A SYSTEMS ANALYSIS APPROACH TO DEVELOPING CROPPING SYSTEMS IN THE SEMI-ARID TROPICS

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ABSTRACT

The semi-arid tropics (SAT) are characterized by a high climatic water demand. The mean annual temperature is greater than 18°C and rainfall exceeds evapotranspiration for only 2 to 4½ months in the dry and 4½ to 7 months in wet/dry SAT. The coefficient of variability of rainfall ranges from 20 to 30 percent. Alfisols and Vertisols are two major soil types found in these areas.

The interdisciplinary farming systems research team at ICRISAT aims to develop basic principles, approaches, and methodologies that can be readily used in alternative, economically viable farming systems in the seasonally dry SAT. Dry-seeding technology on deep Vertisols for double cropping, a small watershed concept for land and water management, and the broadbed-and-furrow system are a few of the technologies developed so far for increased crop production. The simulation technique will be useful to integrate in a holistic way all aspects of operational-scale systems research being carried out in ICRISAT watershed units. The process-based dynamic models of crop production system involving soil, crop, weather, and management data will also be valuable as research tools for analyzing the usefulness of prospective technologies across locations. Preliminary results obtained from a sorghum growth model indicate that under a given set of climatic conditions the analyses could assist in the selection of crop genotypes in relation to the amount of water available in the soil profile at seeding and to the runoff collection available in the reservoirs. Since soil types and rainfall patterns in the SAT show considerable location specificity, such analyses will assist considerably in deriving estimates of the crop growing periods and suitable cropping systems.

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INTRODUCTION

A farming system is based on complicated interactions of several physical, biological, and socio-economic factors that include climate, soil, crops, etc. A suitable farming system is therefore unique for a locale and differs from place to place according to available resources, the state of development of these resources, the methods of production, and the crop(s) grown. Farming systems research should therefore be conducted with a recognition of and a focus towards the interdependencies and interrelationships that exist between elements of the farming systems, and between these elements and the farm environment.

The task of improving farming systems in the semi-arid tropics (SAT)[1/] is complicated by the presence of several constraints in these areas. These include intensive rainfall interspersed with unpredictable droughts, a relatively short rainy season, highly variable rainfall during the rainy season, high evapotranspiration rates throughout the growing season, low soil organic matter content, low infiltration capacity of soils, great water erosion hazard, small farms with fragmented holdings, limited capital resources, severe unemployment during the long dry season, etc. Because of these constraints and the ever-present risk of drought (or flood), farmers are reluctant to invest in high yielding varieties, fertilizers, and other inputs even when available. Thus unstable food production

Contribution of the International Crops Research Institute for the Semi-Arid Tropics; Journal article Approval No.113. For presentation at International Conference of Operations Research in Agriculture and Water Resources, Jerusalem, Israel, November 25-29, 1979.

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[1/] The SAT are characterized by a mean annual temperature greater than 18°C and rainfall that exceeds evapotranspiration for only 2 to 4½ months in the dry and 4½ to 7 months in wet/dry SAT (Troll 1965).

and low crop yields are common in the SAT (Kampen et al. 1974; Kampen & Burford 1979; Kanwar 1979; Krantz et al. 1974; Virmani et al. 1979). Farming systems scientists at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) realized early that single component approaches could not solve the complex problems encountered in these areas. Therefore their investigations involve all facets of resource inventory, development, management, utilization, and all factors involving crop production in a systems approach. An interdisciplinary research team is engaged in many facets of operational-scale systems research on natural watershed units at ICRISAT. Attempts are made to increase and stabilize agricultural production through improved soil, water, and crop management practices. Some of the technologies developed to attain increased crop production will be discussed in this paper.

Systems research relies to a considerable extent on the use of models (Wright 1971; Nix 1979). Models can be used to integrate all aspects of operational scale systems research in a holistic way and to identify the major components of the system. Because models represent only the relevant features of reality, they are relatively easy to manipulate. Therefore models will be useful to evaluate the relative potentials for various prospective technologies developed at research centers across different agroclimatic locations in the SAT. It is envisaged that process-based dynamic crop production models involving soil-crop-weather-management factors will be useful as research tools in developing systems that provide for efficient and productive crop growth in the SAT.

The watershed-based resource utilization research conducted at ICRISAT, the existing cropping systems in the SAT, and the use of modeling and simulation technique in systems research are discussed in the following pages.

WATERSHED-BASED RESOURCE UTILIZATION RESEARCH

Major components of the technology that was developed in watershed-based resource utilization research include dry sowing on deep Vertisols, runoff collection and supplemental irrigation, the broadbed-and-furrow system of cultivation, etc.

Dry sowing in deep Vertisols

Vertisols are one of the major soil types found in the Indian SAT. They have low bulk density and high porosity in the immediate surface layers. The subsoils are extremely hard when dry and very sticky when wet and consequently are difficult to till. In India, nearly 20 million ha of these soils are presently fallowed during the rainy season (Krantz et al. 1974). An important factor that has facilitated cropping of deep Vertisols during the rainy season has been the realization that crops can be sown in a dry seedbed shortly ahead of the early rains in areas where precipitation commences fairly reliably and where there is a good probability of followup rains to ensure establishment of the germinating crop. Cropping during the rainy season may provide the farmer with opportunities for two crops in one year.

Rainfall collection and supplemental irrigation

The collection of surface runoff during periods of excess rainfall and its subsequent use during dry periods markedly decreases the risks involved in rainfed agriculture. Alfisols, another major soil type found in the SAT, have high bulk density and low porosity in the surface layer but below the surface they are of variable texture. These soils are easily cultivated when moist but become very hard when dry. Rainfall collection and supplemental irrigation are particularly important on Alfisols and shallow Vertisols because of their limited water retention capacity (large quantities of water may be lost as runoff or deep drainage during the rainy season). On these soils, crops frequently suffer from moisture stress due to dry periods in the rainy season.

A particular example of the beneficial effect of supplemental irrigation is the response observed in the rainy season of 1974, when a 30-day dry period coincided with the grain formation stage of sorghum (ICRISAT 1975). A supplemental irrigation of only 5 cm to sorghum in operational scale research watersheds increased yields by almost 100% over those of rainfed crops. The gross value of the increase due to this water application was 2780 Rs/ha.

The deep Vertisols rarely require supplemental irrigation for the rainy season. However, supplemental water can always be used on a postrainy crop and often a second crop can be benefitted by a small initial quantity of water (Kampen & Krishna 1978).

Broadbed-and-furrow systems

Establishment of a broadbed-and-furrow system with an amplitude of 150 cm was found to be successful in facilitating cultural operations controlling excess water (Kampen 1979). The broadbed is about 100-cm wide with a sunken furrow of about 50 cm. The furrows are graded so that water discharges into grassed waterways, which may lead to a small surface reservoir. With the broadbed it is possible to plant two, three, or four rows at 75-, 45-, and 30-cm row spacings, respectively (Fig. 1). Comparisons of flat planting with cultivation on broadbeds are presented in Table 2. Results indicate substantial yield advantages of the graded broadbed system on deep Vertisols (Kampen 1979). Erosion and runoff are relatively low in this system on deep Vertisols because the excess water is led off at a controlled velocity in many furrows rather than in concentrated streams down the steepest slope. Drainage during wet periods is also facilitated.

CROPPING SYSTEMS IN THE SAT

Several systems of cropping such as intercropping, relay cropping, and ratoon cropping are being examined on both the Vertisols and Alfisols at ICRISAT. Attempts are being made to develop systems that provide efficient and productive crop growth from the start of the rainy season until as far into the postrainy season as residual soil moisture will allow. Much emphasis has been given to intercropping because of its popularity with the poorer farmers operating in low rainfall and high risk situations in the SAT (TAC 1978). It also minimizes evaporation losses. The typical intercropping combinations studied consist of sorghum/pigeonpea, pearl millet/groundnut, sorghum/chickpea, and sorghum/pearl millet.

Climate, soils, and crops are the building blocks for improving the cropping systems of a locality. Soil types and rainfall patterns in the SAT show considerable location specificity. Therefore, the new concepts, approaches, and methodologies developed at ICRISAT for improving crop production in the SAT need to be integrated and tested at other locations of the SAT before wholesale adoption in those regions. Crop production simulation models that utilize soil, crop, weather, and management factors will be valuable research tools in the development and extension of technology.

MODELING AND SIMULATION TECHNIQUES IN SYSTEMS RESEARCH

Systems simulation offers a [illegible] of studying decision problems of farming systems taking into account the full complexity and uncertainty of reality. Systems analysis research is generally carried out with models that, to varying degrees of precision, simulate the real system. The kind of model one should utilize depends on the user's objectives. The purpose of our modeling research at ICRISAT is:

1. To develop a framework for interaction with other ICRISAT programs and disciplines; to bring together information on different aspects of crop growth and development.

2. To develop a quantitative understanding of crop responses to the environment leading to yield prediction.

3. To identify areas where quantitative knowledge is required to plan alternate strategies for croppping, land use, and water management practices.

4. To answer the classical "what if" questions, or more appropriately, to optimize physical, human, and economic resources.

5. To suggest priorities for research and development that may aid in making crop management decisions.

To identify the kind of approach we should utilize, different types of models used in crop growth, plant development, and yield prediction have been surveyed; they are presented in summary from in Table 2. Each of these approaches has its merits and demerits. For example, common assumptions in statistical models are not often met, although these models used mostly for yield predictions. Purely statistical models do not really represent plant growth and development processes. Physiological models have the potential of helping us increase our understanding about the basic interactions in the soil-plant-atmospheric system. However, a disadvantage is that it is often difficult to apply these models to large areas because of data requirements. Some of these models are very complex in that they attempt to simulate the vital physiological processes of the plant step by step. Most systems of interest, e.g., soil water balance, plant growth and development etc., are dynamic in nature. We are therefore convinced that dynamic crop growth models involving soil-crop-weather-management factors and leading to yield prediction will suit our purpose.

A considerable amount of modeling research has already been done on corn, wheat, and soybean (Swanson and Nyankori 1979, Huda 1978, Feyerherm 1977). Among the five crops of interest to ICRISAT, only sorghum has received some attention, and thus it was decided to work on sorghum initially. It seemed desirable to test the existing sorghum models for adaptation in the SAT rather than to develop new models. If the analyses of the sorghum model satisfactorily serve the purposes outlined earlier, then the work will be extended to other crops raised in sole or intercropping situations.

Sorghum growth model

Arkin et al. (1976) developed a dynamic sorghum growth model (SORGF) that calculates the daily growth and development of an average grain sorghum plant in a field stand by considering the physical and physiological processes of light interception, photosynthesis, respiration, and water use that are independently computed and used as submodels. The appearance of leaves, their growth rate, and the timing of these events are generated in the model. Most of the equations describing the physiological processes are empirically derived from field measurements. A generalized flow diagram of SORGF is given in Figure 2. The model operates on a daily basis and utilizes soil, crop, weather, and management factors. The input data required are given in Table 3.

Testing SORGF: The SORGF model was computerized and is currently available on the ICRISAT computer system. The minimum data set required to test this model were not readily available at ICRISAT. However, the meteorological data that were needed to test this model were available for both the rainy and postrainy seasons of 1978. Assumptions regarding other input data such as soil, crop, and management, etc., were made in consultation with the concerned ICRISAT scientists so that first approximation results of the model can be obtained. The assumptions are as follows (1) Dates of sowing were 14 June and 10 October for rainy and postrainy-season crops, respectively. (2) Depth of sowing was 5 cm. (3) Row spacing was 75 cm. (4) Adequate fertilization, weed control and other plant protection measures were undertaken. (5) No irrigation was given. And (6) Crop stand was 180,000 plants/ha.

Results obtained from the 1978 rainy season are presented in Figure 3. These results indicate that under the climatic conditions at ICRISAT Center during this time (amount of rainfall received during June-October was 1077 mm), a sorghum cultivar producing 18-20 leaves with a maturity duration of 90-100 days would be needed to achieve optimum grain yields in the range of 6000 to 7000 kg/ha. These results are reasonably in agreement with the reality since some of the best cultivars recommended for this region take about 100 days to mature and yield approximately 6 metric tons/ha under optimum management conditions.

In the postrainy season, the crop thrives on the conserved profile soil moisture hence water becomes the main limiting factor for crop production. Therefore, an attempt was made to simulate sorghum yield for the 1978 postrainy season in response to varying levels of initial profile soil moisture. The results are presented in Table 4. The duration of sorghum had been defined by the number of maximum leaves utilized as input data by the model. The input data were 18 and 14 for long and short-duration crops respectively. The model simulations show that a long-duration crop would take approximately 94 days to mature, whereas the short-duration crop would mature in 68 days. The results indicate:

1. Short-duration sorghum yields are higher than long-duration sorghum when available soil water in root profile at sowing is only 10 cm.
2. Long-duration sorghum yields are higher than short-duration sorghum when available profile water at sowing is ≥ 15 cm.
3. Optimum yields of short-duration sogrhum can be obtained with 15-cm available soil water; long-duration crop yields are highest with 20-cm available soil water at sowing.

Such analyses could be useful in developing strategies for optimizing the use of water (available in the soil profile and in the surface storage tanks at the beginning of the postrainy season). This information along with surface watershed hydrology data could be used in building a stochastic model based on long-term rainfall observations for optimizing crop production.

The preliminary simulation results are encouraging, and further testing including the sensitivity analysis of the model is underway. The preliminary results show a need for modifying and developing subroutines in order to derive specific answers under the conditions encountered in the semi-arid tropics in particular. The Ritchie (1972) model, which has been used in SORGF, is found to underestimate the daily evaporation rate from the crop surface at ICRISAT Center. Attempts are being made to calculate daily soil water balance using data on rainfall, open-pan evaporation, available soil water at sowing, water storage capacity for different layers of soil profile, crop characteristics, etc.

At the present time we do not have field data to compare the simulation results. Therefore it became necessary to conduct field experiments in order to collect the essential sets of soil, crop, weather, and management data for testing the SORGF model. A multilocation cooperative experiment on sorghum at a few benchmark locations in the SAT will be useful to modify some of the submodels used in SORGF to adapt them to specific regions. In other words these experiments will help examine the location specificity of the model. Thus from 1979 onwards, the multilocation experiment on sorghum is being conducted at the ICRISAT Center and at eight other centers in India.

CONCLUSIONS

We believe that the use of models in systems analysis is complementary to the study of real systems. The simulation models that involve soil, crop, weather, and management factors have the potential of integrating information available from different experiments and identifying major components of the system. First approximation answers will be obtained to such questions, for example, as what will happen to the yield when crop production factors such as date of sowing, depth of sowing, row spacing, available soil water at sowing, soil water storage-capacity, plant stand, agroclimatic conditions, etc., are changed. Field experiments are usually conducted to evaluate the effects of these production factors singly or in a combination, but they are time-consuming and expensive. Crop modeling research could help in synthesis of such empirical data and thus could minimize field experiments. Moreover, such models could be useful research tools to examine the possible agronomic consequences of introducing new technologies into a range of agroclimatic situations. Answers to these questions will help identify the crops or genotypes needed to obtain optimum yields for a particular agroclimatic location. Such simulations would also help to identify improved technologies that would be best suited for the crop chosen for that locality. Once such questions are understood for one crop, e.g., sorghum, the expertise could be extended for others to identify types of crops that produce compatible combinations in both time and space to obtain optimum yields.

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Table 1. Mean monetary values of flat vs. semipermanent broadbed-and-furrow system on Vertisol watersheds using improved technology in 1976 and 1977 (after Kampen, 1979)

Watershed No.	Land Management	Year	Intercrop			Sequential crop			Means	
			Maize (Rs/ha)	Pigeonpea (Rs/ha)	Total (Rs/ha)	Maize (Rs/ha)	Chickpea (Rs/ha)	Total (Rs/ha)	Both systems (Rs/ha)	Both years (Rs/ha)
1, 2, 3A	Beds	1976	2840	2080	4920	2730	950	3680	4300	
1, 2, 3A	Beds	1977	2270	2770	5040	2880	2400	5280	5160	
Means										4730
3B, 4B	Flat	1976	2530	1680	4210	2300	570	2870	3540	
3B, 4B	Flat	1977	2450	1810	4260	2790	2200	4980	4620	
Means										4080
L.S.D. (.05)										280
C.V. (%)										9.2

Table 2. Different approaches of crop weather ling

Authors	Type of models listed
(1974)	Deterministic; and stochastic
Jensen (1975)	Statistical; state-of-the-art physiological and statistically based crop weather soil moisture
Baier (1977)	Crop growth simulation; statistically based crop weather analysis; and multiple regression
Shaw (1977)	Mathematical or statistical; biological and combination

Table 3. Input data required for 'SORGF' - a sorghum simulation model (Arkin et al. 1976)

Plant data

Leaf number - total number of leaves produced
Leaf area - maximum area of each individual leaf, cm^2

Planting data

Planting date, month, year
Plant population, plants/ha
Row width, cm

Climatic data (daily from planting to maturity)

Maximum temperature, °C
Minimum temperature, °C
Solar radiation, ly/day
Rainfall, cm/day

Soil data

Available water-holding capacity, cm
Initial available water content, cm

Location data
Latitude, deg

Table 4. Yield simulation of 'SORGF' utilizing 1978 postrainy-season ICRISAT data

Available soil water at sowing (cm)	Grain yield (kg/ha)	
	Crop duration	
	Long	Short
10	1342	2101
15	4101	3099
20	4659	3156
25	4723	3165

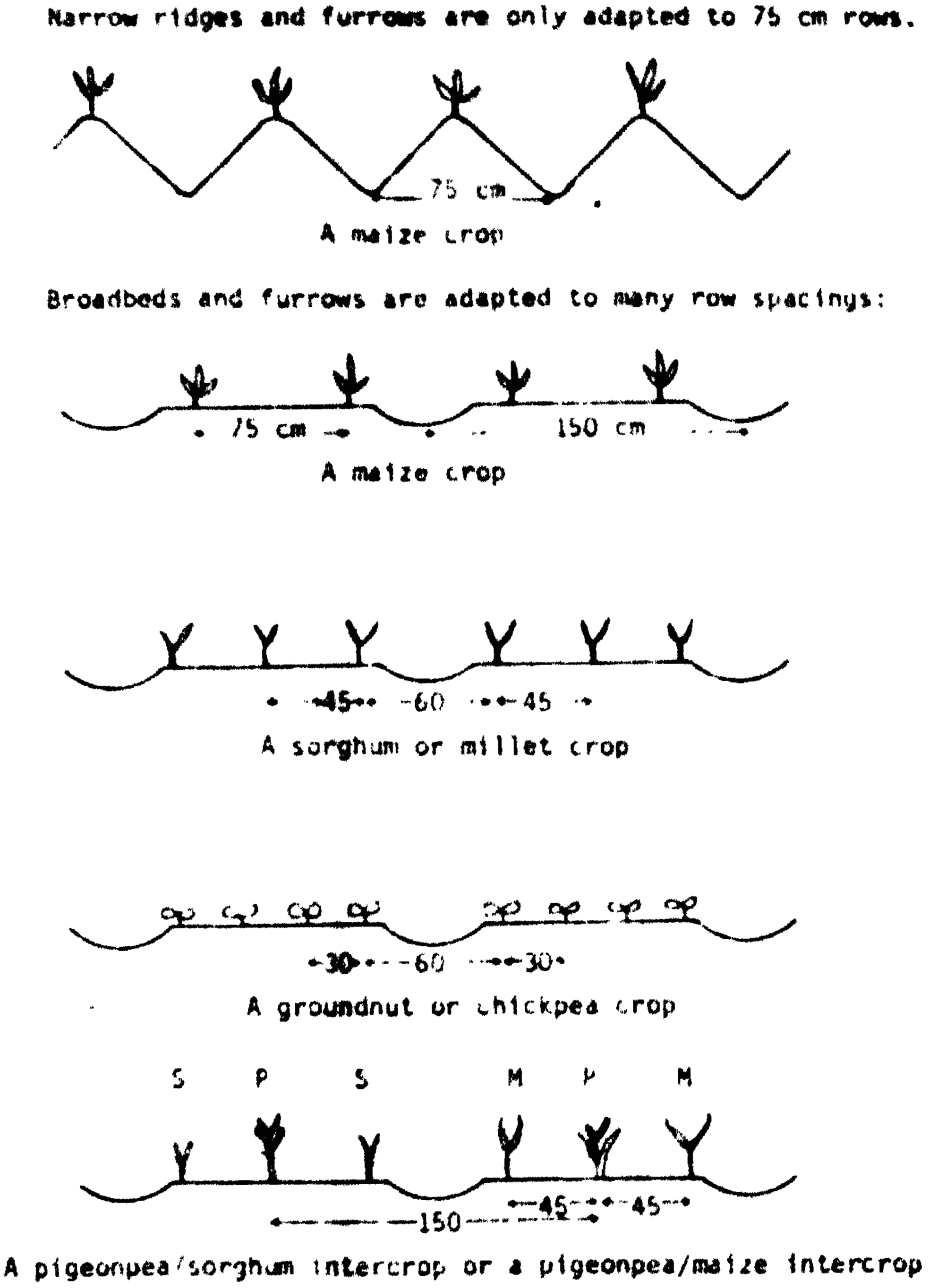

Figure 1. Alternative cropping systems and row arrangements on broadbeds (150 cm); all dimensions in cm (after Kampen, 1979)

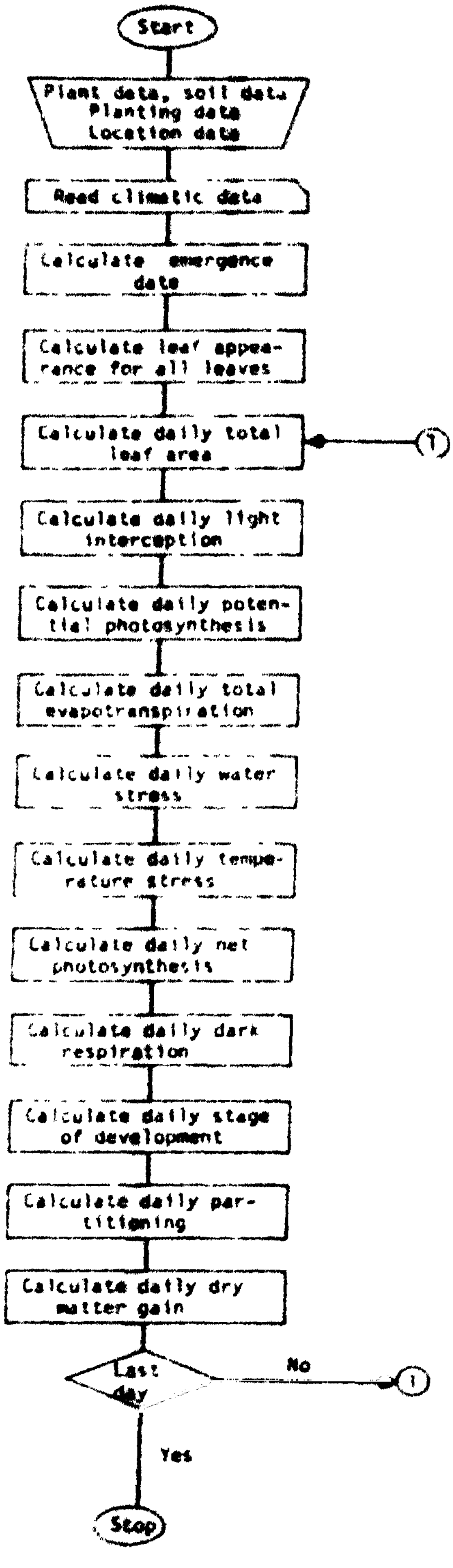

Figure 2. A generalized flow diagram of the growth model (SORGF)

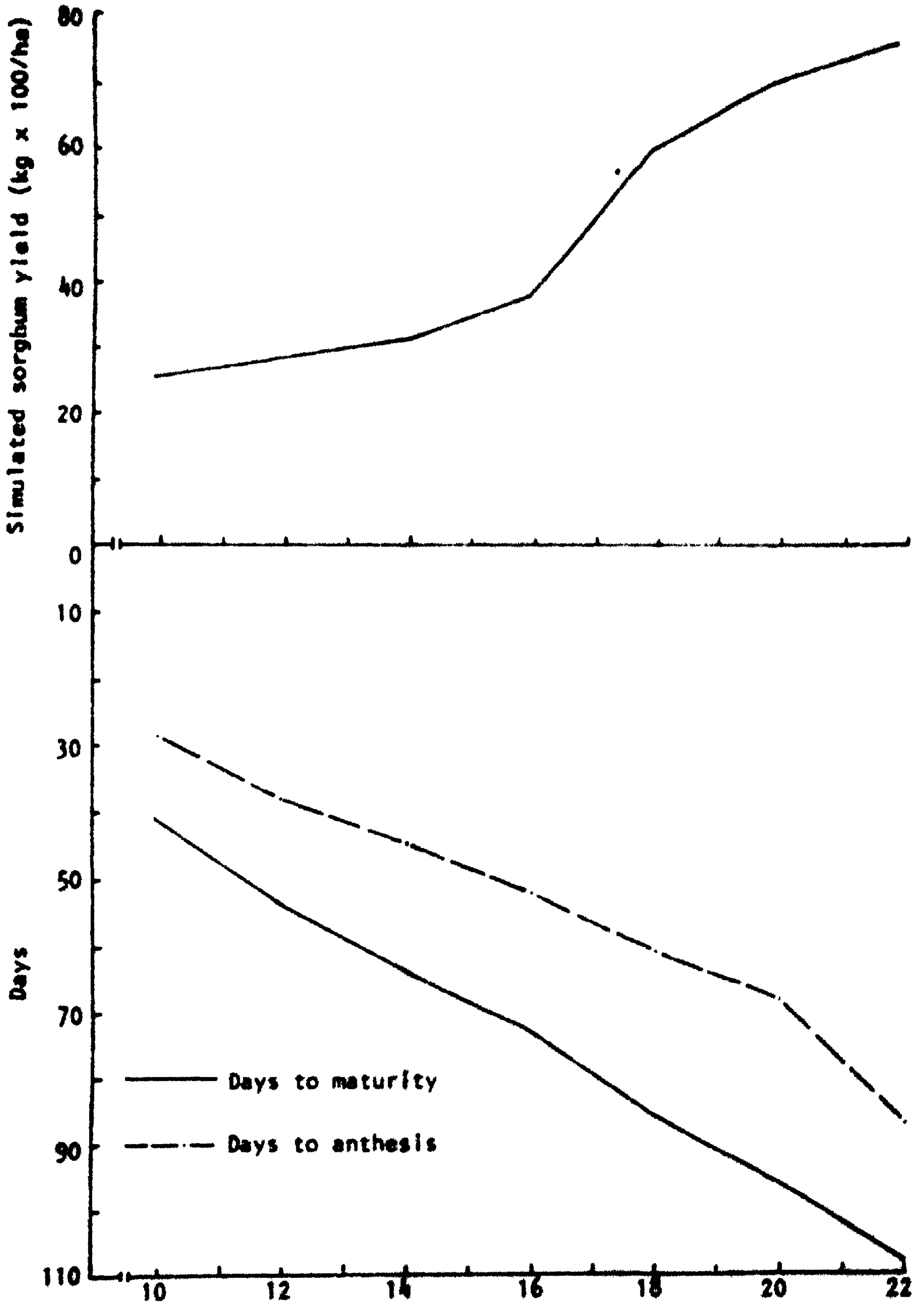

Figure 3. Simulation results of SORGF using 1978 rainyseason ICRISAT data