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Evaluation and application of the CROPGRO-Soybean simulation model in a Vertic Inceptisol

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Abstract

Crop simulation models are valuable research tools in agricultural decision making. In order to increase its general applicability, models need to be evaluated in diverse conditions. To achieve this, CROPGRO-Soybean model was evaluated on Vertic Inceptisols in a climatically variable semi-arid tropical condition. The model predicted reasonably the temporal changes in leaf area index, biomass and grain yield. The model was used to develop yield–evapotranspiration (ET) relationship, and to assess the influence of soil water-storage capacity on yield. Yield was linearly related to ET and was reduced non-linearly as soil depth decreased. The yield reduction was minimal when depth decreased from 90 to 67 cm but severe reduction occurred when depth decreased below 45 cm. There exists a threshold soil depth (37 cm), below which crop productivity in Vertic Inceptisols cannot be sustained, even in good rainfall years. There is an urgent need to develop sustainable natural resource management technology to prevent further degradation of Vertic Inceptisol. CROPGRO-Soybean model can be successfully used as a research tool to evaluate the risks associated in adapting such technologies. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Crop modelling; CROPGRO-Soybean; Model evaluation and application; Vertic Inceptisols

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1. Introduction

Vertisols and Vertic Inceptisols are highly weathered dark black soils, rich ($>30\%$) in expandable clay minerals throughout the soil profile. They have great agricultural productivity potential in semi-arid tropics (SAT), because of their natural fertility and high water-holding capacity. Both soils are distributed throughout the world between $45°$ north and south of the equator. With the natural resource endowments these soils with assured rainfall have the potential to contribute to the "green revolution" of rainfed agriculture. Vertic Inceptisols are often located in the upper and middle part of a toposequence on lands exceeding 2% slope. Consequently, these soils suffer from soil erosion leading to the loss of fertile topsoil along with essential nutrients and beneficial soil organisms. Inappropriate management practices in these soils generally lead to slow and poor crop canopy development and accentuate the soil erosion and degradation processes. Soil degradation processes generally result in the loss of soil depth causing a reduction in water-holding capacity, denying the inherent benefits of these soils to the rainfed agriculture. Soybean has been extensively grown in central India in both Vertisol and Vertic Inceptisols. The acreage has increased from 30,000 ha in 1980 to over 5.5 million ha in 1997 (Fig. 1). However, the productivity has been stagnant at less than 1 t ha^{-1}. Soybean yield ranged from 2.3 to 2.6 t ha^{-1} (at 12% moisture) in an operational level experiment (Singh et al., 1999a) and is considered as the potentially attainable yield at this experimental site. The yield gap between current farm level soybean productivity and researcher-managed operational level experiments is at least 1.5 t ha^{-1}. Because of the capacity to fix nitrogen biologically and to add organic crop
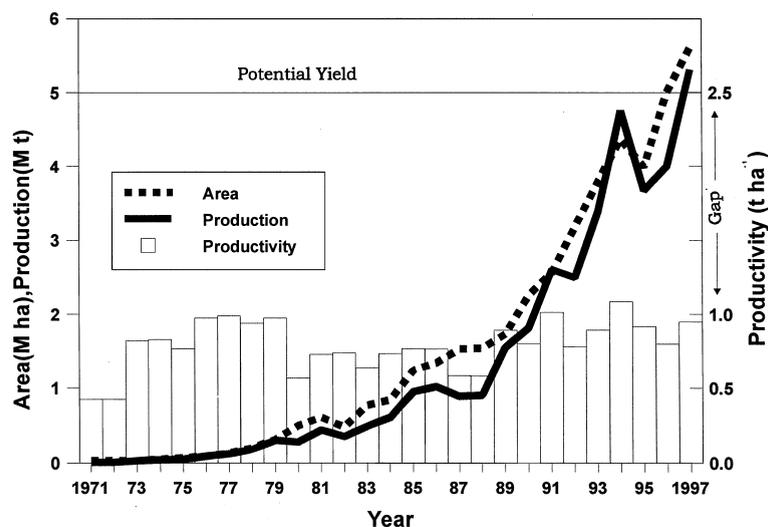
Fig. 1. Area, production and productivity of soybean in India (1971–97) and differences in yield (yield gap) between farm-level and researcher-managed experiments. Data for potential yield was obtained from Singh et al. (1999a).

residues to the soil surface at maturity, soybean plants have soil fertility building effect and help to sustain agricultural production in degraded soils. In order to maintain intergenerational equity in the climatically variable SAT, it is important to manage skilfully the soil, water and nutrient resources in these soils and sustain soybean productivity at a higher than present level.

Ideally, holistic long-term experiments in various agroecological zones are needed to quantify the significance of management practices that influence crop production before they can be transferred to other areas. However, traditionally and in practice, site-specific field experiments are generally conducted to identify improved crop production strategies at "representative" bench mark sites and results are then extrapolated to similar agroecological sites (Nix, 1984). In temporally and spatially variable climatic conditions in the SAT, such site-specific experiments require enormous efforts, because a large number of seasons, cultivars and soil types have to be sampled. Crop simulation models greatly facilitate optimisation of crop and its management strategies. Long-term field experiments when coupled with crop simulation models would be of great value to determine crop productivity changes due to soil degradation. Crop simulation models can also be used to indentify land-use changes, to predict risks involved and to evaluate consequences of alternative crop management practices in alleviating the risks. However, without an empirical evaluation, crop simulation models have limited use and sometimes may be dangerously misleading (IBSRAM, 1994). Many crop simulation models have been evaluated and used as a research tool to assess risks associated with various management strategies, and to assist decision-making process (Muchow and Belamy, 1991; Uehara, 1994; MacRobert and Savage, 1998; Thornton and Wilkens, 1998).

Evaluation of a crop simulation model involves establishing confidence in its capability to predict outcomes experienced in the real world. A frequently used method for evaluation of models involves comparing observed values with simulated results in a scatter diagram. Normally a linear regression is used to fit a straight line between observed and simulated values (Smith and Rose, 1995; Ohnishi et al., 1997). Then either parametric (Hammer and Muchow, 1991; Kiniry et al., 1997), or non-parametric (Heiniger et al., 1997) statistical tests are used to determine whether the intercept of linear regression is equal to zero and the slope is equal to or not significantly different from unity. However, Harrison (1990) and Mitchell (1997) argued against using linear regression as a validation tool because of its inherent inappropriateness and violation of assumptions associated with using regression as a tool, and difficulties experienced in accrediting a true null hypothesis. Mitchell (1997) and Mitchell and Sheehy (1997) provided an alternate objective and simple method, free of a priori assumptions. This method uses the deviations (prediction minus observation) plotted against the observed values and specifies two criteria for adequacy of the model. They are the envelope of acceptable precision and proportion of points that must lie within the envelope. In this method, no statistical tests are involved and hence the problem of satisfying assumptions is avoided.

CROPGRO-Soybean model (Hoogenboom et al., 1994; Boote et al., 1998) embedded in the Decision Support Systems for Agro-technology Transfer (DSSAT Vol. 3; Tsuji et al., 1994) is a process-oriented dynamic and generic crop simulation

model. The model operates on a daily time step. It can simulate crop growth and development of four different legumes (soybean, peanut, common bean, chickpea). A description of the processes in CROPGRO and a sensitivity analysis for temperature and agronomic management factors are provided by Boote et al. (1998). The CROPGRO-Soybean model reasonably predicts growth and yield in various subtropical and temperate locations in North America (Boote et al., 1997). In order to make this model non-site-specific and increase its applicability, there is a need to test its performance under moisture-stressed SAT conditions. Our objectives were: (1) to evaluate the CROPGRO-Soybean model in SAT for its ability to simulate growth and seed yield; (2) to apply the model to develop yield response to seasonal evapotranspiration (ET); and (3) to evaluate the influence of soil water-storage capacity on yield for Vertic Inceptisols.

2. Materials and methods

2.1. Model evaluation

The study was conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), near Hyderabad, India (17°32′ N latitude, 78°16′ E longitude, 540 m elevation) during the rainy seasons (June–October) of 1995–98. Daily weather data (maximum and minimum temperature, solar radiation, rainfall) were obtained from the central meteorological station (0.5 km from the experimental site). Data for evaluating the CROPGRO-Soybean simulation model came from a large operational-scale landscape watershed (6 ha) study that involved evaluating soil, water and nutrient management practices for sustaining productivity of soybean-based cropping systems. Due to natural variability in soil depth (the depth of black soil material) the watershed was divided into shallow (< 50 cm soil depth) and medium-deep (> 50 cm soil depth) blocks. Each block contained two landform treatments namely broadbed-and-furrow and flat systems. Each of the hydrological units in the watershed were partitioned into 6–8 subplots (ranging in size from 0.07 to 0.2 ha each). The design of the watershed and detailed description of the factorial combination of two soil depths and two landforms are given by Singh et al. (1999a). The experiment was conducted during the rainy seasons (June–September) of 1995–98. Detailed observations on phenology and crop growth measurements were made in individual subplots. The genetic coefficients for the soybean cultivar PK 470 were determined with the genetic coefficient calculator GENCALC (Hunt et al., 1993) using data collected during the 1995 experiment. The biomass data from 1996 and 1997 and grain yield data from 1996 to 1998 were used as independent data sets for model evaluation.

The soil is Vertic Inceptisol (fine, montmorillonitic, isohyperthermic family of paralithic Vertic Ustopepts). The soybean cultivar PK470, a medium maturity type, was planted between June 25 and 30 each year, depending on the onset of the rainy season. A pre-plant fertilizer, 250 kg ha^{-1} of single super phosphate was broadcast and incorporated. Soybean seeds, treated with *Rhizobium* culture, were planted in

excess, initially in 30-cm rows. The seedling emerged approximately 5 days after planting each year and the plants were thinned to a final plant population of 30 plants m^{-2}. Regular plant protection measures were followed to maintain pest-free conditions.

An area of 0.5 m^2 was sampled biweekly from each plots until final harvest. Plants were cut near the ground surface and from each sample three representative plants were subsampled. The subsample was separated into leaf, petiole, stem, dried leaves and pods. Leaf area was measured with a leaf area meter. The component plant parts from the subsample and the rest of plants from the sample were dried at 60°C for 72 h in a force draft oven. Fractions of dry matter in different plant parts of the subsample were used to derive the dry weights of plant parts in the entire sample. At maturity plants were harvested from a 45-m^2 area and machine threshed. The seeds were dried at 60°C for 48 h and weighed. The mean data from the subplots of hydrological units were used in the analyses.

2.2. Model application

A long-term computer simulation experiment was defined repeating a sequence of soybean in the rainy season followed by a fallow period, which ran from harvest to the beginning of subsequent planting of soybean in the following year. This rainfed soybean–fallow rotation was repeated over 22 years, starting from 1975 until 1996 using historical weather records. The soil moisture values at various depths of the soil profile on June 1, 1975 were used as initial conditions. A planting window between June 15 and 30 was selected, but actual planting in a given year was determined by soil moisture conditions in the top 20 cm of the profile. Within the automatic planting window, if the soil moisture in the top 20 cm of the profile remained between 10 and 100% of available soil moisture of the profile, then the crop was planted on that day. A plant population of 30 plants m^{-2} was maintained at a row spacing of 30 cm. The model was run with nitrogen balance and symbiotic nitrogen fixation routines turned on. No nitrogen fertilizer was applied to the crop and all crop residues were returned to the soil each year. The results of simulation experiment are presented as Cumulative Probability Function (CPF) plot where the distribution of yield is ordered from smallest to largest value and is plotted against equal increments of cumulative probability (Thornton and Hoggenboom, 1994;

Table 1
Soil profile depth and plant extractable soil water in the soil profile used in simulation study

Soil profile depth (cm)	Plant extractable soil water (mm)
25	50
37	70
45	85
52	95
67	115
90	150

Thornton et al., 1995; Bowen et al., 1998). To study the influence of available water stored in the soil profile on soybean yield, six soil depths ranging from 25 to 90 cm were used in the simulation study. These soil depths were representative of soybean-growing Vertic Inceptisols. The plant extractable water for the different soil profile depths is given in Table 1.

3. Results and discussion

3.1. Model evaluation

The CROPGRO-Soybean model was evaluated using two different methods. In the first method to evaluate the model, we used observed and simulated data of temporal changes in leaf area index (LAI) and biomass. The mean data collected from the flat landform treatment in medium-deep soil during 1996 season was used to evaluate the model. The temporal changes in LAI are presented in Fig. 2A. The model predictions of LAI closely agreed with the observed values during most of the life cycle. During the initial exponential increasing phase of LAI development, the model over-predicted LAI, and also the model under-predicted the maximum LAI. The model predicted the reduction in LAI due to natural senescence of leaves after 60 days accurately. Reduction in LAI was due to progressive senescence of green leaves. Leaf senescence is dependent on the mobilisation of protein (carbon and nitrogen) from vegetative tissues to reproductive tissues and is closely related to predictions of onset of pod initiation during reproductive development.

The temporal changes in crop canopy dry weight and its distribution to pods and seeds along with the predicted values are presented in Fig. 2B. The model simulated accurately dry weight changes. In several cooler season locations in the USA, the CROPGRO-Soybean model predicted the temporal changes in LAI and biomass reasonably well (Boote et al., 1997). The close agreement between simulated and observed temporal changes in LAI and biomass, in both cooler (Boote et al., 1997) and warmer rainfed conditions (present study), indicates the robustness of CROP-GRO-Soybean model to simulate growth of soybean plants.

The CROPGRO-Soybean model was also evaluated using a second objective method suggested by Mitchell and Sheehy (1997). The mean temporal biomass data collected from 30 days after sowing till physiological maturity of the plants during 1996 and 1997 seasons from the shallow and medium-deep soils of flat landform treatment were used for model evaluation (Fig. 3). The average standard deviation (S.D.) for total biomass measured from several experiments with similar crop management strategies at this experimental site was used as an envelope of acceptable precision between observed and simulated values. The S.D. can also serve as an estimate for reasonable expectation about the model's ability to simulate to a degree somewhat less precise than the actual measurement (Mitchell, 1997). The average S.D. for total biomass of soybean from several independent experiments under similar management conditions at this site was 55 g m^{-2} and was used as an envelope of acceptable precision. A concept of 0.95 confidence limit as usually followed in

statistical testing hypothesis was suggested by Mitchell and Sheehy (1997) to judge the model's capability to predict. Results indicated that the deviations were randomly scattered above and below the reference zero line (Fig. 3) and all points fell within the envelope indicating the acceptable performance of the CROPGRO-Soybean model.

Mean grain yield data from flat and broadbed-and-furrow landform treatments in the shallow and medium-deep soil depths during 1996 to 1998 were used to evaluate
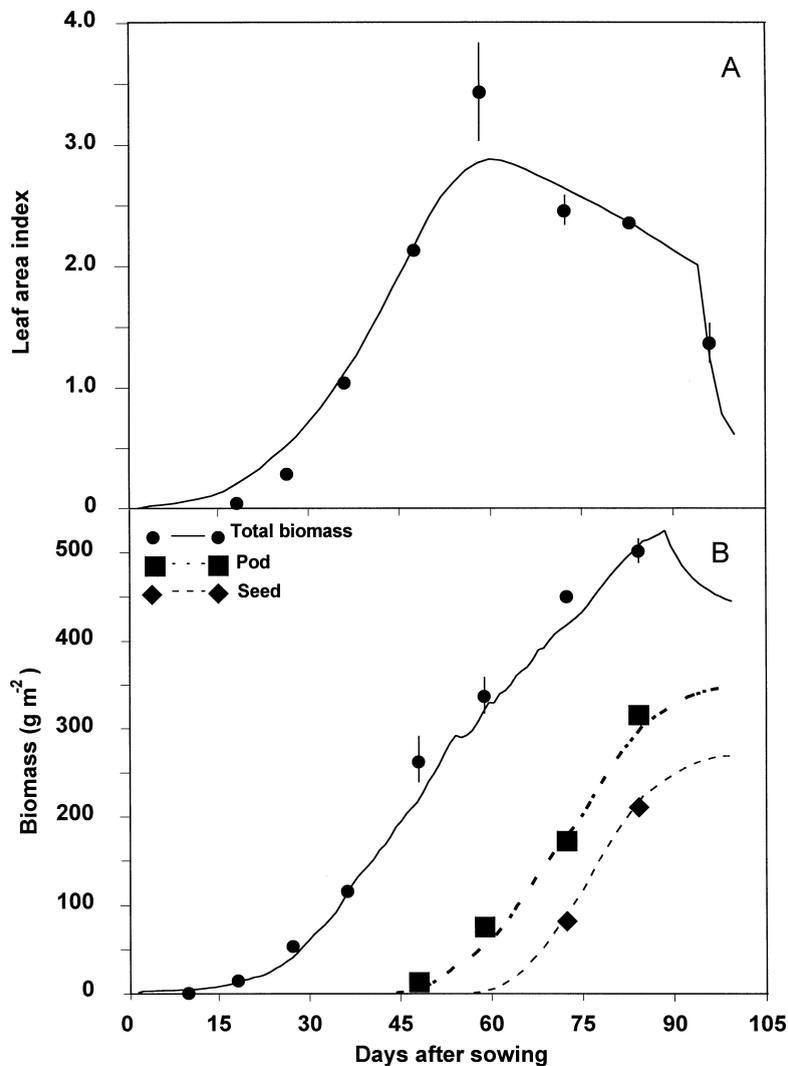
Fig. 2. Simulated (lines) and observed (symbols) of temporal changes in (A) leaf area index, and (B) total biomass, pod and seed yield. Vertical bars indicate twice the standard error of mean, when greater than symbol size.

the model. The average S.D. value for soybean grain yield from several experiments at this site was 25 g m^{-2} and was used as an envelope of precision. A comparison of the model performance for grain yield is given in Fig. 4. Ten out of 12 points (83%) fell within the envelope of precision. Based on the two methods of evaluating the model, CROPGRO-Soybean adequately simulates the biomass production, its distribution and grain yield in a tropically variable SAT climate. However, the model prediction of LAI during early plant growth needs further evaluation.

3.2. Model application

3.2.1. Yield and ET

The historical seasonal rainfall (July–September) during the 22 years of the simulated period ranged from 425 to 1050 mm. In 18 out of 22 years the seasonal rainfall exceeded 550 mm indicating that soybean could be successfully grown in Vertic Inceptisols with adequate soil water-storing capacity. Simulated seasonal ET for the soil depths ranging from 37 to 90 cm and simulated yield were used to develop the relationship between ET and yield. Seasonal ET ranged from 320 to 500 mm and averaged 427 mm. Simulated yield ranged from 640 to 3000 kg ha^{-1} and averaged 2200 kg ha^{-1}. Seasonal ET for soybean crops from other field studies ranged from 250 to 430 mm (Brun et al., 1972; Daniels and Scott, 1991). The linear ET–yield relationship was significant ($P < 0.01$) with a slope of 13.9 kg ha^{-1} of soybean yield for every millimeter of seasonal ET above a threshold ET of 260 mm (Fig. 5). The threshold ET was 0.52 of the maximum seasonal ET. The threshold ET represents
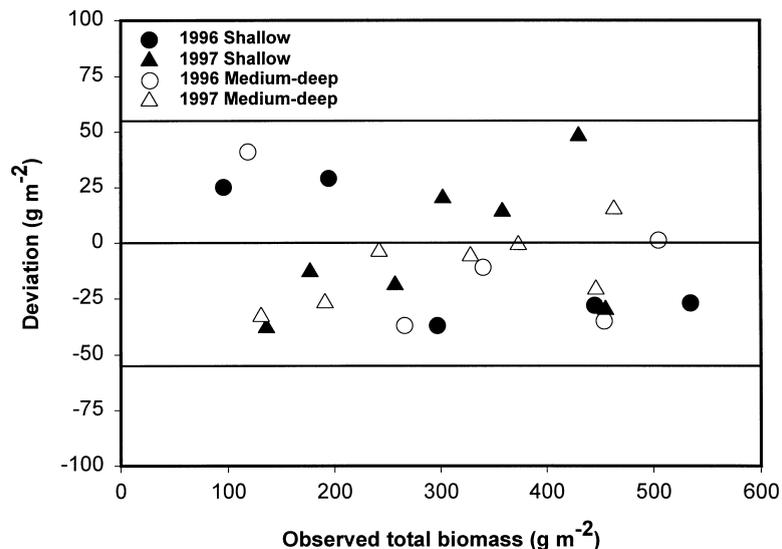
Fig. 3. Deviations of simulated total biomass from observed total biomass during 1996 and 1997 in shallow and medium-deep soil from flat landform treatment. The envelope of acceptable precision is the standard deviation.
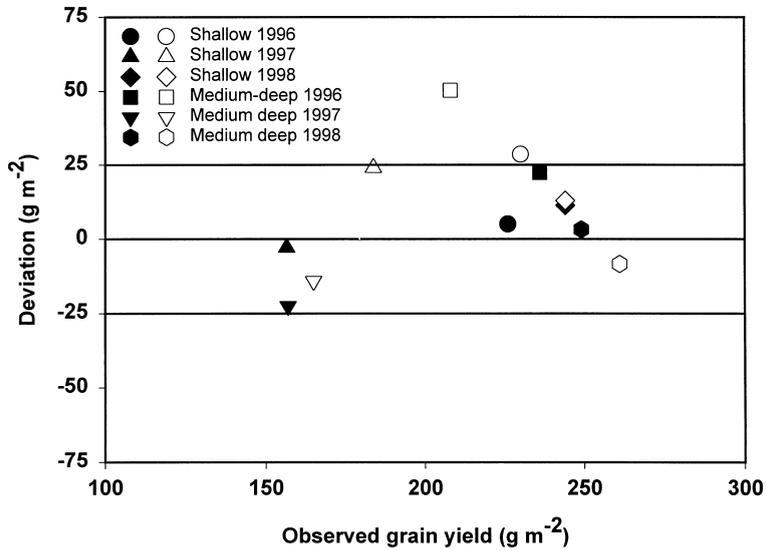
Fig. 4. Deviations of simulated yield from observed yield during 1996–98 from two landform treatments in shallow and medium-deep soil. The closed symbols are from flat, and open symbols are from broadbed-and-furrow landform treatments. The envelope of acceptable precision is the standard deviation.
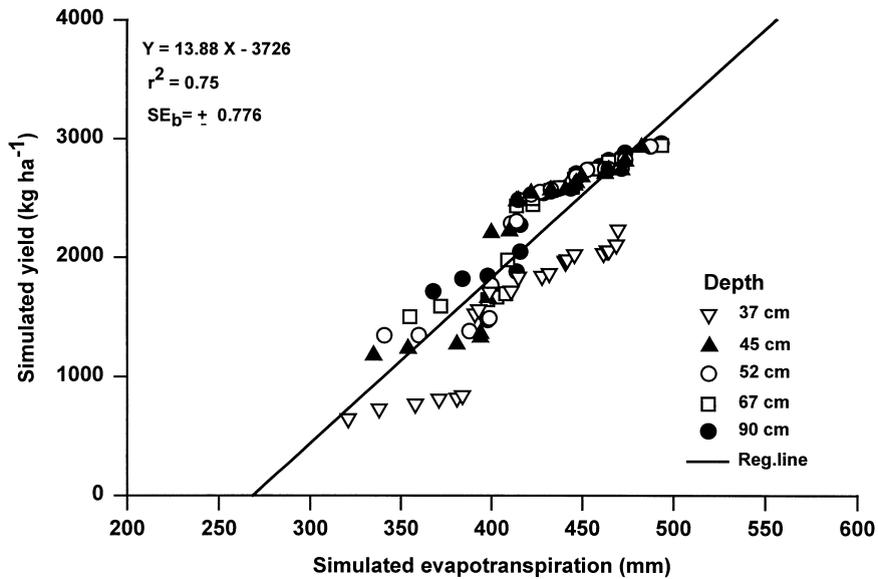
Fig. 5. Relationship of simulated yield and simulated seasonal evapotranspiration for different depths of Vertic Inceptisols.

the soil evaporation and plant transpiration that is necessary to establish and support the soybean plants before grain yield is realized.

The linear relationship between ET and yield is commonly observed in wheat (Musick and Porter, 1990) and in sorghum (Stewart et al., 1983; Stewart and Steiner, 1990). Analyzing a 178 crop-year database of irrigated and dry land wheat data from Texas, Musick et al. (1994) reported a threshold ET of 206 mm was required to initiate yield when the seasonal ET ranged from 310 to 800 mm. The threshold ET for sorghum ranged from 127 to 142 mm when seasonal ET ranged from 200 to 730 mm. The sorghum and wheat ET values have been derived from climates with high evaporative demand and limited precipitation during growing season. In contrast, soybeans in the present study were grown during the rainy season when evaporative demand is usually less and there was frequent precipitation during the season.

3.2.2. Yield and effects of soil depth

The temporal changes in soybean yield and the impact of soil depth on yield are presented in Fig. 6. In 13 out of 22 years the yields were nearly the same in the soils with depths > 37 cm. However, in below-normal rainfall years (rainfall < 550 mm when yield was < 2500 kg ha^{-1}) the effect of soil depth begins to manifest itself by reducing yield. There exists a minimum threshold soil depth, or available soil water-holding capacity, below which soybean yield can be drastically reduced, even in good rainfall years. This is indicated by the clear separation of CPF curve for soil depth 37 cm from the other soil depths, in all the 22 years in all rainfall regimes. In the threshold soil depth the soybean yield ranged from 700 to 2100 kg ha^{-1}.
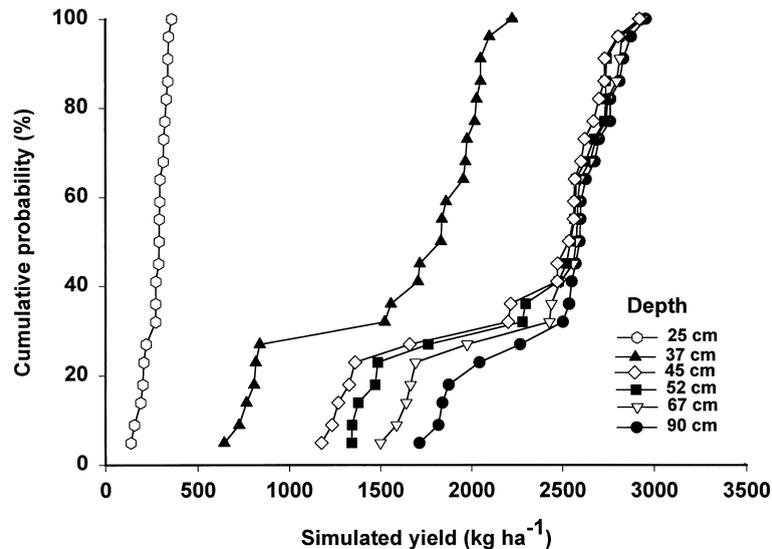
Fig. 6. Cumulative probability functions (CPF) plot showing the influence of depth of Vertic Inceptisols on simulated soybean yield during 1975–96.

Mean simulated yield over 22 years for various soil depths were used to derive a non-linear yield–soil depth relationship (Fig. 7). When the effective soil depth was reduced from 90 to 67 cm, soybean yield decreased 4 kg cm^{-1} in the soil depth. A greater yield reduction of 82 kg cm^{-1} in soil depth occurred as soil depth decreased from 45 to the threshold depth of 37 cm. When soil depth was decreased further to 25 cm, the greatest reduction in yield occurred. The simulated yield during 1975–96 at 25 cm soil depth ranged from 140 to 360 kg ha^{-1}. Crop yield measurements from erosion plots and topsoil de-surfaced plots indicated that crop yields were related to topsoil depth (Power et al., 1981; Thompson et al., 1991). A 4-year study conducted in a farmer's field indicated that a loss of 10 cm soil within 50–150 cm topsoil to subsoil depth, reduced soybean yield by about 6 kg ha^{-1}, but when the soil depth was reduced from 15 to 25 cm the yield reduction was 30 kg ha^{-1}. When rainfall and soil organic matter (SOM) were low, soil depth was a much better predictor of yield (Hairston et al., 1988). However, when SOM in a soil was greater than 3.14%, there was no soybean yield–depth relationship. Rhoton (1990) showed that the greatest soybean yield reduction per increment of soil depth loss occurred when the depth decreased from 60 to 50 cm. Since soil fertility was not a constraint in that study, the greatest yield difference between deep and shallow plots was due to the soil water content at the pod filling stage.

Soybean yield reductions from de-surfaced plots reported in literature and from the present simulation study indicate the need to maintain the depth of topsoil above the minimum threshold depth. Unlike the deeper Vertisols, maintaining soil depth assumes greater importance in shallow Vertic Inceptisols with low SOM levels and low plant extractable soil moisture. To maintain sustainable soybean production in the Vertic Inceptisols appropriate land management systems should be designed such that the soil depth is not allowed to decrease towards the minimum threshold

$$Y = 8217 - 67.93\,X + 0.265\,X^2 - 160782 / X$$
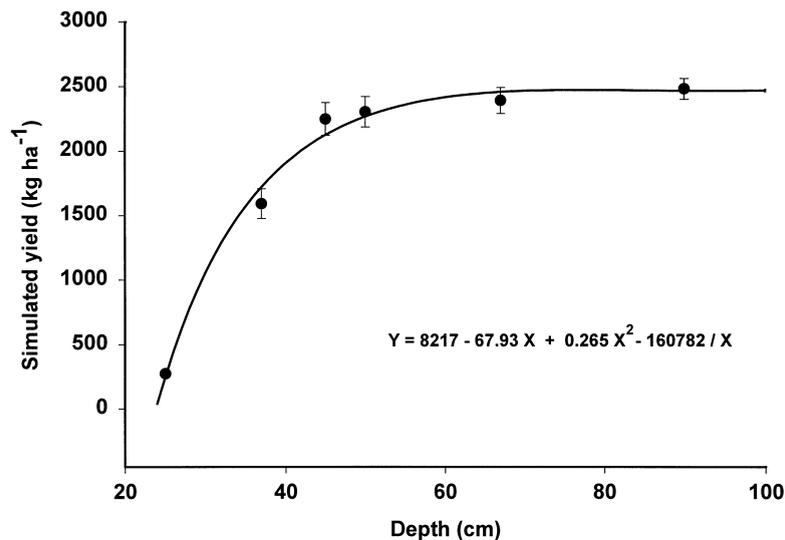
Fig. 7. Effect of Vertic Inceptisols depth on simulated soybean yield.

depth of 37 cm. Results from a large landscape watershed study indicated some suitable measures to increase the rainfall use efficiency by adopting appropriate soil, water and nutrient management strategies (Singh et al., 1999b).

Agricultural productivity of a soil is its intrinsic nature to support crops to produce economically important products. With adequate soil fertility and higher levels of management this intrinsic ability of the soil is largely determined by the capacity of the soil to store and supply soil water between significant rainfall events to the crops, based on their temporal water demand. The greatest negative effect of soil erosion on crop productivity is the decrease of available water-holding capacity of a soil with secondary effects coming from loss of nutrients and soil biota. However, it is difficult to accurately predict the long-term effects of soil depth on crop yield through experimentation. Crop simulation models such as CROPGRO-Soybean model offer tremendous possibilities to achieve this objective.

4. Conclusion

The CROPGRO-Soybean model embedded in DSSAT Vol. 3 can reasonably simulate total biomass and yield of soybean both in moisture-deficit tropical situations and in cooler temperate and subtropical locations. The long-term simulation study has indicated a non-linear yield and soil depth relationship. It also demonstrated the existence of a threshold soil depth, below which soybean productivity cannot be sustained, even during good rainfall years. In shallow Vertic Inceptisols (< 37 cm deep), growing of soybean could be a riskier enterprise, since the soil will run out of water during the reproductive and seed maturity stage. This study indicated a need to develop appropriate natural resource management systems that can prevent further soil degradation in Vertic Inceptisols. With soybean as an emerging commercial crop and the existence of a market-driven economy, there is a need to grow more soybeans and to sustain its productivity. This would require identifying niche areas for growing soybeans and developing appropriate and sustainable natural resource management technology in Vertic Inceptisols. The CROPGRO-Soybean model can be successfully used as a research tool to explore the effects of complex and alternate management decisions to sustain soybean production and evaluate the risks associated with adopting such decisions in the SAT.

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