

Modeling the crop growth - A review

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सार – विकासशील देशों के समग्र आर्थिक और सामाजिक भलाई में कृषि महत्वपूर्ण भूमिका निभाती है। अब यह फसल विकास और उपज पूर्वानुमान मॉडल जैसे तकनीकी और प्रबंधकीय हस्तक्षेपों के माध्यम से खाद्य उत्पादन की गुणवत्ता और मात्रा बढ़ाने का सही विकल्प है। सांख्यिकीय, यांत्रिकी, नियतात्मक, स्टोकास्टिक, डायनेमिक, स्टैटिक, सिमुलेशन जैसे विभिन्न प्रकार के मॉडल फसल विकास और उपज का आकलन करने और पूर्वानुमान करने के लिए उपयोग में हैं। फसल वृद्धि और उपज पर जलवायु परिवर्तन के संभावित प्रभावों के पूर्वानुमान के लिए फसल विकास मॉडल भी एक बहुत प्रभावी उपकरण है। कृषि में विभिन्न व्यावहारिक समस्याओं को हल करने के लिए फसल विकास मॉडल उपयोगी हैं। पूरी दुनिया में सिमुलेशन मॉडल को विकसित करने और मान्य करने के लिए मानव संसाधन क्षमता में पर्याप्त सुधार करना होगा। इस शोध पत्र में विभिन्न फसल विकास मॉडलिंग दृष्टिकोणों पर चर्चा की गई है। इसमें फसल मॉडलिंग में जलवायु परिवर्तन की भूमिका और कृषि गतिविधियों में फसल विकास मॉडल के अनुप्रयोगों पर भी चर्चा की गई है। यहाँ कुछ सफलतापूर्वक उपयोग किए गए फसल विकास मॉडल पर विस्तार से चर्चा की गई है।

ABSTRACT. Agriculture plays a key role in overall economic and social wellbeing of the specially developing countries. Now it is the right option to increase the quality and quantity of food production through the technological and managerial interventions like crop growth and yield prediction models. Various kinds of models such as Statistical, Mechanistic, Deterministic, Stochastic, Dynamic, Static, Simulations are in use for assessing and predicting crop growth and yield. Crop growth model is also a very effective tool for predicting possible impacts of climatic change on crop growth and yield. Crop growth models are useful for solving various practical problems in agriculture. Adequate human resource capacity has to be improved to develop and validate simulation models across the globe. This paper discusses various crop growth modeling approaches. Role of climate change in crop modeling and applications of crop growth models in agricultural activities are also discussed. A few successfully used crop growth models are discussed in detail.

Key words – Crop, Growth, Simulation, Models, Climate change.

1. Introduction

Crop is defined as an “Aggregation of individual plant species grown in a unit area for economic purpose”. Growth is defined as an “Irreversible increase in size and volume and is the consequence of differentiation and distribution occurring in the plant” (Murthy, 2003). Simulation is defined as “Reproducing the essence of a system without reproducing the system itself” (Murthy, 2003). In simulation, the essential characteristics of the system are reproduced using a model, which is then studied in an abbreviated time scale.

Agriculture plays a key role in overall economic and social wellbeing of developing world including India. For the obvious reason of its centrality, agriculture in India has a large share in GDP (16%) and employment (49%)

but still one fifth of our population is under malnutrition. According to FAO (2015) about 815 million people of the 7.6 billion people in the world, or 10.7%, are suffering from chronic undernourishment and do not have enough food to lead a healthy active life. There are 11 million people undernourished in developed countries in 2016. One in four of the world's children are stunted and the proportion rise to one in three in developing countries. As per the 2018 Global Hunger Index (GHI), India was ranked 103rd from 100th in 2017 of 119 qualifying countries. So, meeting the two square meals of the exponentially growing population are the major challenges of farming and scientific communities. The global warming and climate changes are further boosting these challenges of food security. There is now scientific consensus that the world is getting warmer due to GHG emissions and hence, increasing weather variability,

TABLE 1
Chronology of crop weather modeling

Author and years	Crop models
Slatyer, 1960	Simple Water Balance Models
De Wit, 1965	Model photosynthetic rates of crop canopies
De Wit <i>et al.</i> , 1970	Elementary Crop growth Simulator construction (ELCROS)
Goudriaan, 1977	Introduction of micrometeorology in the models
De Wit and Goudriaan, 1978	Basic Crop Growth Simulator (BACROS)
IBSNAT, 1982	IBSNAT began the development of DSSAT model
Kropff <i>et al.</i> , 1994	ORYZA1 Model was developed.
Aggarwal <i>et al.</i> , 1994	India's 1 st crop model WTGROWS was developed followed by InfoCrop

frequency of worsening extreme events will impact the agriculture sector more and more adversely. Various agricultural activities such as land clearing, cultivation of crops, irrigation, animal husbandry, fisheries and aquaculture have a significant impact on the emission of GHGs (IPCC, 2014).

Climate change is no longer a distant scientific prognosis but is becoming a reality. The IPCC in its Fifth Assessment Report (2014) has reiterated that warming of the climatic system is unequivocal and mentioned a globally averaged combined land and ocean surface warming of 0.85 °C during the period from 1880 to 2012. Guiteras (2009) found that crop yields will decline by 4.5-9.0% in the short-run (2010-2039) and by a whopping 25% in the long-run (2070-2099) in the absence of suitable adaptations by farmers. It is, therefore, important to quantify the possible impacts of climate change on crop yields. Aggarwal and Sinha (1993) have predicted agricultural decline with climate change, which have been subsequently confirmed by Mall and Aggarwal (2002) and Pathak *et al.* (2015). Estimating the effect of climate change on crop production in India is difficult due to the variety of cropping systems and levels of technology used. Information need for agricultural decision making at various levels has been increasing rapidly due to the increasing demand for agricultural products and increased pressure on land, water and other natural resources (Jones *et al.*, 2003).

Land is a limited natural resource that cannot be expended to bring under agrarian activities. Field experiments to evaluate appropriate agronomic practices are laborious, time consuming and expensive; especially when a number of parameters are to be tested and require multi-year data for verification. The only option left is to increase the quality and quantity of food production

through technological and managerial intervention tools like crop growth and yield prediction models. Crop growth models are also useful tools to study the impact of climate change on crop growth and yield in diverse agro-environments. A crop model can be described as a quantitative scheme for predicting the growth, development and yield of a crop, given a set of genetic features and environmental variables (Monteith, 1996). According to United States Department of Agriculture (USDA), Crop Models are computer programs that mimic the growth and development of crops.

2. Development of models

Crop models have a long history (Table 1), during which their focus and application have altered in response to societal needs (Jones *et al.*, 2016). They have contributed to decision support system (Kadiyala *et al.*, 2015), risk assessment (Rader *et al.*, 2009) and resulted in practical agricultural development. Sinclair and Seligman (1996) opine that birth of crop modeling took place in the 1960's when simple relationships between light interception and photosynthesis were developed. According to them, the 1970's corresponded with the juvenile stage during which comprehensive models were developed, aimed at understanding the interactions between phenophases, environmental factors and crop growth. They were in adolescent stage in the 1980's wherein simplified models called summary models were developed. In 1990's crop modeling has reached the maturity phase when awareness increased about limitations and strengths of the crop growth models.

A new age in agricultural science started during 1960s with the pioneering work of de Wit on crop growth models. The first model depicts the photosynthetic rates of crop canopies to estimate crop yield (De Wit, 1965). This

TABLE 2

Dynamic simulation models

Categories	Types
Based on phases of development	Preliminary models
	Comprehensive models
	Summary models
Based on Input-Output relationships	Deterministic models
	Stochastic models
Based on the purpose	Statistical models
	Mechanistic models
	Static models
	Descriptive models
	Explanatory models
	Dynamic models
	Simulation models
Optimizing models	

very early model was called as Elementary Crop growth Simulator (de Wit *et al.*, 1970). Goudriaan (1977) introduced the concept of micrometeorology in models. The quantification of canopy resistance to gas exchanges for the better improvement of the simulation of transpiration which contributed to the introduction of Basic Crop growth Simulator (BACROS) by de Wit and Goudriaan (1978).

The International Benchmark Sites Network for Agro-technology Transfer (IBSNAT) sponsored by the United States Department of Agriculture began the development of a modeling project for tropical and sub tropical environments in 1982. The principal objective of this project was to understand how the system and its components function (Jones *et al.*, 2003). The Decision Support System for Agro-Technology Transfer (DSSAT) which is currently being used as a research and teaching tool was initiated under the auspices of the International Benchmark Sites Network for Agro-technology Transfer (IBSNAT) funded by the US Agency for International Development (USAID). The DSSAT was designed to enter, store and manipulate weather, soil and crop data to run the crop simulation model and analyze crop model outputs (Hoogenboom *et al.*, 1999; Jones *et al.*, 2003). The DSSAT helped decision-makers by substantially reducing the time and cost of field experimentation.

Hume and Callander (1990) proposed that a dynamic simulation model (Table 2) is the one whose output varies with time and in which processes are characterized to predict changes in crop status with time as a function of biogeochemical parameters. During this period a large number of rice models were developed *viz.*, ORYZA1 (Kropff *et al.*, 1994), CERES-Rice (Singh *et al.*, 1993), TRYM (Williams *et al.*, 1994), VSM (Kobayashi, 1994),

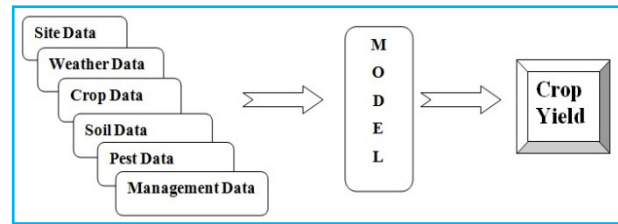


Fig. 1. Inputs and system approach of crop growth models

SIMRIW (Horie *et al.*, 1992), RICAM (Yin and Qi, 1994) and a rice-weed competition model (Graf *et al.*, 1990) and ORYZA2000 (Bouman *et al.*, 2001). ORYZA was an eco-physiological model which simulates growth and development of rice including water, C and N balance (Bouman *et al.*, 2001) in lowland, upland and aerobic ecosystems. It was calibrated and validated for 18 popular rice varieties in 15 locations throughout Asia. Since (2009), ORYZA2000 has been modified from a crop model towards a cropping model aimed mainly at abiotic stresses.

The WTGROWS was a mechanistic model which was developed for Indian conditions that simulate the potential production, phenology, soil water balance, soil and plant nitrogen balance, water and nitrogen stress on plant growth and development (Aggarwal *et al.*, 1994). Aggarwal *et al.* (2006) developed and evaluated InfoCrop, a generic and dynamic crop model based on several earlier models. Combined models have also been developed for cotton (Gutierrez *et al.*, 1977; Jones *et al.*, 1975 and Wang *et al.*, 1977), alfalfa (Gutierrez *et al.*, 1976), apple (Rabbinge, 1976), corn (Waggoner *et al.*, 1972) and wheat (Zadoks *et al.*, 1984) to simulate pest or disease development and expected injury to the crops. Crop yields can be predicted by these models before harvest by using the expected weather data. This is one of the foremost applications of the crop models. Various models (Jones and Kiniry, 1986) have been built to predict the performance of a particular cultivar, sown at any time, on any soil, in any climate. This has been achieved with varying levels of success (Hodges *et al.*, 1987; Liu *et al.*, 1989).

3. Input data and working

Hunt and Boote (1998) defined for the first time a minimum amount of input data needed for operating crop growth models. Crop modeling requires information regarding crop, soil, weather, management, insect-pest and phasic development data (Table 3).

Input data may have several ranges ranging between hourly, daily, weekly or monthly time frames (Nix, 1983). A model is recommended and utilized on the basis of available inputs and expected outputs (Fig. 1).

TABLE 3

Various input data required to run crop growth model

Site data	Weather data	Crop data	Soil data	Management data	Pest data
	T-max	Crop & variety	Soil thickness	Tillage	Pest name
Country	T-min	Planting date	Soil pH & E C	Seed rate & depth	Pest types
Station	RH	Crop phenology	N P K & O C status	Irrigation	Insect
Longitude	Rainfall	Root depth	Soil texture, structure	Fertilizer	Diseases
Latitude	Radiation	Crop height	Soil moisture	Residue	Others
Altitude	Wind speed	Critical depletion	F C & W P	Pesticide	Mode of attack
		LAI & Test wt.	Bulk density	Harvesting	Pest population

4. Steps in modeling

There are various steps in modeling which have to be followed for proper decision making (Fig. 2).

5. Applications

Applying model as an expert system leads to more effective use of existing knowledge for extension, agronomic and cropping system, research and breeding, to more efficient experimentation and for further integrating the scientific disciplines involved in crop production (Penning de Vries *et al.*, 1989). Simple simulation models which can be used for farm management decisions are now available in almost every country. In China and Philippines models are used to advise the farmers in rice cultivation (Morris, 1987). In USA (Anon, 1986) and Canada models are used for scheduling irrigation (Singh *et al.*, 1991). Ko *et al.* (2009) applied the EPIC model as a decision support tool to manage irrigated cotton and maize in South Texas. Hilger *et al.* (2000) examined the potential of the EPIC model by coupling it with the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model to estimate crop yields under erratic rainfall in northeast Brazil. The role of soil water availability in potential rain-fed rice productivity in Bangladesh is investigated by Mahmood *et al.* (2004). Cornejo (2003) used CROPWAT and GIS to estimate the irrigation potential of the Trasvase irrigation system on the Santa Elena peninsula in Guayas, Ecuador. Crop performance can be predicted for climates where the crop has not been grown before or not grown under optimal conditions. This has been used for wheat in Southeast Asia (Aggarwal and Penning de Vries, 1989).

Crop models together with GIS can facilitate demarcation of homologous zones at mega, macro, *meso* and *micro* level and have been used to determine potential and attainable yields for given inputs for various crops under various climatic conditions. The models are also

used to study the development of harmful insect-pests and diseases and for applying, the minimum chemicals at such a stage so as to reap the maximum economic benefit and to avoid the occurrence of environmental imbalance. The application of crop models has been widely used across the continents for assessing the impacts of climate change on agriculture. Saseendran *et al.* (2000) and Aggarwal & Mall (2002) studied the effects of climate change on rice in India. Similar, studies were conducted by Yao *et al.* (2007) and Feng *et al.* (2007) on maize in China.

Proper understanding of the effects of climate change on crop productivity through modeling approach will therefore help scientists to guide farmers to make crop management decisions such as selection of crops, cultivars, sowing dates and irrigation scheduling to minimize the climate change risks. In India also, the importance of the crop models is being realized and their use is likely to increase in the years to come. A brief account on applications of different types of models in agriculture is discussed below:

5.1. DSSAT model

Ramaraj *et al.* (2013) studied the impact of climate change in agriculture over Tamil Nadu using DSSAT model on rice and groundnut and observed no trend of impact of predicted temperature on both rice and groundnut yield but CO₂ enrichment had increased the yield of both crops. Biswal *et al.* (2017) calibrated and validated CERES wheat model on DSSAT platform for six major wheat growing districts of Northern India. They concluded that wheat crop prospects in all the six districts (Patiala, Bhiwani, Agra, Bharatpur, Morena and Rohtas) in terms of both conditions (sowing dates and soil moisture) and yield potential were normal with reference to historical years of 2008 and 2013. Tupe *et al.* (2017) conducted a field experiment during kharif seasons of 2012 and 2013 for the evaluation of SOYGRO model with four sowing times (to create different set of environmental conditions for weather variability) and three varieties, in

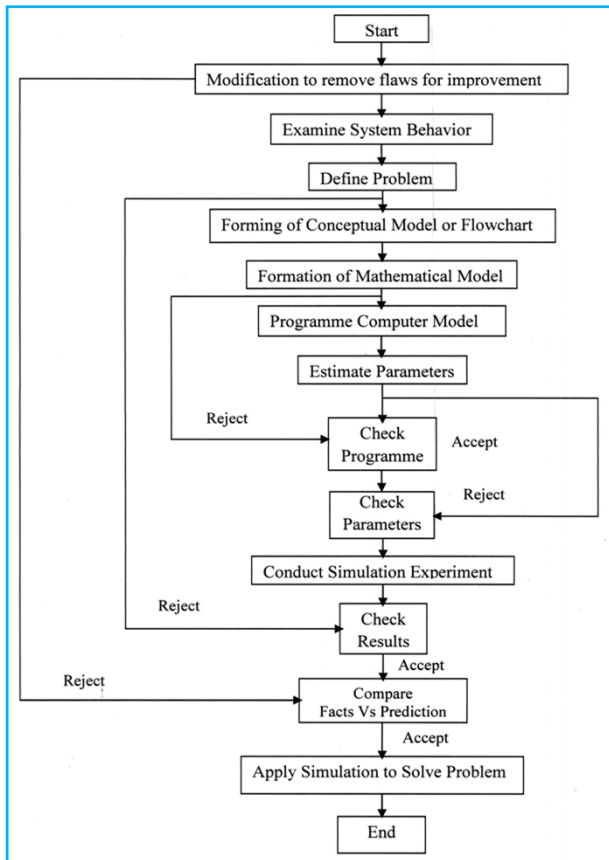


Fig. 2. Phases in construction of a model

four replications. The CROPGRO-soybean model performance in respect of phenological phases and yield was found to be highly reliable. Ray *et al.* (2018) conducted a study to identify the yield and growth changes of Swarna variety of rice in Odisha and revealed that increase in maximum and minimum temperatures affected the grain yield. Shrivastava *et al.* (2018) used DSSAT v4.6 model to simulate soil moisture and evapotranspiration over central India (Madhya Pradesh) during 1990-2011. It was found that the ESA (European Space Agency) derived soil moisture and MODIS evapotranspiration were closer to model simulated soil moisture and evapotranspiration, respectively.

Bhuvaneshwari *et al.* (2014) assessed the impact of climate change on rice using calibrated and validated CERES-Rice model and developed adaptation strategies to sustain rice production in western zone of Tamil Nadu. Model results showed that the rice yield reduction ranged from 4 to 56% with increase in temperature from 1 to 5 °C, respectively from the current climate under different dates of planting from 1st June to 15th July. Singh *et al.* (2017) used modified CERES-Pearl millet model to assess yield gains by modifying plant traits grown at six

locations in arid (Hisar, Jodhpur, Bikaner) and semi-arid (Jaipur, Aurangabad and Bijapur) tropical India and two locations in semi-arid tropical West Africa (Sadore in Niamey and Cinzana in Mali). Yields of heat tolerance substantially increased under climate change at most locations, having the greatest effects at Bikaner (17%) and Sadore (13%). Thus, drought and heat tolerance in pearl millet increased yields under climate change in both the arid and semi-arid tropical climates with greater benefit in relatively hotter environments. Sandeep *et al.* (2018) Calibrated and validated CERES-Sorghum model used to study the impact of climate change on sorghum yields for *kharif* and *rabi* seasons in India. Sorghum crop may confront with warmer temperature in the second half of the century and the rise in night time is more severe than day time temperature during *kharif* (Akola, Dharwad, Surat and Udaipur) and *rabi* (Bijapur, Dharwad, Rahuri and Solapur) seasons. Both *kharif* and *rabi* sorghum yield is exhibiting a decreasing trend towards the end of the 21st century. Negative influences of climatic change over sorghum growing areas of India can be minimized by adapting one or a combination of management practices like adjusting sowing time, application of extra irrigation which is location specific. Gupta and Mishra (2019) used an innovative approach of agro-ecological zones (AEZs) based climate change impact analysis on rice production of India. The analysis has been carried out by using CERES-Rice fed with improved state of art bias corrected climate projections from eight Global Climate Models (GCMs) and showed an expected increase in rice yield of most of the AEZs. Subramanyam *et al.* (2019) conducted a field experiment on two rice varieties Aathira and Vaisakh in Kerala using CERES-Rice model and obtained a good agreement between observed and predicted yields.

Nath *et al.* (2017) evaluated CROPGRO Soybean model for the diverse environment of Akola region of Vidarbhaand revealed that the model simulation performance in respect of phenological phases was highly reliable. Patil and Patel (2017) calibrated and validated the CROPGRO model on chickpea for two consecutive *Rabi* seasons at Anand, Gujarat and concluded that CROPGRO model can be used to simulate the phenology and yield of chickpea. Walikar *et al.* (2018) conducted a field experiment at Jabalpur to validate CROPGRO- Soybean model to assess its productivity under climate change scenarios. They obtained a good agreement between observed and simulated seed yield and biological yield.

5.2. WOFOST model

Tripathy *et al.* (2013) assimilated remotely sensed LAI input data in mechanistic crop simulation model WOFOST for in-season wheat yield forecasting in Punjab. The results indicated that the technique could be used for

spatial yield prediction at regional level. Dua *et al.* (2014) calibrated WOFOST for different Indian potato cultivars *i.e.*, late maturing, medium maturing and early maturing. The results demonstrated that WOFOST model can be used for potato crop under Indian situation but must be validated before it can be widely used. Singh *et al.* (2014) conducted a field experiment on three different rice varieties with three dates of transplanting. The WOFOST model satisfactorily simulated days to anthesis for timely transplanting and for delayed transplanting conditions. Mishra *et al.* (2015) analyzed the sensitivity of three cultivar of wheat to see the possible change in the grain yield using WOFOST model. The results showed increment in yield with increased sunshine hours and *vice versa* while the rise in maximum and minimum temperatures had adverse effect on wheat yield. The increase in the maximum temperature by 5 °C showed a reduction in yield by 24 to 29%. The effect of the minimum temperature was also of the similar order, but variation due to varietal differences was observed.

5.3. APSIM model

Subhash *et al.* (2014) tested the APSIM model to simulate the effects of different irrigation regimes on yield, irrigation water requirement and irrigation water productivity (WPI) of rice, wheat and rice-wheat (R-W) system in upper-gangetic plains of India. The long-term simulated rice yield showed a steadily declining trend while long-term simulated wheat yields showed a lower declining trend. The highest variation was observed under R-W system with the rice irrigation (IR) regime of 8 days alternate wetting and drying (AWD) and five irrigations for wheat with a yield penalty of 25.5%. Gaydon *et al.* (2017) showed that APSIM performed in a statistically robust manner in simulating cropping system performance over a wide range of crops, varieties, environments and management practices in Asia. Simulation of each of these important systems indicated no significant difference between simulated and observed rice grain yields at 95% confidence level. Hence, APSIM's performance across the systems in India can be categorized as acceptable and within the range of experimental data uncertainty. Similarly, performance in simulating the other major crops of the region (notably maize, wheat and cotton), were within the bounds of experimental error.

5.4. WTGROWS model

Kalra *et al.* (2006) indicated that WTGROWS model can be used with remote sensing and relational databases and it can also be updated whenever weather, acreage and fertilizer and other inputs data were received. National wheat yield forecast was done for three seasons on meteorological sub-division scale by using WTGROWS,

relational database layers and satellite image (Kalra *et al.*, 2006). For this, WTGROWS model was run with actual weather data obtained up to a given time and weather normals used for subsequent period and the forecast was prepared. Saxena *et al.* (2006) validated WTGROWS model for PBW343 and UP 2382 wheat varieties at Pantnagar. The percent deviation in simulated yields compared to observed values, ranged from -0.8 to +5.2. The results revealed that this model could be successfully used for environments similar to Pantnagar, after appropriate calibration for genetic and phenological coefficients.

5.5. InfoCrop model

Hebbar *et al.* (2008) conducted experiments in major cotton producing states of India from Hisar to Coimbatore during 2000-2001 and 2004-2005, respectively using InfoCrop-cotton model. Total biomass and seed cotton yield prediction showed an accuracy of 86 and 89%, respectively. The prediction of cotton production was more accurate for partially irrigated or irrigated districts as compared to rainfed districts. Boomiraj *et al.* (2013) presented the results of InfoCrop model evaluation in terms of its validation and impact of climate change on Indian mustard (*Brassica juncea*), sorghum (*Sorghum vulgare*) and maize (*Zea mays*), for six different regions of India (Akola, Anantpur, Coimbatore, Gwalior, Bijapur and Kota). Simulated results of mustard model showed a spatial variation in yield among all regions in both irrigated and rainfed conditions. Kumar *et al.* (2017) simulated the impact of varying levels of maximum and minimum temperature, seasonal rainfall and CO₂ on three varieties of mustard using InfoCrop model. Change in T_{max} and T_{min} by -1 to 1°C, rainfall by 10 to 20% and CO₂ between 415 to 490 ppm showed beneficial impact on the crop and increased the seed yield considerably. Similarly, Kumar *et al.* (2018) conducted a field experiment on mustard and results revealed that the model emphasis on all the parameters to be within the acceptable range (<10%) with significant accuracy.

5.6. ORYZA model

Arora (2006) examined the applicability of the ORYZA2000 model in analyzing the impact of water related options on rice yield in irrigated environments of Punjab. Performance of the model was reasonably good as indicated by close matching between simulated harvest-time grain yield, biomass and soil profile water use with measured data. Results showed that rice yield of late-transplanted (July 1) crop was comparable to that of early-transplanted (May 16) crop and ET-based water productivity was greater in late-planted crop. Kar *et al.* (2009) validated ORYZA1 to predict growth and

productivity of 5 rice varieties in India (Orissa) during kharif. The study revealed that simulated values of dry weight of leaves, dry weight of stem, panicle weight, above-ground biomass, LAI and grain yield were not statistically significant (5% level) for both CERES-Rice and ORYZA1 with observed values. Yadav *et al.* (2011) tested the ability of the ORYZA2000 model to simulate the effects of water management on rice growth and predicted that there was always some yield penalty when moving from CF to alternate wetting and drying (AWD). Soundharajan and Sudheer (2013) proposed an auto-calibration procedure of ORYZA2000 for its application in South India. The auto-calibrated model was tested for its performance using a validation data set from the experimental data. The results showed that the calibrated ORYZA 2000 model was capable of simulating the full irrigation and water stress condition of rice crop effectively and can be used to develop deficit irrigation management schedules.

5.7. FAO-CROPWAT model

Surendran *et al.* (2015) estimated the crop water requirements of rice, coconut, banana, arecanut, vegetables, pulses, rubber, tea, coffee and cotton in Palakkad district of Kerala using CROPWAT 8.0 model. Similarly, Surendran *et al.* (2017) calculated the water needs for various crops (rice, coconut, rubber, pepper, banana, brinjal, tomato, tapioca, cardamom, tea etc) in different agro-ecological units (AEUs) of Kollam district using FAO-CROPWAT. An overall water balance of the district was attempted by considering irrigation, domestic and industrial demand of AEUs, under current scenario and future demand. Ravishankar *et al.* (2018) assessed the existing water supply-demand gap of the Nawagarh Distributary, in Chhattisgarh using CROPWAT 8.0 model. Similar study was conducted in Shipra river basin by Trivedi *et al.* (2018) to determine actual evapotranspiration in the area.

5.8. AquaCrop model

Sethi *et al.* (2016) attempted to understand the response of paddy to irrigation by using the FAO AquaCrop model and showed that the model would be useful for predicting the paddy crop yield and irrigation water productivity under different irrigation scenarios. Pareek *et al.* (2017) calibrated & validated this model for Tarai region of Uttarakhand and observed that winter wheat yield & biomass can be simulated with relative accuracy using this model. He found that the agreement between simulated and observed wheat grain yield was satisfactory (with correlation coefficient = 0.94, RMSE = 0.27). On the basis of statistical indicators it was concluded that the model fitted the observed data set very

well. Kumar *et al.* (2018) conducted a field experiment on maize in Rabi at Pusa, Bihar) to evaluate the FAO-AquaCrop model. They concluded that the AquaCrop model was more accurate in predicting the Rabi maize yield under full and 75% of Control Irrigation (CI) as compared to the Rainfed and 50% CI. Similarly, Raja *et al.* (2018) studied this model for maize in Kashmir during Kharif seasons and found that the model performed satisfactorily for predicting the canopy cover and in-season biomass under varying environments.

5.9. Crop modeling in Himachal Pradesh

Kumar and Sharma (2004) used CERES-Rice model under Himachal Pradesh conditions and predicted phenology reasonably well. The association between observed and simulated days to flowering and physiological maturity was found to be significant. However, the model did not correctly predict biomass yield at maturity. Rana *et al.* (2011) examined the impact of climate change on mustard crop using InfoCrop simulation model and concluded that delayed sowing windows under elevated temperature proved beneficial under sub-humid and sub temperate climate of Himachal Pradesh. Pal *et al.* (2013) studied the performance of wheat yield using CERES-wheat model and found that six month forecast did not have significant skill, however, with the advancement of season thereby reducing the period of forecast, the forecast skill improved progressively. Rana *et al.* (2014) validated InfoCrop model to assess the impacts of the projected climate change on soybean production. They observed that the elevated levels of 50 and 100 ppm of CO₂ increased soybean yield by 5.0 to 10.2%. The projected yield losses due to elevated levels of temperature by 1°C and 2°C ranged between 1.3 to 3.5% and 4.5 to 6.0%, respectively for all planting windows. They finally concluded that rise in temperature with elevated carbon dioxide in general increase the yield in region.

6. Benefits and limitations

6.1. Benefits

Modeling approach can provide the following benefits:

- (i) *Crop system management* : To evaluate optimum management production for cultural practice.
 - (a) Seed Rate : Optimum seed rate can be found out with the help of these models.
 - (b) Irrigation : Optimum amount and time of application can be simulated.

(c) Fertilizer : Optimum amount of fertilizer and time of application of the fertilizer can be simulated.

(ii) *Yield Gap analysis* : Potential yield can be simulated using these models and the difference between potential yield and actual yield is the yield gap.

(iii) Yield Prediction and Forecasting.

(iv) Evaluation of climate change.

(v) Useful for solving various practical problems in agriculture.

(vi) These are resource conserving tools.

(vii) These can be used in precision farming studies.

(viii) These are very effective tool for predicting possible impacts of climate change on crop growth and yield.

(ix) Helps in adaptation strategies, by which the negative impacts due to climate change can be minimized.

6.2. Limitations

(i) At times, inaccurate projections of natural processes.

(ii) Unreliable and unrealistic projections of changes in climate variability.

(iii) Misuse of models.

(iv) Inappropriate results for Heterogeneous plot.

(v) Inherent soil heterogeneity over relatively small distances.

(vi) Model performance is limited to the quality of input data.

(vii) Sampling errors also contribute to inaccuracies in the observed data.

(viii) Rudimentary model validation methodology.

(ix) Plant, soil and meteorological data are rarely precise and come from nearby sites.

(x) An ideal crop model cannot be developed because of complex biological system.

7. Conclusions

An attempt has been made to illustrate about the importance, crop growth models play, as an agronomic

and user friendly research tool to evaluate the various agronomic practices for optimum crop production and climate change impacts. Crop weather modeling can play a significant role in system approach by providing a powerful capability for scenario analysis. Crop modeling has been developed extensively over the past 50 years and a diverse range of crop models are now available. It is considered that effective crop modeling must combine a scientific approach to enhance the understanding of application orientation and to retain a focus on prediction and problem-solving. The major importance of models is that issues like yield forecasting, operations management, consequences of management decisions on environmental issues, are well supported by modeling. Greater use of crop simulation models has also been suggested to increase the efficiency of different trials. While simulation models successfully capture the temporal variation, they use a lumped parameter approach that assumes the spatial variability of the soils, crops or climate. Thus, modeling represents a better way of synthesizing knowledge about different components of a system, summarizing data and transferring better research results to users.

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