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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