22.5 cm was maintained in all the years of experiment. Each plot was 10 m × 6 m. Grain/seed yield of crops was recorded from a net plot size of 1 m × 1 m in 3 locations of the treatment plot. Both the soybean and wheat crops were harvested manually by sickle at ground level and threshed with an electrically operated mechanized thresher.

2.3.5. Soil sampling and analysis

Soil water data were available for two years of the experiment (2002–2003 and 2003–2004) for validation of the SOILWAT module. Soil samples (depth-wise at 15 cm interval) were collected at 15-day intervals during the crop growing seasons and then soil water content was determined gravimetrically by drying to a constant weight at 104 °C. The volumetric soil water contents were calculated by multiplying gravimetric water content at a given depth interval with BD at the corresponding depth.

The soil NH_4- and NO_3-N content, soil organic C and total N in straw and grain samples of both soybean and wheat were analyzed following standard methods of analysis (Richards, 1993). The concentration of N in straw and grain of soybean and wheat were multiplied by the straw and grain yields to obtain the total uptake of these nutrients.

2.3.6. Simulating soybean–wheat rotation using APSIM

The comparison of the measured and simulated grain yields of soybean and wheat, water content during the growing season (selected years), and soil organic C content of the profile was made for 2002–2004 period from the on-going long-term experiment. The potential yields were simulated for four years under rainfed condition for soybean and irrigated conditions for wheat. The model simulation was initiated on 1st May at the beginning of the experiment when the soil profile was considered to be at the lower limit of available water. The simulation was carried out on daily time step and predicted values for grain yield, water balance, and N uptake were used for comparing with the observed data obtained from the experiment.

2.3.7. Statistical evaluation of model performance

The model evaluation was performed on the 3 treatments and the four years of data of experiment for water content of the profile, grain yield, N uptake by the soybean and wheat crops, and soil organic C. Measured and predicted data were compared graphically and analyzed statistically (Loague and Green, 1991). The statistical criteria are based on the analysis of residual errors, i.e., the difference between observed and simulated values. We computed the root mean square error (RMSE) (Eq. (1)) and the modelling efficiency (EF) (Smith et al., 1996), (Eq. (2)) as follows:

$$\text{Root mean square error} \quad (\text{RMSE}) = \sqrt{\left(\sum_{i=1}^{i=n} \frac{(P_i - O_i)^2}{n} \right)} \qquad (1)$$

$$\text{Modelling efficiency} \quad (\text{EF}) = 1 - \left[\frac{\sum_{i=1}^{i=n}(P_i - O_i)^2}{\sum_{i=1}^{i=n}(O_i - \bar{O})^2} \right] \qquad (2)$$

where P_i, predicted value, O_i, observed value, $\bar{O}$, mean of the observed values, n, number of observation.

For good model performance, values of RMSE (Eq. (1)) should be close to 0; high values of RMSE indicate poor model performance. The EF (Eq. (2)) compares the deviations between predicted and observed values to the variance of the observed values. Values for EF can be positive or negative with a maximum value of 1. An EF value of 1 denotes a perfect match of predicted and measured values. RMSE and EF were calculated for individual treatments for water content of the profile, grain yield and N uptake. Data were analyzed using analysis of variance (ANOVA) and test of significance were done using t-test (Gomez and Gomez, 1984). The significant differences among treatments were compared with the critical difference at 5% level of probability.

3. Results

3.1. Parameterization of soybean and wheat cultivar

For datasets used to determine the genetic coefficients for the cultivars good agreement was obtained between the predicted and observed values (Figs. 1 and 2). The error in prediction of days to flowering and date to physiological maturity for both crops was within 1 day. The measured grain yield of soybean at harvest was 1.8 t ha^{-1} compared to the simulated grain yield of 1.7 kg ha^{-1}. Similarly, the observed grain yield of wheat was 4.0 kg ha^{-1} compared
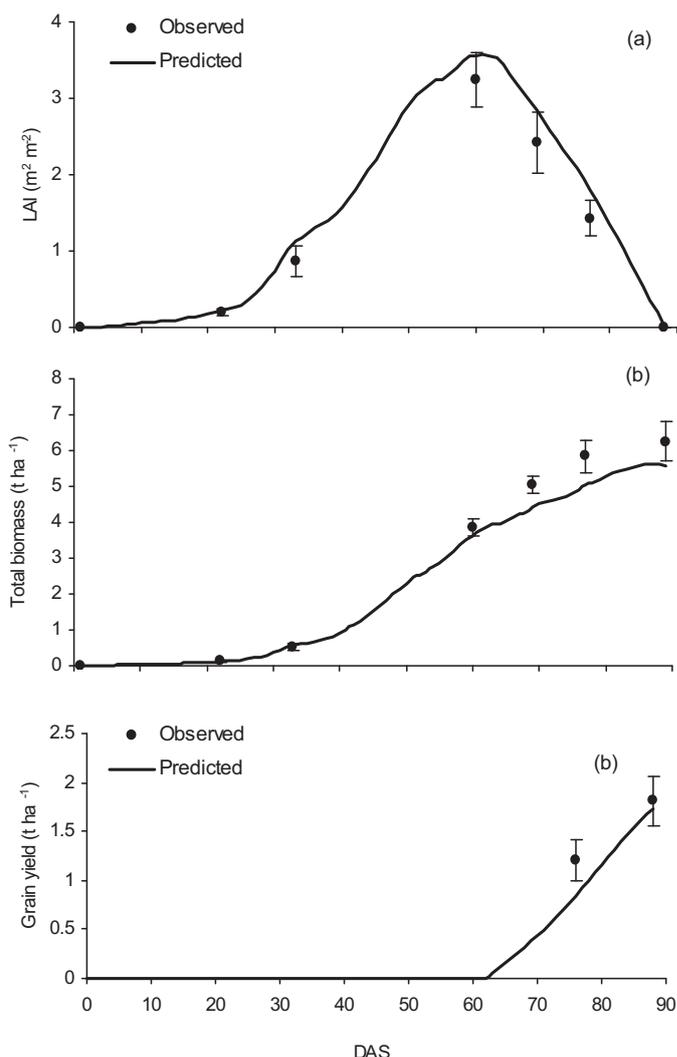

Fig. 1. Parameterization of APSIM model for soybean cultivar (JS 335) showing observed and predicted values for (a) LAI, (b) total biomass yield and (C) grain yield. Vertical bar represents standard deviation. DAS: days after sowing.

to the predicted yield of 4.2 t ha^{-1}. The measured total biomass and the predicted biomass values were comparable (Table 4). Therefore, the APSIM soybean and wheat modules were able to simulate the observed days to 50% flowering, physiological maturity, total biomass and grain yield for these crops reasonably well for central Indian conditions in this parameterization study.

3.2. Model validation

3.2.1. Water balance of the profile

For simulation of soil water content of the profile under rainfed condition for soybean and irrigated conditions for wheat, the model was validated for soil water changes in the soil profile using the data collected from the long-term experiment. For the growing seasons of 2002–2003 and 2003–2004, Fig. 3 shows the trend in the soil water contents at 0–15 cm and 60–90 cm depths for the control for the observed data and predicted values. The correlation between the observed and predicted soil water content at 0–15 cm, 15–30 cm, 30–60 cm and 60–90 cm depths for the three treatments are presented in Fig. 4. The soil remained wet in the top 90 cm depth in both the soybean growing seasons. However, for wheat there was lower water content in the profile even after application of a pre-sowing irrigation in 2002–2003, whereas the soil water content

Table 4
APSIM model predicted and observed values for soybean cultivar, JS 335 and wheat cultivar, Sujata.

Parameters	Soybean (JS 335)		Wheat (Sujata)	
	Observed	Predicted	Observed	Predicted
Date to 50% flowering	12/09/2005	11/09/2005	07/02/2004	06/02/2004
LAI at 50% flowering	3.07	3.56	3.76	3.47
Total biomass (t ha^{-1})	6.2	5.6	13.3	13.7
Date to physiological maturity	16/10/2005	17/10/2005	12/03/2004	13/03/2004
Grain yield (t ha^{-1})	1.8	1.7	4.0	4.2

remained high in the following wheat season 2003–2004 due to the four irrigations applied to the crop (Fig. 3). Compared to the year 2002–2003, the soil water content remained high and within the plant water available capacity range at all depths in both the crop growing seasons of 2003–2004.

For the control, the model prediction of water content during soybean and wheat growth was relatively accurate with all the peaks for rainfall and irrigation were quite visible (Fig. 3). In the year 2002–2003, the trends in soil water content during the drying of the soil profile due to limited irrigation was closely predicted by the model. The model also showed the peaks of rainfall recharging

Fig. 2. Parameterization of APSIM model for wheat cultivar (Sujata) showing observed and predicted values for (a) LAI, (b) total biomass yield and (C) grain yield. Vertical bar represents standard deviation. DAS: days after sowing.

the soil profile during wheat growing season of 2002–2003. For all the treatments, the goodness of fit was better for 0–15 cm soil layer than 60–90 cm depth as demonstrated by the statistical criteria used for the evaluation of the model simulation (Table 5). The overall EF ranged from 0.26 to 0.58 and RMSE ranged from 0.036 to 0.044. This is also further demonstrated by the relationships between observed and predicted data (R^2 ranged from 0.71 to 0.88) of soil water content at all depths (Fig. 4).

3.2.2. Grain yield and N uptake of soybean and wheat

The measured grain yield of soybean in the control was significantly lower than in the inorganic and organic treatments (Fig. 5a). The grain yields in organic and inorganic treatments did not differ significantly for the years 2002–2003 and 2005–2006, however, organic treatment had significantly higher grain yield for the year 2003–2004. There was a large inter-annual variation in the grain yield of soybean. For example, the soybean yield in the year 2004–2005 was lower in all the three treatments than in the other years because of a severe insect pest attack. The crop was damaged due to attack of girdle beetle (*Oberiopsis brevis*) in the vegetative stage and yellow mosaic virus in the reproductive stage. The crop stand in the field had partially filled grains in the pods. There was no definitive trend in N uptake by soybean, but year to year variation in N yield of soybean was observed (Fig. 6a).

The grain yields of wheat in the inorganic and organic treatments were significantly higher than the control for all the years (Fig. 5b). However, there was no significant difference in yield between inorganic and organic treatments in any of the years studied. Again, there was a year to year variation in grain yield of wheat, and a similar trend in the N uptake by wheat under different treatments (Fig. 6b).

The model overestimated the soybean grain yield for the control for all the years (Fig. 5a). For the inorganic and organic treatments the model over-estimated the grain yield of soybean for the year 2002–2003, while it under-estimated the yield in the years studied. Similar trend was also observed for N uptake by soybean (Fig. 6a). With the exception of the control, the overall model prediction of soybean grain yield for the inorganic and organic treatments was reasonably good. The predicted grain yield for the same year was
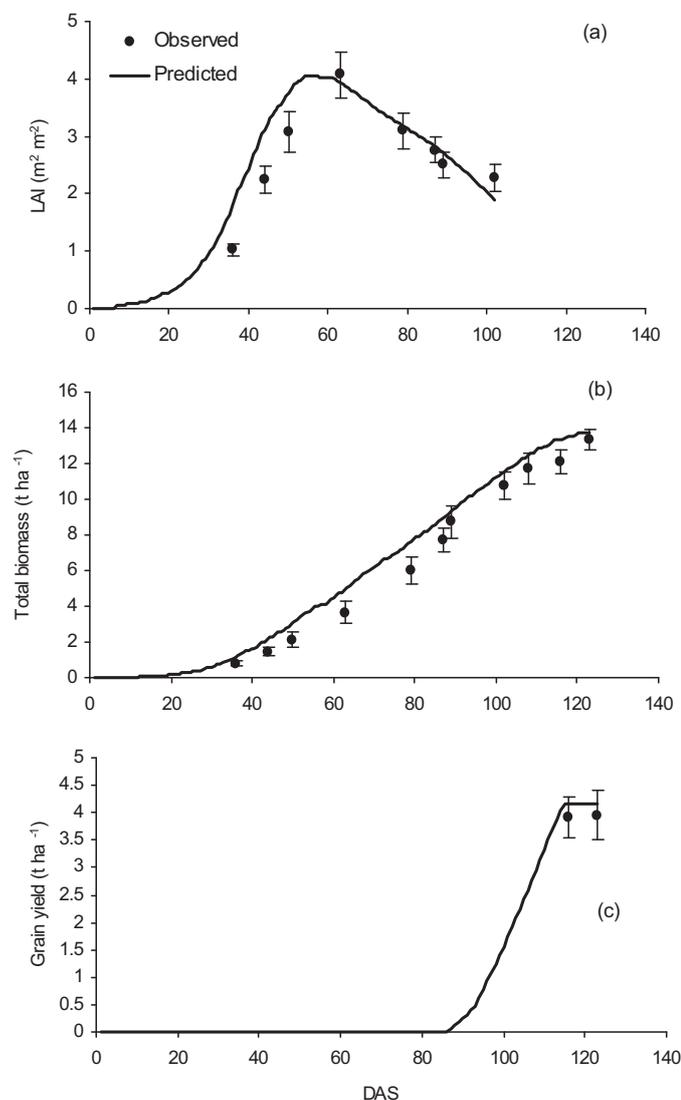
Table 5
Statistical criteria (model efficiency, EF and root mean square error, RMSE) for evaluating the soil water content at 0–15 cm and 60–90 cm depths under different treatments.

Treatment	Depth (cm)	EF	RMSE
Control	0–15	0.40	0.042
	60–90	−0.03	0.046
Inorganic	0–15	0.65	0.044
	60–90	−0.09	0.047
Organic	0–15	0.69	0.028
	60–90	0.15	0.042
All treatments			
Control	All depths	0.26	0.044
Inorganic	All depths	0.37	0.043
Organic	All depths	0.58	0.036
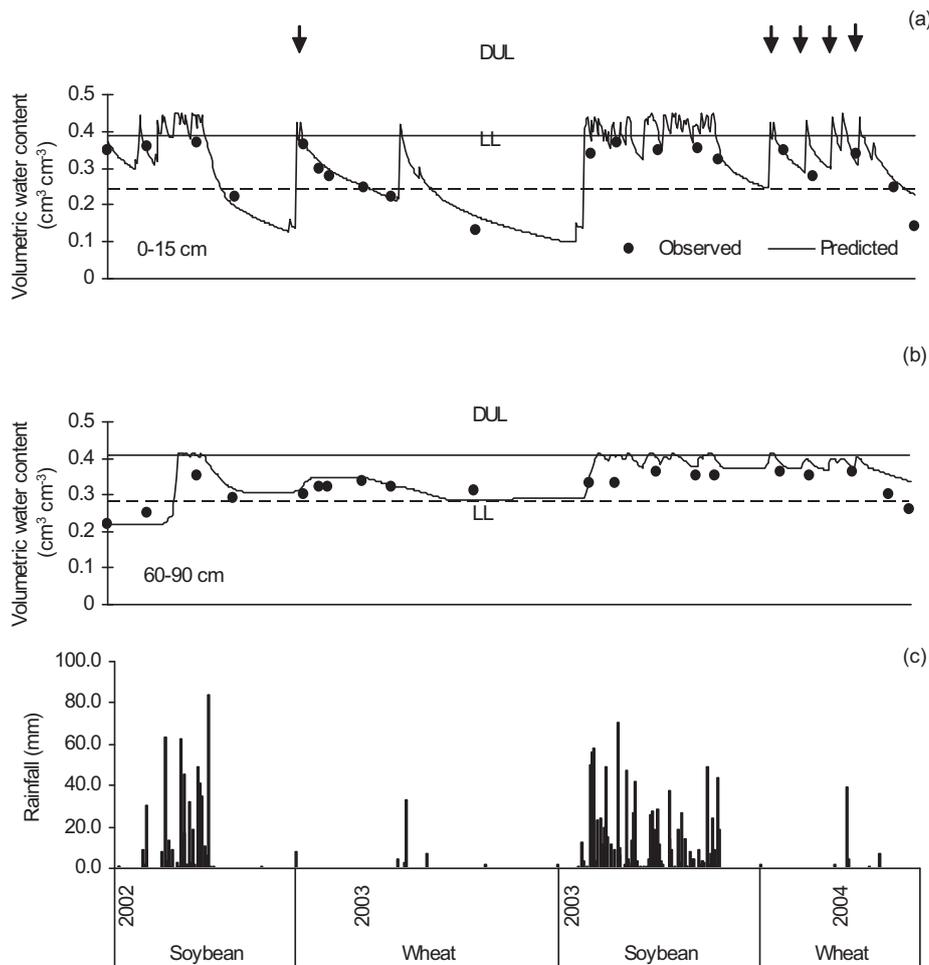
Fig. 3. Observed vs predicted soil water contents at 0–15 cm and 60–90 cm depths in the control. DUL – drained upper limit and LL – crop lower limit. Arrow represents irrigation.

similar under different nutrient treatments although the model simulated the inter-annual variations in grain yields of soybean reasonably well. The exception was the low grain yields in 2004–2005 soybean seasons due to severe insect pest damage, which was not considered by the model. Predicted N uptake by soybean followed a similar trend to that of the yield (Fig. 6a). The observed average grain yield in the control, inorganic and organic treatments was 1.2 t ha^{-1} compared to the predicted average yield of 1.3 t ha^{-1}. Similarly, the observed average total N uptake by soybean in these treatments was 109 kg ha^{-1} compared to the predicted average N uptake of 124 kg ha^{-1}. The observed N uptake by soybean in the experiment ranged from 74 kg ha^{-1} to 154 kg ha^{-1} whereas the predicted N uptake ranged from 104 to 145 kg ha^{-1}. The EF for the grain yield of soybean was 0.27, while the EF of for the N uptake was 0.13.

The model realistically predicted grain yield and N uptake by the wheat crops with year to year differences presumably reflecting differences in irrigation applied in different years (Figs. 5b and 6b). The effect of different nutrient treatments on grain yield of wheat was also well predicted by the model. The observed average grain yield at harvest of the control, inorganic and organic treatments was 2.2 t ha^{-1} compared to the simulated average yield of 2.1 t ha^{-1}. The EF value of 0.91 between observed and predicted grain yield of wheat indicated a close agreement between them for these diverse treatments. The observed N uptake by wheat in the experiment ranged from 17 kg ha^{-1} to 119 kg ha^{-1} whereas the predicted N uptake ranged from 17 to 116 kg ha^{-1}.

The observed average total N uptake for wheat of the control, inorganic and organic treatment data sets was 66 kg ha^{-1} as against predicted average of 63 kg ha^{-1}. The RMSE value of 13 and EF value of 0.86 suggested a close agreement between the predicted and observed data for these treatments. This showed that the APSIM model prediction of grain yield and N uptake by wheat was better than that for the soybean yield and N uptake.

3.3. Soil organic carbon content of the profile

The SOC content at the 0–15 cm depth was similar in the control during the four cropping seasons while it increased markedly for the organic treatment (Fig. 7). The SOC content for the organic treatment relative to control and inorganic treatments increased from year to year.

The model slightly underestimated the SOC at 0–15 cm depth for the control and inorganic treatments. But the shape of the observed and predicted curve presented a better fitting of the observed and predicted data. Overall, there was a good agreement between the observed and predicted SOC content at 0–15 cm depth for all three treatments as indicated by EF value of 0.62 (Fig. 7). However, overall RMSE value (0.11) was higher than that obtained from the combined RMSE value (0.028) for the control and inorganic treatments combined together (data not shown).

The model predicted soil organic C under the control and inorganic treatments better than the organic treatment (Fig. 7).
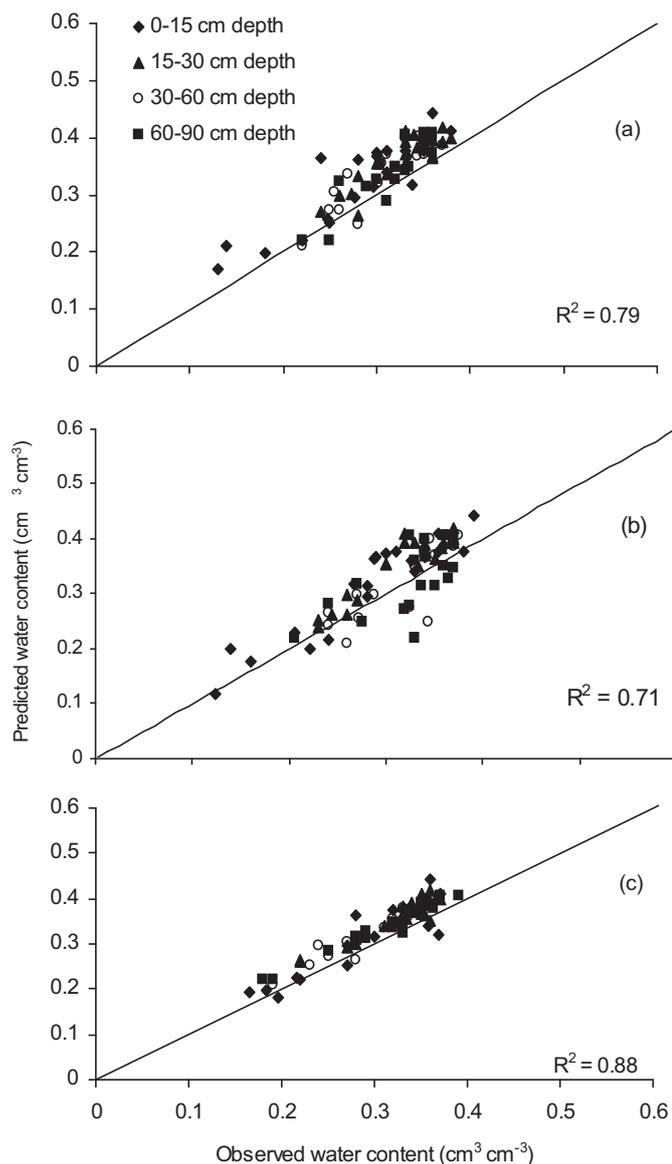
Fig. 4. Observed vs. simulated soil water content at different depths for (a) the control (b) inorganic treatment, and (c) organic treatment for 2002–2003 and 2003–2004 growing seasons. 1:1 line is shown in each case.

However, the overall prediction of soil organic C across all the three treatments was satisfactory considering the EF value of 0.62 and RMSE of 0.11.

4. Discussion

4.1. Water content of the soil profile

Plant available soil water is one of the main determinants of crop yield in semi-arid environments. The surface soil dried to the lower limit of water availability in the wheat growing season of 2002–2003 (Fig. 3a), and this was well accounted for by the model simulation. The drying of the soil profile during this period was expected since only one irrigation could be given. The drying of the profile coincided with many critical stages of crop growth, for example, crown root initiation and tillering. Irrigation at early critical growth stages of wheat is considered to be important, and water stress at these stages severely reduces the yield of wheat (Behera and Panda, 2009). The rainfall received in the later part of the crop
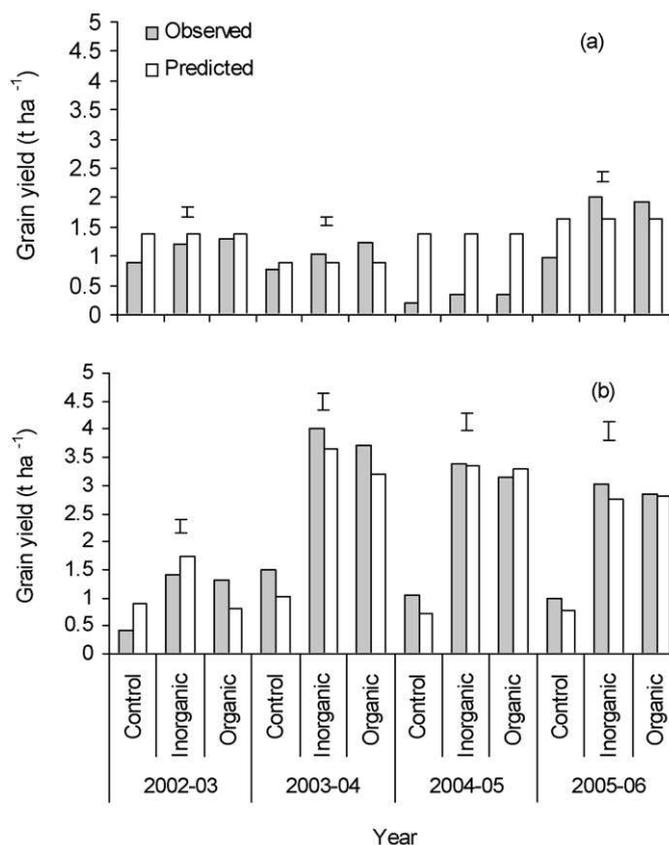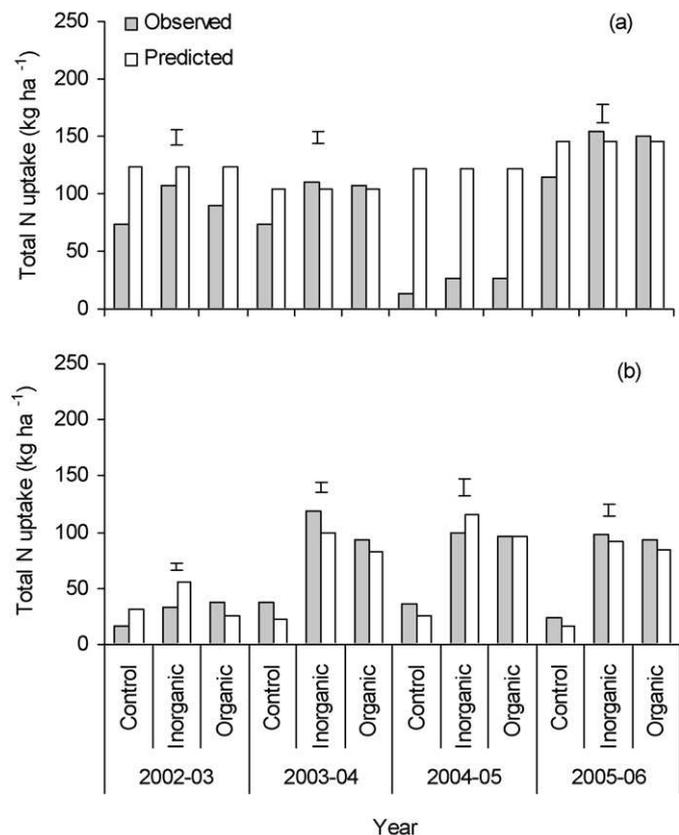

Fig. 5. Grain yield of (a) soybean and (b) wheat as predicted by the model in different treatments. Vertical bars represent lsd (5%). The year 2004–2005 was not considered for statistical analysis in the soybean season due to severe insect-pest damage to the crop.

growth although rewetted the soil profile (Fig. 3c) but had no effect on wheat yield.

In our study, the model predicted pattern of water availability up to 90 cm of soil depth in the control, inorganic and organic treatments, which agreed well with the measured soil water data (Figs. 3 and 4). For the inorganic and organic treatments, low water availability in soil profile after the wheat harvest, relative to the control, was well represented in the model simulation. Soil water extraction from deeper layers was higher in the fertilized plots than unfertilized plots. Similar results were obtained by Hati et al. (2001) who found that the fertilized plots contained less water at harvest than the unfertilized plots in Vertisols.

Larger differences between the observed and predicted soil water content occurred at the lower soil depths, with RMSE varying from 0.042 to 0.047. In this study, the larger deviations for the lower depths were probably attributed to the errors associated with field measurements due to larger soil variability at depths and were also cited as possible causes of discrepancy between the observed and predicted data by other researchers (Faria et al., 1994). Moreover, the time of sampling also causes variability between model estimates and observed field data, for example, the increase in soil evaporation following cracking of drying soil might have contributed to this discrepancy between simulated and measured data (Singh et al., 1999). The current version of the crop simulation models does not account for the effect of soil cracking on soil evaporation. Similar results were observed by Connolly et al. (2002) from APSIM simulation of soil water, who reported better prediction of the soil water changes by the APSIM model on bare soils than on soils covered with vegetation, presumably water loss from

Fig. 6. Observed vs predicted N uptake by (a) soybean and (b) wheat in different treatments. Vertical bar represents lsd (5%). The year 2004–2005 was not considered for statistical analysis in soybean season due to severe insect-pest damage to the crop.

evaporation following cracking of drying Vertisol from water use by vegetation.

4.2. Grain yield and N uptake

In the experiment the observed soybean yield in the control was lower than those in the inorganic and organic treatments. It is likely that soybean responded to nutrient inputs, for example P and micronutrients derived from manures and added fertilizers
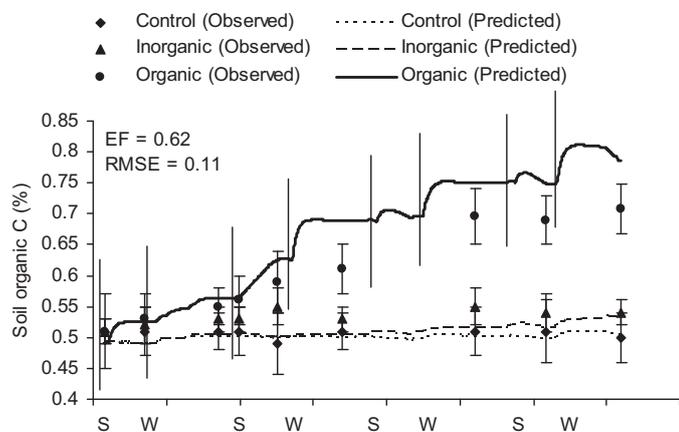
Fig. 7. Effect of nutrient management practices on SOC content (0–15 cm depth) after 4 cropping seasons as predicted by the model. Vertical lines represent each FYM addition to the soil in soybean and wheat growing seasons. Vertical bar represents standard deviation. S: soybean and W: wheat.

(Reddy et al., 1999, 2000), which was not accounted for in the model simulations since the model predicted similar grain yields in all the three treatments.

The discrepancy between the observed and predicted soybean grain yield in the control may be due to 'P' limiting condition in the control rather than the model itself although the model makes no claim to simulating any response of P application. The model assumes that there is no 'P' limiting condition in the control although it received no P and soil available P (Olsen P) level was low ($4 \, mg \, P \, kg^{-1}$); most likely P was limiting soybean yield and N uptake in the control. The observed dataset indicated a clear effect of nutrient treatment on grain yield and N uptake by soybean, which was not satisfactorily simulated by the APSIM model (Figs. 5a and 6a).

The observed soybean yield in different seasons differed for the same nutrient management practices (Fig. 6a), showing the inter-annual variation in grain yield due to variability in total rainfall and rainfall distribution. The model also predicted similar pattern in soybean yields as observed in the years 2002–2003 and 2004–2005 and 2005–2006 except the year 2003–2004, which was due to severe insect-pests attack and this was not accounted for by the APSIM model. Our study showed similar variation in soybean yield as reported by other researchers (Lal et al., 1999; Mohanty et al., 2007). Lal et al. (1999) reported that the temporal variations in rainfall (associated with the observed swings in the continuity of monsoon) during the cropping season plays a dominant role in the inter-annual variability of rainfed soybean crop yields in Madhya Pradesh state, India. Apart from rainfall amount and distribution, other crop management factors e.g. dates of sowing (Bhatia et al., 1999) and solar radiation may be important in soybean yield during the experimental period (Bhatia et al., 2008).

The average predicted N uptake ($124 \, kg \, ha^{-1}$) by soybean suggested greater input from biologically fixed N_2 than the observed value ($109 \, kg \, ha^{-1}$). The supply from external sources for example, fertilizer was $20 \, kg \, N \, ha^{-1}$ and from soil system was $45 \, kg \, N \, ha^{-1}$. Remaining N uptake by the soybean crop was through biological N_2 fixation. This is in agreement with the research reported by Salvagiotti et al. (2008) who reported that on an average, N_2 fixation accounted for 52% of total N uptake, but the proportion of fixed N decreased with increasing fertilizer-N additions. The EF value of 0.27 between the observed and predicted grain yield of soybean showed a reasonable prediction by the model. Similar level of agreement (EF = 0.13) between the observed and predicted N uptake by soybean was obtained.

The yield variation for wheat observed in different years due to different amount of irrigation water received by the crop was also satisfactorily simulated by the model (Fig. 5b). The yield in the year 2002–2003, which only received one pre-sowing irrigation of 80 mm, was lower than the yield in 2003–2004 which received four irrigations (one pre-sowing + three post sowing) (Fig. 5b). Wheat is quite sensitive to water stress, therefore, it needs frequent irrigation for good growth and yield (Alderfasi and Nielsen, 2001). There was sharp decrease in soil water content (below crop lower limit) of the surface layer (0–15 cm) during the wheat growing season of 2002–2003 (Fig. 3a). The magnitude of the adverse effect of water stress on crop growth and yield depends on the stage of crop development, and duration and degree of water stress (Zhang et al., 1998). For the majority of the wheat growing period during year 2002–2003 the crop was affected by water stress, which markedly decreased the grain yield relative to the other years where total of 4 irrigations (320 mm water) were given. The model predicted similar level of water stress during wheat growing periods in 2002–2003. The simulation for this period showed that the wheat crop suffered from water stress from floral initiation to end of grain filling which might have severely affected the grain yield. The model predicted a similar pattern of yields across treatments to

that of the observed values. The overall prediction of wheat grain yield for the control, inorganic and organic treatments was good (EF = 0.91). Nitrogen uptake of wheat crop was also affected by water stress for all the treatments under observation and model predicted the effect on N uptake well (EF = 0.86).

The model prediction of grain yield and N uptake of wheat from the organic treatment was quite satisfactory considering the fact that the FYM in the model for the simulation was parameterized based on the laboratory incubation data. The difference in mean predicted total N uptake (average of 3-year excluding 2002–2003) by the wheat crop in the treatment that received 24 t FYM and in the control (no N) is assumed to be due to the N supply from FYM, which was 66 kg ha^{-1} relative to the measured value of 62 kg ha^{-1}. Also, the model predicted satisfactorily the increase in wheat grain yield by 2.7 times in the organic treatment over control. The RMSE between the observed and predicted wheat yield corresponded to 11% of the observed yield which is quite satisfactory.

Further, the scenario analysis by the model showed that grain yield of wheat was reduced considerably by reducing the FYM application from 24 t to 12 t, 10 t and 8 t ha^{-1} (data not shown). This showed the model is sensitive to application of N through FYM source in maintaining the grain yield at par with the inorganic sources of N. Such type of model prediction will assist in estimating the yields and productivity of different crops and cropping systems where plant available N is supplied from organic sources.

4.3. Soil organic carbon content of the profile

The inorganic fertilizers affect soil environment by increasing the above-ground and root biomass due to immediate supply of plant nutrients in sufficient quantities. This in turn increases the soil organic matter content (Sarkar et al., 2003; Bostick et al., 2007). In our study, the SOC in the control did not show any changes over a period of four years, while the inorganic treatment showed an increase in soil organic C content from the initial value (Fig. 7). The model predicted a decrease in soil organic C content in the control and increase in the inorganic treatment. The increase in soil organic C content under inorganic treatments could be related to production of more above- and below-ground plant biomass as reported by other researchers (Manjaiah and Singh, 2001). Manna et al. (2007) reported decline in soil organic C content where no N fertilizer was applied in long-term experiments in India.

The simulation of soil organic C of 0–15 cm soil depth by the model was satisfactory considering the pattern of soil organic C observed from the experimental data as well as the EF value (0.62) (Fig. 7). In the simulation the model indicated the rise in soil organic C content at each time of FYM addition to soybean or wheat. A small increase in the later part of the soybean and wheat growth period is probably due to this being the period of highest primary biological and root productivity. Application of FYM enhances the soil organic C level in soil (Shen et al., 1997) and its application in the organic treatment increased the organic C content of surface (0–15 cm) soil relative to the control as well as inorganic treatment.

The model predicted a smooth increase in soil organic C content each time FYM was added rather than a step increase. The model output only includes BIOM-C and HUM-C not FOM-C, so the smooth change reflects the conversion of FOM-C to BIOM-C and HUM-C. A direct chemical measurement of soil organic C includes any added FYM-C and would show a step change. For the organic treatment, the model overestimated the soil organic C content and could be a result of inappropriately low rate of decomposition of FYM in the model leading to more soil organic C content in the surface soil layer. This would arise if the model underestimates the rate of decomposition of FYM and/or the proportion of decomposing C that is evolved as CO$_2$.

5. Conclusion

The APSIM model was parameterized and validated for the soybean (cv. JS 335) and wheat (cv. Sujata) crops for central Indian conditions. The capability of the model to simulate grain yield and N uptake for soybean crop in both inorganic and organic treatments was satisfactory while that for the control (unfertilized treatment), it was poor. The poor prediction was attributed to P limiting condition of the control rather than the model. The predicted variability of grain yield due to the variation of total rainfall and rainfall distribution from year to year during soybean growing season was well predicted by the model.

For wheat the model predicted grain yield and N uptake well in all treatments. In wheat the predicted crop yield was most strongly influenced by variation in the amount of irrigation and N used during its growing season.

Furthermore, the model can be used in evaluation of irrigation strategy in wheat. By using the model, it is possible to explore for better irrigation options that would give maximum grain and biomass yield. In the experiment, wheat under water stress condition (2002–2003) showed markedly lower performance in grain yield and N uptake compared to fully irrigated condition.

The ability of the model to predict accurately both grain yield and N uptake by wheat across ranges of treatments involving both inorganic and organic sources of nutrients provides some confidence in applying the model for analyzing N management from inorganic, organic and integrated nutrient sources for the soybean–wheat system.

Prediction of soil organic C was acceptable in the control and inorganic treatments, but the model overestimated accumulation in the organic treatment. The discrepancy between the observed and predicted data was attributed to the low rate of decomposition of FYM by the model, and therefore, requires further improvement.

Acknowledgements

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