1. Introduction

Systems approach has been used by engineers since the 1950's for the study of complex and dynamic processes but their use by scientists working in biological fields is relatively recent. A system is defined as any well delineated part of reality which may contain a number of interrelated elements forming the systems structure. These functioning components interact in various ways and the interaction between components can be physical, economic or social. A system is defined by the user on the basis of objectives and the intrinsic structure of the system as measured and observed. For an agronomist a system may be represented by a rice crop with leaf, stem and root (plant organs) and growth and transpiration (processes) as elements which interact strongly. A system is 'dynamic' when its state changes over time. This change could be 'continuous' when its behaviour and state change relatively slowly or 'discrete' when the changes are fast, sudden or large. A model is a simplified representation of a system and simulation is the study of the system and its behaviour using models.

2. Models

Planners, economists and researchers have always been interested in finding out ways and means to estimate crop yields in advance to the extent possible. With this objective, several regression models have been developed by many workers to predict the relationship with agricultural productivity and its components. These models when dealing with multi-year time series usually include a technology trend factor, thus lumping everything other than climatic factors in one regressor. However, such analysis where the effects of some specific factors is determined without consideration of interactions and feedbacks from other controlling elements can often be misleading. In addition to the climatic factors, there is a large number of edaphic, hydrologic, biotic, agronomic and socio-economic factors that influence crop growth and productivity.

Crop growth is a very complex phenomenon and a product of a series of complicated interactions of soil, plant and weather. Dynamic crop growth simulation is a relatively recent technique that facilitates quantitative understanding of the effects of these factors, and agronomic management factors on crop growth and productivity. These models are quantitative description of the mechanisms and processes that result in growth of the crop. The processes could be crop physiological, meteorological, physical and chemical processes. Such a modelling assumes that the rate of change of system can be closely approximated by considering the rate of processes to be constant during short time periods. This is based on state variable approach in which current states (for example, weights of plant parts, evapotranspiration, leaf area index) are updated after every short interval (usually one day) considering the previous state and the rate which is influenced by internal crop properties and environment. This is repeated till the crop is mature. Models that deal with crop growth simulation can be distinguished into two categories: Descriptive and Explanatory.
Descriptive models define the behaviour of a system in a simple manner. These models show the existence of relations between the elements of a system but reflect very little, if at all, of the mechanisms involved underlying the behaviour of that system. A very simple example of a descriptive model has been shown in fig. 1, where the biomass production of maize under optimum conditions as a function of time has been modelled using a simple regression equation (Sibma, 1987). The model fits the data for that year very well but it fails totally for other years (Fig.2) which highlights the limitations of descriptive models. It is always possible to add more variables (Agarwal and Jain, 1982) and improve the estimates but in the absence of any quantitative relationships of the processes contributing towards dry matter production the accuracy of the prediction would always be suspect as for maize. The scope of incorporating the effect of management practices is limited in such models.

Explanatory models consist of quantitative descriptions of the mechanisms and processes involved that are responsible for the behaviour of the system. For an explanatory model the system is analyzed and its processes and mechanisms are quantified separately. The model is then built by integrating these descriptions for the entire system. Fig. 3 shows the processes that have to be considered and disciplines involved for simulating crop growth under varying environmental conditions (Penning de Vries et al., 1989).

Explanatory models are means by which knowledge about systems and their performances is made portable and accessible to users whose livelihood and welfare depend on the systems performance. Models are extremely useful because the critical environmental problems caused by agricultural practices are system problems not disciplinary ones. Their solutions demand a multi-disciplinary approach linking basic and applied sciences.

The behaviour of a crop growth model can be explained by the basic physiological, physical and chemical processes and the effects of environmental factors on them.

3. Crop Production Levels

Based on growth limiting factors viz. water and nutrients, four levels of crop production have been identified.

Production Level 1: This is an ideal situation in which the crop does not suffer from any shortage of water or nutrients in the entire growing season. Its growth and development depends only on the weather conditions and crop characteristics. Fig. 4 is a flow diagram showing the processes that are to be considered at this level.
Fig. 1: A descriptive model relating biomass production of maize crop as a function of time for the year 1972.

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BM = \frac{12.0}{1.0 + 23.0 \times e^{-0.8 \times T}}
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Fig. 2: Biomass production of maize crop under optimal conditions for different years.
Figure 3: Processes and disciplines involved in developing explanatory models for simulating crop growth.

Figure 4: Flow diagram showing the processes involved at Crop Production Level 1.
Production Level 2: The growth of a crop is limited by shortage of water for at least some part of the growing season. This situation frequently occurs in semi-arid regions and also in areas where the rainfall is inadequate and/or poorly distributed.

Production Level 3: Nitrogen shortage during the growing season limits the crop growth at this production level. Water shortage or adverse weather conditions occur in the remaining part of the season. This condition is very frequent in the agricultural systems all over the world.

Production Level 4: Crop growth is restricted by low levels of phosphorus and other mineral nutrients in the soil during the growing season.

Growth reducing factors such as diseases, insect pests and weeds, can occur at each of these Production Levels giving them an extra dimension. Simulating crop growth, therefore, implies that for an explanatory crop growth model, researchers from diverse disciplines must work in close, self-imposed coordination to achieve a common goal.

Fig. 5 shows the output of a model for simulating the growth and development of wheat crop (Aggarwal et al., 1994) under non-water, non-nutrient limiting conditions. The effect of both water and nitrogen availability on crop performance has been incorporated into this model. The results show that the model has performed satisfactorily for a wide spectrum of locations across the country.

One of the main drawbacks of the process-based deterministic explanatory models is that the output is not stochastic in nature. To attach a level of uncertainty their output needs to be labeled with some probability. One way to achieve this is to use site specific weather data or historical weather data of a representative site for a large number of years. Another alternative is to use weather generators to generate weather data for a number of years using available data for a limited period. The output of the model drawn on probability graph now accounts for the naturally occurring variation in the weather parameters. Fig. 6 was obtained after carrying out such an exercise with historical weather data for Delhi (Aggarwal et al., 1994). The figure gives the probability associated with yield levels to be expected when wheat is irrigated once only twenty one days after sowing at different nitrogen levels.

One of the practical difficulties encountered in use of explanatory models is the availability of reliable data required as input. Quite often data on some initial parameters are not easily available and they have to be estimated which implies a degree of uncertainty associated with the estimates. Monte Carlo (MC) simulation is a useful technique to quantify uncertainty or spatial variation in input parameters on simulated output. In this technique, the model is run a large number of times using random values drawn from probability distribution for specific input parameters. The distribution of simulated output is represented as a probability distribution as a function of input certainty. The first step is to select an input parameter that influences the output significantly. Through sensitivity analysis SPSOIL (Seepage and percolation rate of soil) was selected as an input for a model to predict rough rice production under rainfed conditions. 200 randomly generated parameter sets for 11 years of weather data representing 2200 rough rice yields were used to calculate exceedance
probability distributions (Bouman et al., 1994). The results have been presented in fig. 7. The figure shows high variability in simulated rice yields indicating the risks involved in growing rice without irrigation.

Figure 5: Comparison of measured and simulated grain yields in potential production environments.

Figure 6: Effect of nitrogen application on cumulative probability distribution of grain production of wheat at Delhi.
In the absence of some key parameters needed as input, it may be worthwhile to explore the possibility of estimating them based on some routinely available and/or easily measurable properties. In case of Crop Production Level 2 where crop growth is to be simulated under limited water availability conditions, four critical soil hydrophysical parameters viz., soil water content at saturation (Sat), field capacity (FC), wilting point (WP) and air dryness (AD), are required as input. The dependence of these parameters on some routinely measured properties can be exploited to estimate their values satisfactorily as shown in fig. 8 (Singh, 1994).

Figure 7: Exceedance probability of rough rice yields as average for the whole land unit (thick line) and different SPSOIL rates in Philippines

4. Networking
A good number of researchers have been actively involved in the development and building up of crop growth simulation models all over the world but most of these models are never fully tested or validated over a wide range of conditions restricting their use. The applicability of a model lies in it being globally tested which would allow the imperfections and weaknesses of the model to be exposed leading to its refinement.

Two projects can be cited as examples which have followed this approach by establishing a network to evaluate crop models. One of them is IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) project based at Honolulu, Hawaii (Uehara and Tsuji, 1993) with their series of crop models called CERES (Crop Environment Resource Evaluation through Synthesis)-WHEAT, CERES-RICE etc. The other one is SARP (Simulation and Systems Analysis for Rice Production) based in Wageningen, The Netherlands (ten Berge, 1993). SARP started initially with rice but has now diversified to include crops vital to that region. The ultimate objective is to have a Decision Support System which is essentially a computer software to match crop requirements to the physical characteristics of the land using a data base management system, a set of validated crop models to simulate Genotype (G) x Environment (E) x Management (M) interactions and application programmes to simulate experiments to ascertain the uncertainty associated with
the proposed strategies. This can then be used as a tool to assist policy makers to make better choices NOW to ensure a better future.

![Predicted and observed soil water content](image)

Figure 8: Observed and predicted values of four critical soil water contents for ten selected soils estimated from simple regression models based on easily measured soil properties

5. Application of Crop Simulation Modelling

### Environmental Characterization:
Crop models together with GIS can greatly facilitate demarcation of homologous zones at mega-, macro-, meso- as well as micro level depending upon the availability of data and objectives. These tools have been used to determine potential and attainable yields for a given level of inputs for various crops. Potential yield of cultivars varies with season/year and location. Estimates of such yields for different varieties can establish a reference point for site quality and remove the confounding effects associated with large climatic variation.

### Optimising Crop Management:
Once potential yields have been quantified, these can be converted to attainable yields to determine magnitudes of yield gap. Crop growth modelling can be used to in matching agro-technology with the farmers resources and in analysing the precise reasons for yield gap. Recent studies have shown that simulation models can help fine tune the N fertiliser application recommendations in irrigated rice (Berge et al., 1996). Studies done in China, India, Indonesia and Philippines showed that simulation model recommendations helped in increasing the fertiliser use efficiency by 15-20%.
Pest and Disease Management: At a regional level, GIS, requisite environmental data coupled with epidemic simulation models further provide geographic delineation of disease and insect pest risk zones. These zones can also help us in making strategic decisions on deployment strategies for varieties and to determine how long host plant resistance would be expected to last. Historical climate data from sites have been shown to be useful for characterizing the conduciveness of a site to specific diseases. Attempts are also being made to integrate disease predictive systems with online weather and weather-interpolation systems.

Yield loss studies have conventionally quantified the relations between nitrogen application rate, disease severity, season and grain yield. This has resulted in a qualitative understanding of the host-pathogen-environment interactions and in disease management recommendations. However, validity of such recommendations is limited, as they are strongly influenced by disease onset, disease spreading rate, farm management practices, environmental conditions and their interactions. Physiologically based simulation models can be applied to understand the damage mechanisms and analyse their effects on crop growth and yield of rice.

Impact of Climate Change: Crop models are being used to estimate the impact of increased carbon dioxide and temperature on crop production (Matthews et al., 1995). It was assumed that the trends in potential yields would also be shown in actual yield. These models can utilize the input from Global Circulation Models (GCM) to quantify the impact of climate changes.

Yield Forecasting: Reasonably precise estimates of acreage and yield before the actual harvest are of immense value in policy planning. The relatively small cost and speed of assessment makes crop growth simulation models promising for areas where significant daily weather data are readily available. In this approach, the model is run using actual weather data during the cropping season for the geographical region of interest. Weather data for typical years are used to continue simulations until harvest. Horie et al. (1992) showed an example where crop models, regional weather databases and historical yield data is used to forecast rice yields for different regions of Japan. There is an urgent need to develop such models for Indian situation. A schematic diagram of the various components of such a system would be integrated is shown as fig. 9.

Optimal Sowing Dates for Hybrid Seed Production: A major constraint to utilizing hybrid seed technology is the need to buy fresh seeds every planting season and the high cost of seed production. This limited seed production is largely due to poor out-crossing and asynchronous flowering of male and female parents. Environmental factors such as temperature, humidity, and
wind speed as the time of pollination and fertilization play a great role in regulating outcrossing percentage. To synchronise these at several locations to determine the optimal planting dates, crop simulation modelling is a more efficient tool in making decisions about the planting calendar of parents in different environments (Xu, 1995).

**Increased Efficiency of Multi-environment Evaluation:** Development and release of a variety is a complex process that may extend over a period of 10-15 years. Once the breeding lines have become homozygous, they are bulked and then tested in observational, replicated and multi-location yield trials. These multi-site trials are expensive and need several crop seasons/locations to understand genotype by environment (G x E) interactions.

Since the systems approach integrates different components of agroecosystems, it can play a great role in increasing the efficiency of plant breeding process, in particular multi-environment testing of genotypes. Crop models together with GIS can facilitate biological characterization of the physical environment (geography, soil, climate, etc.), and thus define key environmental domains for which improved varieties are to be developed. Alternatively, the same methodology can be used to determine the adaptation domains of genotypes. A modelling approach can also provide estimates of yield probability in target environments based on the understanding of G x E interactions. Such studies can help in reducing the number of sites/season required for field evaluation and thus increase the efficiency of the whole process of variety development.

A very simple role for crop modelling would be the provision of an index of site quality for use in traditional GxE analysis. This could be achieved by simulating performance of number of check varieties over a wide range of weather conditions at each site. Regression of observed test variety lines on the simulated index would give an idea of stability.

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Figure 9: A crop growth monitoring and yield forecasting system
Regression of the same check variety yields on the simulated index would give an idea of the effect of specific weather conditions.

Definition of breeding environments could also be achieved by crop models by modelling a set of probe genotypes known to discriminate between breeding environments. A target region could be divided into breeding domains in which different sets of germplasm could be tested.

By modelling a range of probable genotypes and selected environments known to discriminate between the genotypes, it is possible that the crop parameters determining the specific interaction could be identified. Hypothetical varieties could then be modelled combining the crop parameters conferring most advantage as an indication of suitable traits and breeding targets.

6. Conclusion
Models are means to capture, condense and organize knowledge. A well tested model can be a very effective scientific tool for tailor-made introduction of new production technologies, working out alternative crop production strategies, provide answers to the 'WHAT IF' questions raised by technology adopters, to identify problems and prioritize research, to optimize precious resources by reducing the number of field experiments, to assist in policy and strategy applications, for environmental characterization and agroecological zoning, for seeking new domains and as a very effective teaching aid.

A number of opportunities are now available for the use of crop simulation models for quantifying the effects of various factors including weather on agriculture. The key areas are biophysical characterization of agro-environments, evaluating impact of climate change, optimising crop, pest and disease management, and increasing the efficiency of multi-environment testing, forecasting crop yields, etc. to name a few. It is now possible to explain with simulation models the effects of environmental variability on crop growth and yield. The response of standard cultivars to environment can be predicted with confidence. In future, the systems approach, with its well-developed analytical framework, databases, and powerful simulation models, will be handy to provide answers to many to the current agricultural issues in a relatively shorter time frame. To do this more effectively, greater efforts should be made to develop models that can integrate the effect of all important factors operating in the field environment, for instance, weather, edaphic conditions, management, incidence and effect of pests, and socio-economics.

7. Future Needs
One of the issues still unresolved is the undue credit which the modellers are generally accused of taking from the data generators. This aspect is certainly worth looking into.

There is always scope for improving existing models and other decision tools and it will always remain a continuous process.
Development of a data base is not as exciting as model development but equally important if not more so. There is a need to compile and reorganize existing data and to design, plan and implement a global programme with the sole objective of constructing a Minimum Data Set (MDS) for soil, crop and weather variables. These characteristics can be integrated using Geographical Information Systems (GIS) to form user oriented decision support systems.

The development of new decision aids is taking place at such a fast pace that there is an immediate need to train a critical number of researchers, educators, administrators and policy makers so that the best possible benefit may be derived from them.

References


