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Linking Crop Models With a Geographic Information System to Assist Decisionmaking: A Prototype for the Indian Semiarid Tropics

IFDC International Fertilizer Development Center

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CONTENTS

SUMMARY 3

INTRODUCTION 5

THE CERES-SORGHUM MODEL 5

GEOGRAPHIC INFORMATION SYSTEMS 9

COUPLING CERES-SORGHUM AND THE GIS 11

PROSPECTS AND CONCLUSIONS 19

REFERENCES 21

APPENDIX 23

MAPS 1-13 27

SUMMARY

Crop simulation models that are able to predict the effects of weather and various soil properties, water management, and agronomic practices on nutrient dynamics and crop growth processes can contribute much to our understanding of the behavior of fertilizer in cropping systems, leading to improvements in the efficiency of fertilizer management. The optimization of fertilization strategies, given the uncertainties of climate, is generally difficult, and the problem is compounded in many developing regions of the world where key fertilizer-related data are sparse. Where adequate climatic, soil, and crop data exist, simulation models allow some extrapolation into these less developed areas and thus provide some insights into fertilizer behavior in different environments. Even where adequate data exist, simulation models are generally run in a mode that renders the results specific to one site. Input data can be changed to investigate crop responses to different management regimes at other sites, but decisionmakers often need information that relates to a whole region, where there may be a wide mix of soil types and weather conditions. In addition, this information needs to be presented in such a way that nonspecialists can readily pick out the important conclusions. One way in which such information can be produced is through coupling crop simulation models with a Geographic Information System (GIS), a data base and analysis system that contains the spatial data needed to run the models and that maps model outputs of interest to decisionmakers.

This document outlines the need for crop model geographic information systems, the possible uses of such systems, and the methods required in their construction. It also describes, as an example, a study investigating nitrogen fertilizer efficiency in Maharashtra State in the Indian semiarid tropics, using a simulation model of the development, growth, and yield of sorghum coupled with a GIS. The spatial data bases of the GIS contain information on soils, weather, and other inputs needed by the sorghum model, and the system allows regional analyses of model output to be performed and maps to be drawn. There are substantial limitations in the example, and the results should be treated with caution, but the main objective of this document is to demonstrate the power and utility of the approach.

A crop model GIS could be used in a number of ways: (1) to act as a store of information on farming systems that can be updated to produce timely statistics of current land use patterns and production levels and how they are changing over time; (2) as a short-term policy tool, in relation to forecasting for the coming year or the current season, where regional simulations of yield and resource use would give an estimate of requirements for imports of agricultural inputs and exports of commodities, aid requirements in response to a bad season, or likely international loan requirements; and (3) as a long-term policy tool, to investigate the effects on regional production and resource requirements of economic, technological, or climatic change, or of substantial policy or trade changes to the economic environment within which farmers operate.

INTRODUCTION

Given the uncertainties of climate and the diversity of soil characteristics in the tropics, optimization of regional fertilizer use strategies is difficult. In the developed countries, fertilizer and crop management recommendations are based on soil testing and correlation of results with data from a large number of field trials over many seasons. However, few developing nations are able to conduct the extensive series of experiments necessary, or to maintain the laboratories and data bases required, to establish such systems. In these cases, crop simulation models, validated with specific experimental data from the region, can be used to extend the results of field experimentation to sites that have not yet been tested. In addition, models can be used to predict yield trends in a region, the impact of a wide variety of management practices on crop performance (such as the effects of particular fertilizer strategies on yield, nitrogen use efficiency, and nitrogen loss), and the environmental impact of soil erosion, nutrient leaching, and water runoff.

Crop simulation models are generally run in a mode that renders the results specific to a particular environment. This environment (the soil type, the weather, etc.) is described in terms of input data to the model, and simulations are then run that predict the growth, development, and yield of the crop in response to the interactions between management practices and the environment. The input data that describe the environment can be changed to investigate crop responses to different management regimes at other sites, but decisionmakers often need information that relates to a whole region, where there may be a wide mix of soil types and weather conditions. In addition, crop models can produce vast quantities of output, and this output needs to be assembled and presented in such a way that nonspecialists can immediately pick out the important results. One way in which such information can be assembled is through the coupling of crop simulation models with a Geographic Information System (GIS), a data base and analysis system that contains the spatial data needed to run the models and that maps model outputs of interest to the decisionmaker.

This document discusses the construction and application of a prototype information system based on two tools: a crop simulation model of the growth, development, and yield of sorghum (*Sorghum bicolor* L.) and a commercially available GIS. A study that investigates nitrogen fertilizer efficiency in the State of Maharashtra in the Indian semiarid tropics is described as an example. The spatial data bases of the GIS contain information on soils, weather, and other inputs needed by the sorghum model, and the system allows regional analyses of model output to be performed and maps to be drawn. There are substantial limitations in the example used, and the results obtained should be treated with caution, but the main objective of this document is to demonstrate the power and utility of the approach.

The principal objectives of the work were as follows:

- To investigate the feasibility of linking crop growth models with a GIS and developing suitable methodology to allow this to be done.
- To indicate the potential use of such an information system for policymakers, researchers, and extension workers.

Subsequent sections of this report address both these objectives and briefly describe the sorghum simulation model, the GIS, and the methodology used to link the two. Results from the example study are presented, and on-going work at IFDC on modelling and GIS linkages is outlined. Finally, some of the potential uses of such a system are described, together with a brief research and application agenda.

THE CERES-SORGHUM MODEL

IFDC has been involved with the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project since 1984. IBSNAT, an initiative funded by the United States Agency for International Development (USAID) through the University of Hawaii, has been (and continues to be) an umbrella project for the development and application of crop modelling and systems simulation techniques for the tropics and subtropics. A major output of this work has been the development and testing of a set of simulation models for twelve major food crops (six cereals, three grain legumes, and three roots and tubers). These IBSNAT models have been designed to require a minimum of input data, which can be readily obtained from typical agronomic experiments. A state of balance, wherein all processes are described at a similar level of detail, has also been a consideration. Where possible, simple, well-understood procedures have been used for describing the processes simulated. In several circumstances, where gaps in knowledge exist, empirical relationships have been employed. Many of the applications of these models will require multiple-year or multiple-site simulations. Because many simulations are required, it is desirable that the models be computationally efficient to reduce computer time. Other design considerations have been to make the models user-friendly and to ensure that they perform reliably over a wide range of crop growth circumstances. The models have also been designed to run on as wide a variety of computing equipment as possible, with special emphasis on cheap and widely available IBM-compatible personal computers (Uehara, 1989).

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A brief description of some important components of the CERES-Sorghum model can be found in the Appendix. CERES-Sorghum is one of the CERES family of cereal models that IFDC has been involved in developing in collaboration with Michigan State University and IBSNAT (the other CERES models are for wheat, maize, rice, pearl millet, and barley). The model allows the quantitative determination of growth and yield of the sorghum crop (Virmani et al., 1989). The growth of the crop is simulated with a daily time step from sowing to maturity on the basis of physiological processes as determined by the crop's response to soil and aerial environmental conditions. The model has components that deal with phasic development, biomass partitioning between the growing organs, yield, soil water balance, and nitrogen balance. Modules for the simulation of soil and plant phosphorus dynamics are under development.

The model is thus sensitive to a wide range of management factors such as variety, planting date, and fertilizer and irrigation schedules, as well as to environmental factors such as weather and soil type. The data required to run the model go somewhat beyond the type of information that is commonly collected from most agronomic field trials; however, a well-defined experimental protocol exists for gathering the necessary information (IBSNAT, 1988; 1990a; 1990b; some details are provided in the Appendix).

Assessing the Performance of CERES-Sorghum

There are a number of steps to be taken in applying a crop simulation model in a particular situation. These are important steps because the validity of any conclusions that may be drawn from a complex application of a crop model is dependent on the validity of the model.

The first stage of model assessment, called validation, involves testing the model against actual field trials; in other words, the user attempts to reproduce, through simulation, a particular field trial carried out in the region of interest. Model input data are assembled, and the model is run under conditions as nearly identical to those of the actual trial as possible; thus, weather records for the field trial are used, and initial soil conditions are set to those observed in the field, as are the crop management inputs (date of planting, row spacing, fertilizer additions, etc.). Simulated model output is then compared with field trial results. Crop yield is often the principal output of interest, but because of the detailed outputs that the model produces, many other outputs can be compared with field measurements also. If, for example, leaf area indices were measured during the season in the field trial, these can be compared with the simulated values.

The CERES cereal models have been extensively tested in diverse environments. In particular, one objective of the research program in India conducted in collaboration with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) was to focus on the refinement and validation of the CERES-Sorghum model. As noted above, the model incorporates a soil water balance which includes calculations of runoff, evaporation, drainage, and extraction of soil water by the crop. In environments such as the semiarid tropics, where timing and placement of fertilizer applications may be critical, the simulation of root distribution enables the model to have sensitivity to fertilizer management; this also allows an estimation of nitrate leaching in a cropping system.

The CERES-Sorghum model was validated in the Indian semiarid tropics using experimental data from five seasons (1985 to 1989). Principal among these were the nitrogen dynamics experiments conducted in 1988/89 at ICRISAT. The studies involved both shallow and deep Vertisols in seasons that ranged from drier than normal to one that was abnormally wet. Each of the data sets had a range of nitrogen rates and often a range of other treatments, among them irrigation and/or fertilizer timing. The capacity of the model to predict crop yield, plant biomass, and nitrogen uptake was tested by comparing the field data with model predictions. Results of these comparisons are shown in Figures 1 to 3. Simulated and observed grain yields are shown in Figure 1, ranging from 1.2 to nearly 9 tonnes per ha, brought about by the interaction of factors to which the model is sensitive, i.e., weather, soil conditions, and management. Simulated and observed aboveground biomass is compared in Figure 2, and nitrogen uptake in Figure 3. If the model were a perfect predictor, then all data points would lie on the 1:1 diagonal line. There are many reasons why there is deviation from the 1:1 line, including observation errors, model specification errors, model input data errors, and incomplete control of factors in the field that the model does not include (such as pests, weeds, and disease). In general, the model performed reasonably well with these data sets.

A separate validation trial was conducted on a deep Alfisol and a shallow Vertisol with urea and KNO_3 and with sequential harvests throughout the growing season. Again, the model produced reasonable estimates; simulated yields were within 15% of the observed yields (Figure 4). The model correctly simulated the response of sorghum to nitrogen application in the experiments and, for the shallow Vertisol, correctly predicted that urea-nitrogen would give slightly higher yields than the nitrate source. Similarly, although these data are not shown, the model predicted total biomass

at maturity and total nitrogen uptake by the crop reasonably accurately.

Nitrogen Fertilizer Strategy Evaluation

Once the model has been demonstrated to work adequately through the validation process for the sites and regions of interest, it can be used to conduct simulation experiments. Such experiments can be designed to aid tactical as well as strategic decisionmaking, and they provide a further check on the "reasonableness" of model outputs. Further, crop modelling can facilitate adoption and transfer of agrotechnology packages. For example, varieties or management options that perform well in simulations for the location under study can be evaluated by the model, then tested on research stations and farms. To capture the risks and uncertainties associated with weather, simulations can be run

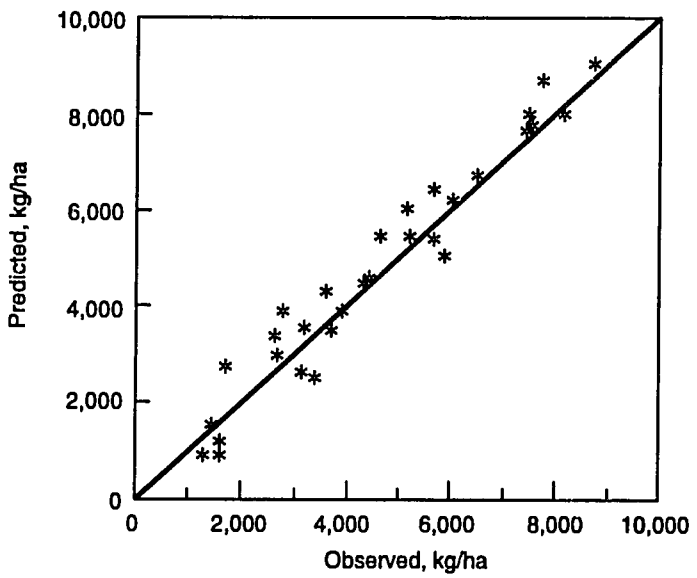

Figure 1. Comparison of Observed and Predicted Sorghum Grain Yield, Pune, Maharashtra State.

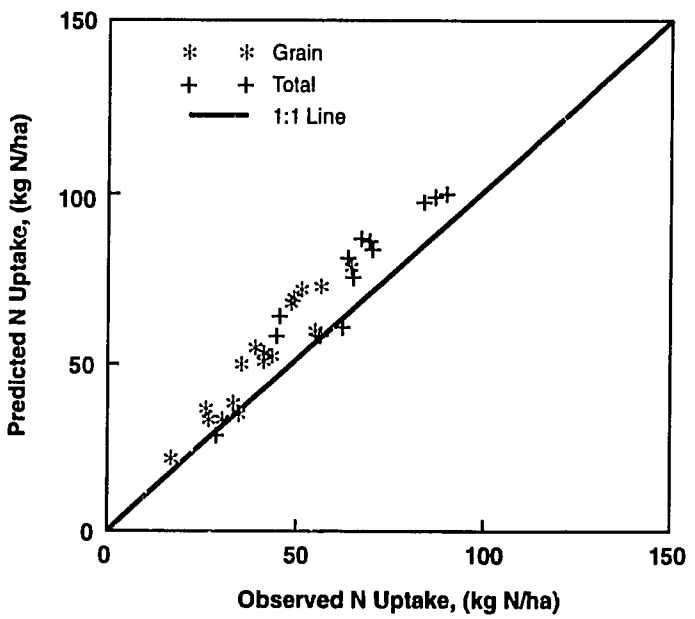

Figure 3. Comparison of Observed and Predicted Nitrogen Uptake by Sorghum, Pune, Maharashtra State.

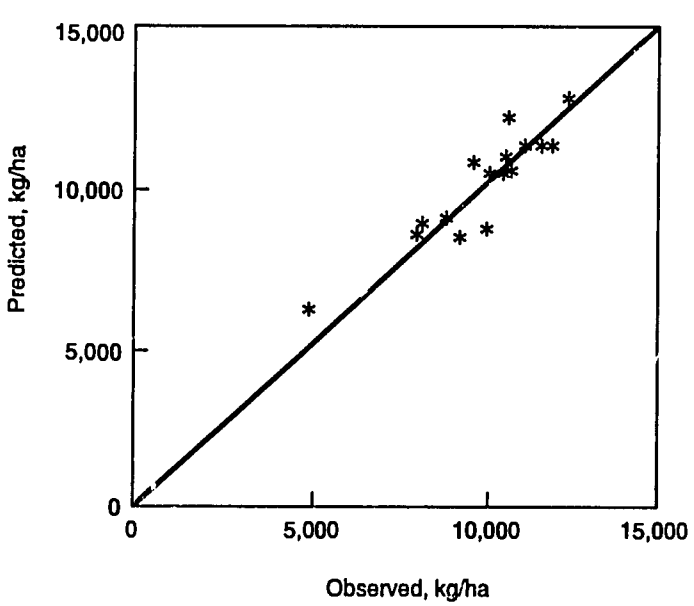

Figure 2. Comparison of Observed and Predicted Aboveground Sorghum Biomass, Pune, Maharashtra State.

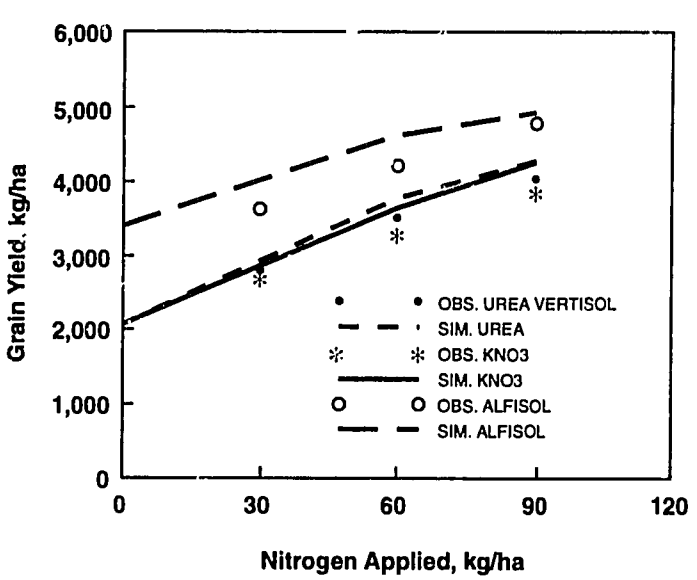

Figure 4. Observed and Predicted Sorghum Grain Yield in Response to Nitrogen Application on Two Soils, Pune, Maharashtra State.

under different weather conditions based on historical or statistically generated weather records.

A validated crop simulation model can be used to evaluate the impact of growing a different crop, using a new variety, changing the planting date, increasing the plant stand, and modifying fertilizer and irrigation management. With recently incorporated modifications, it can also simulate the impact of long-term climatic change on yield, crop duration, and nutrient losses. Modelling is now being used to evaluate long-term agricultural productivity and sustainability (Bowen et al., 1993).

The CERES-Sorghum model was used to evaluate fertilizer strategies as affected by weather variability and soil diversity in the Indian semiarid tropics. Losses of nitrogen, fertilizer recovery, grain yield, and the processes affecting these vary greatly from year to year in any location, given these factors.

Long-term weather records from the region can be used to provide a more extensive picture of the variation of fertilizer response over time. Crop responses to fertilizer application can thus be evaluated with respect to such soil characteristics as fertility, depth, water-holding capacity, and texture. As an example, the CERES-Sorghum model was employed to simulate crop growth and fertilizer response over 25 seasons using daily weather data from Pune, in Maharashtra State. Soils from this site represent the two major soil orders found in the Indian semiarid tropics, Vertisols and Alfisols. The soils are described in Table 1. In this simulation experiment, 18 strategies were evaluated: three soil types, two soil depths, and three nitrogen rates. Nitrogen was applied as urea at three rates: 0, 30, and 60 kg N per ha at planting. A single sorghum variety, CSH-9, was grown for all the strategies, planted in mid-June.

Simulated grain yield response with no nitrogen fertilizer applied, replicated for 25 years of historical weather data, indicates large variations in response from one year to the next and among soil types (Figure 5). On a shallow Alfisol (Udic Rhodustalf), the yields were always below 1.0 tonnes per ha. During very dry years (which occur about one year in five), complete crop failures were predicted on all soils. Vertisols always outyield the Alfisols, with concomitant increases in year-to-year yield variability. Similar trends were observed on the deeper soils. The grain yields on these deeper, less drought-prone soils ranged from 0 to 4 tonnes per ha.

A substantial response to nitrogen application rates of both 30 and 60 kg per ha occurred, as shown by the clear separation of the cumulative probability density functions in Figure 6. This response was observed on the Vertisol as well as the Alfisol. The grain yield response for each nitrogen treatment was higher for the Vertisol; maximum yields at 60

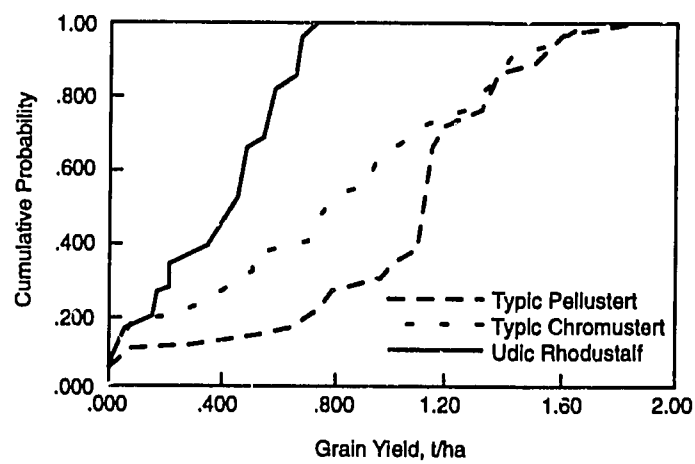

Figure 5. Cumulative Probability Functions of Simulated Sorghum Grain Yield on Shallow Vertisols and an Alfisol in Pune, Maharashtra State.

Table 1. Characteristics of Soils Used in CERES-Sorghum Evaluation Simulations

Soil	Depth (cm)	Extractable Water (cm)	Soil Mineral N (kg N/ha)
Typic Chromustert	240	28.6	64
	120	14.4	33
Typic Pellustert	170	19.8	55
	90	10.5	30
Udic Rhodustalf	180	16.4	50
	90	8.0	25

kg N per ha were 4.5 tonnes per ha on the Vertisol and 3.0 tonnes per ha on the Alfisol. For both the shallow Alfisol and the shallow Vertisol, the year-to-year variability was least with a fertilizer application of 30 kg N per ha.

On deep soils, there were again marked responses to fertilizer. The grain yields were also more stable with fertilization, as shown by comparatively little year-to-year variability in yield for the 25 season replications (Figure 7). The maximum yields for this environment at 60 kg N per ha were 6 tonnes per ha on the Vertisol and 4.5 tonnes per ha on the Alfisol. With no nitrogen fertilization, the yields were similar for both soils.

From the above results, it is apparent that nitrogen fertilizer recovery is lower on the Alfisols; this is also what field experiments have shown. The cumulative probability functions in Figure 8 clearly show that nitrogen losses are much higher on the Alfisol than on the Vertisol at all nitrogen application rates. This is true for the deep soils as well. Another interesting trend was the higher nitrogen losses that occurred from unfertilized soils for many of the 25 season replications. The simulation indicates that there is better utilization of nitrogen released from the soil when nitrogen fertilizer is applied.

GEOGRAPHIC INFORMATION SYSTEMS

A Geographic Information System (GIS) is a computer-based system that combines a capability for geographic and cartographic analysis with a capability for data base management. These systems allow input, storage, manipulation, analysis, and display of data spatially. Data from a wide

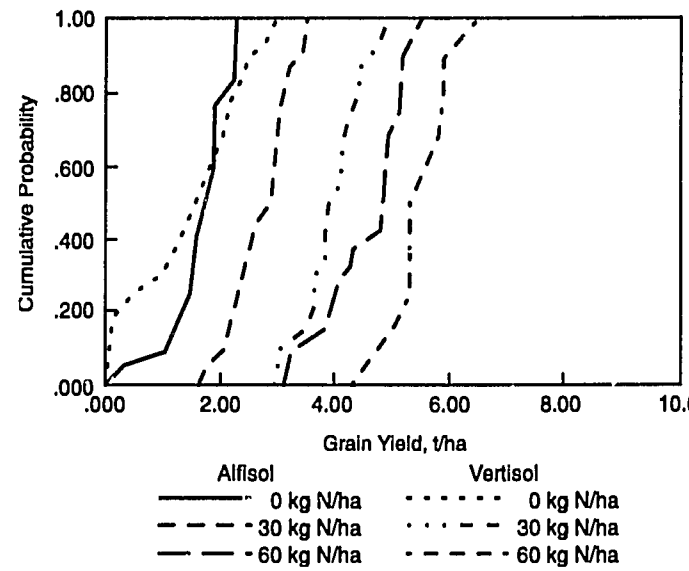

Figure 7. Cumulative Probability Functions of Simulated Sorghum Grain Yield Response to Three Fertilizer Strategies on a Deep Vertisol and Alfisol in Pune, Maharashtra State.

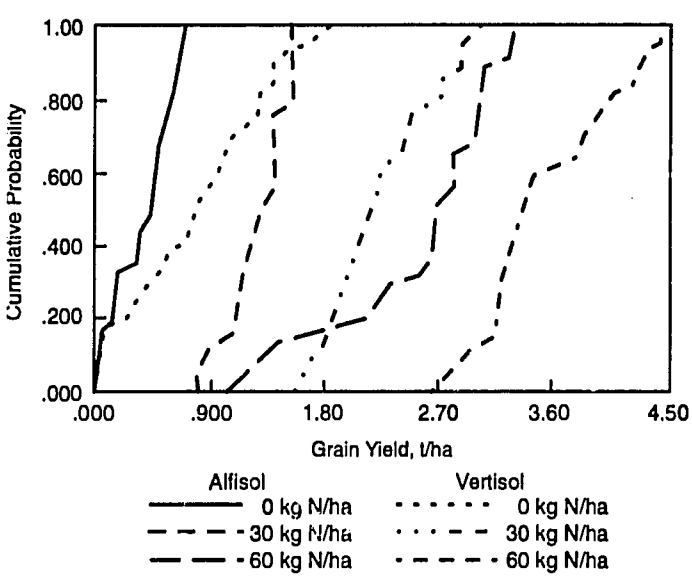

Figure 6. Cumulative Probability Functions of Simulated Sorghum Grain Yield Response to Three Fertilizer Strategies on a Shallow Vertisol and Alfisol in Pune, Maharashtra State.

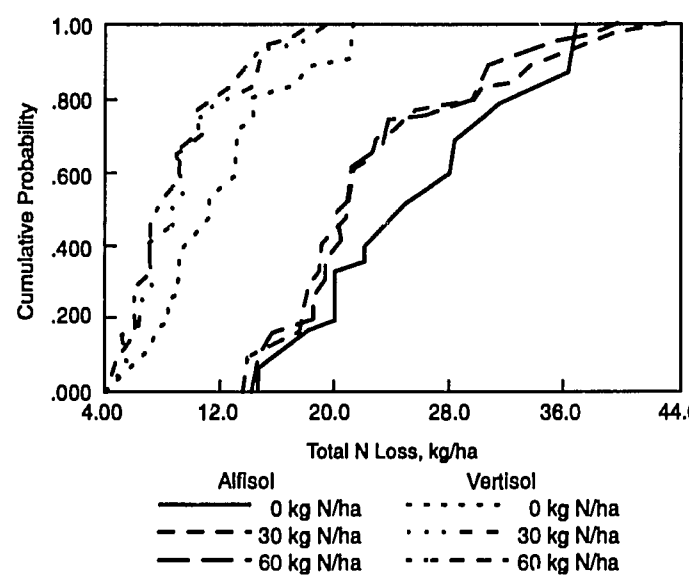

Figure 8. Cumulative Probability Functions of Simulated Nitrogen Loss for Sorghum Under Three Fertilization Regimes on a Shallow Vertisol and Alfisol in Pune, Maharashtra State.

variety of sources may be integrated in the data base of a GIS. Typically, there are a number of "layers" of data relating to land characteristics (such as soil type, vegetation, climate, land use, and topography) and infrastructure (such as roads, towns, and political divisions). There may be many other types of layers, such as demography, socioeconomics, and type of farming system. A general GIS is represented schematically in Figure 9, showing the relationship between the graphics base of the GIS and the component types of spatial data, called "attributes."

In response to the general need for information at different levels of complexity, Harrison and Sharma (1992) identify three levels at which a GIS can be used for resource management. The first level provides a simple inventory of current resources and their characteristics in a region. The second level involves the management of data from a wide variety of sources, housed within a single framework. At this level, the integration of different types of data can allow inferences to be drawn that might not otherwise be apparent; thus, three maps of a region showing soils, the ratio of actual to potential evapotranspiration, and topography might be used to infer production potential for a particular crop. The third level involves spatial analysis and modelling, which allows the answering of complicated "what ... if" questions

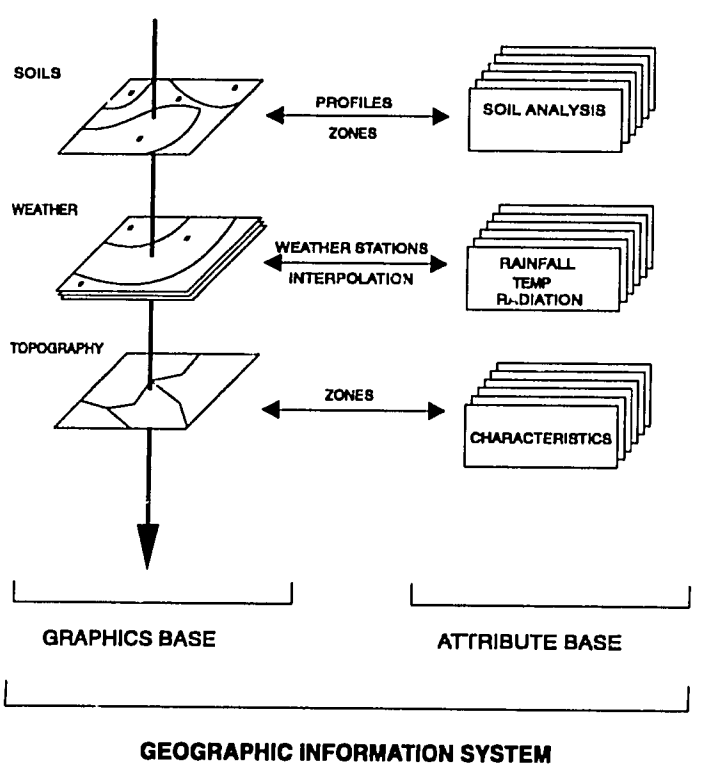

Figure 9. GIS: The Relationship Between Data (Attributes) and Graphics.

(such as, what is the regional yield response if variety X is grown in the area rather than variety Y?). This third level is developed in this study, and it involves interlinking process-oriented simulation models with the spatial analysis capabilities of the GIS.

It should be noted that this interlinking is comparatively straightforward; conceptually, a process-based simulation model such as CERES-Sorghum, written in FORTRAN, operates on the basis of a single location, whereas the GIS deals with space and spatial variability. A certain amount of sophisticated programming is required (to be briefly described in a subsequent section) to interface simulation models and the GIS.

The principal unit of a GIS is a computer representation of an area of the earth's surface called a polygon or mapping unit. A polygon is an area of land or sea that has a particular characteristic, such as a soil of type "X". All the points within the polygon are assumed to have this same characteristic. Thus if a region has two soil types, X and Y, then the value of either X or Y (called attributes) is assigned to each point in the region. A contiguous area of soil type X or Y is thus a polygon.

Different layers of polygons of different attributes can be superimposed to produce new coverages of the region of interest. Thus if, in addition to soils of type X or Y, a region has a layer of information relating to topography classified as "level" or "steeply sloping," then the polygons for soil type can be combined, or overlaid, with the polygons for topography to produce a new set of polygons that will usually be subdivided. This new coverage contains new polygons, each of which is described in terms of two attributes: soil type and topography. In this example, both the soils map and the topographical map have polygons of only two types (X or Y, steep or flat). When these are overlaid, there are now four types of polygons: soil type X, with topography level or sloping; and soil type Y, with topography level or sloping. Data can be built up in a similar fashion from many different layers to produce overlays of great complexity.

Overlays, as well as the basic layers that make up an overlay, can be manipulated, analyzed, and mapped. Two layers might be manipulated, for example, by simply multiplying the polygon sizes in a layer for cropping area by a scalar in a layer for average crop yield, to produce a third layer of crop production per polygon. This third layer might be analyzed by calculating the regional production per hectare, for example, and then mapped to allow policymakers to identify areas of low production within the region.

GIS thus provides two major benefits:

- A framework whereby large quantities of information for a region from a wide variety of sources (including the outputs of complex biophysical or socioeconomic models) can be entered into a computer data system and manipulated, integrated, analyzed, and mapped.
- Outputs that would enable nontechnical users to see the results of what may be highly technical and complex analyses in map form, to help them understand the interrelationships between many different factors.

COUPLING CERES-SORGHUM AND THE GIS

The essential point of linking a GIS to a crop model is this: the GIS contains spatial data that can be used as input to the model, enabling the model to be run for various combinations of input data in the data base. In this way, the limitation that a model must be run for discrete points in space can be overcome. Furthermore, the results of all the model runs (and there may be many) can be imported back into the GIS and analyzed and mapped, and the resultant spatial information can be presented with a great deal of impact. This process is illustrated in Figure 10, which shows the interlinking of the graphics base and the data base of the GIS. In essence, the GIS stores model input data; the model is run for all combinations of factors that show spatial variation (such as soil type), and the model outputs are then imported into the spatial data base of the GIS for analysis, manipulation, and display.

There are many ways of coupling a GIS with crop simulation models. In the present prototype study, three GIS layers were combined: soils information for the region, climatic data, and topographic data of the same area. A new coverage of the study area was produced, integrating all three types of information, and the sorghum model was then run for each polygon (each polygon being characterized by a particular combination of soil, climatic, and topographic information) with a variety of different management scenarios. The object was to produce maps of model outputs that clearly identified the following:

- Areas of potentially poor fertilizer efficiency and low yield response, and areas where yield response to fertilizer is high.
- Areas where other crops might be better than sorghum in terms of risk, grain yield, and economic return to the farmer.
- Areas where the risk of nitrogen loss through denitrification or leaching is high.
- Areas where fertilizer use will be highly profitable or unprofitable, according to a simple economic analysis at the enterprise level.

Data From the Study Region

The study region selected was the State of Maharashtra, India. Soils information for Maharashtra at a scale of 1:5,000,000 was obtained from the FAO soils map of the world (UNESCO, 1977). The soils map was entered into the computer using a digitizer, a peripheral device used to convert a drawing or map into a digital format. A coverage, or map layer, was created in PC-ARC/INFO, a GIS software package developed by the Environmental System Research Institute (ESRI, 1992). The map coverage was then transformed from digitizer inches to an Albers Equal-Area Conic map projection (a mathematical conversion used to create a flat map from a spherical surface). The transformation was required so that the area of the polygons could be accurately calculated in square meters. The soils map is shown as Map 1. For information on the soil classification key, the reader is referred to UNESCO (1977). These soils are mainly Alfisols and Vertisols. Some general profile information for the five soil types used in subsequent analysis is shown in Table 2.

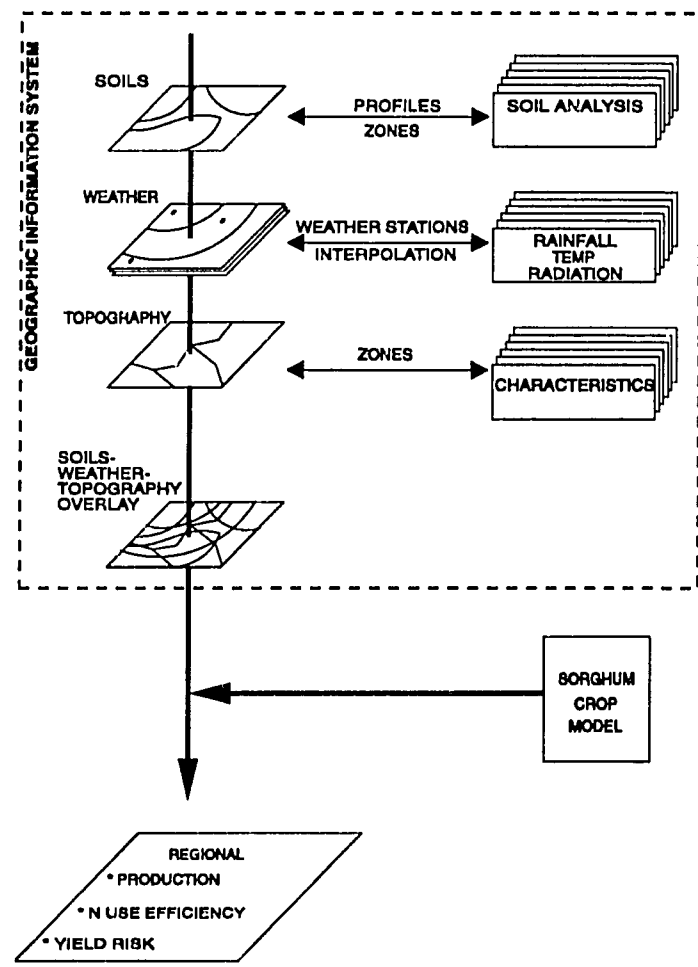

Figure 10. The Relationship Between a GIS and a Crop Model.

Table 2. Soil Descriptions for Five Soil Types in Maharashtra

1 **Pellic Vertisol** Vp Deep black soil

Physiography—Nearly level plain in gently undulating plateau
Drainage—Somewhat poorly drained
Parent material—Basalt
Vegetation—Few dry deciduous trees; mainly under sorghum and cotton.
Soil depth—132 cm (Shallow 90 cm; Deep 170 cm)

2 **Chromic Vertisol** Vc Very deep black soil

Physiography—Level plain in undulating plateau
Drainage—Somewhat poorly drained
Parent material—Basalt
Vegetation—Thorny leguminous and some dry deciduous trees; mainly under sorghum, cotton and wheat
Soil depth—183 cm (Shallow 121 cm, Deep 240 cm)

3 **Chromic Luvisol** Lc Deep red loam

Physiography—Gently undulating
Drainage—Well drained
Parent material—Gneiss
Vegetation—Short grass, a few thorny shrubs and some trees
Soil depth—183 cm (Shallow 100 cm, Deep 240 cm)

4 **Eutric Cambisol** Be Noncalcareous brown floodplain soil

Physiography—Gently undulating
Drainage—Moderately well drained
Parent material—Mixed alluvium
Vegetation—Rice in summer and other crops in winter
Soil depth—137 cm (Shallow 89 cm, Deep 180 cm)

5 **Eutric Fluvisol** Je Noncalcareous alluvium

Physiography—Gently undulating
Drainage—Seasonally poorly drained
Parent material—Noncalcareous, mixed alluvium
Vegetation—Under rice
Soil depth—73 cm (Shallow 50 cm, Deep 90 cm)

An elevation map for the State of Maharashtra (Prakashan, 1982) was digitized and transformed to create another map coverage (Map 2). Elevation information was subsequently used in defining appropriate cropping polygons and in carrying out spatial weather interpolation (see below).

For this prototype study, historical weather records from five sites in the state were used. The location of these weather stations is shown in Map 3. Mean monthly rainfall and standard deviation for the five historical sites are shown in Figure 11.

In order to obtain more extensive weather coverage of the state, coefficients were calculated for a statistical weather generator for the five sites having historical daily data. These coefficients describe a statistical model in which the simulated daily records are, statistically, nearly indistinguishable from the historical records. The weather generator WGEN (Richardson, 1985) was used, as implemented in IBSNAT's Decision Support System for Agrotechnology Transfer (DSSAT) software (IBSNAT, 1989). Using data from these original five sites and the statistical package Surfer (Golden Software, 1989), we created coefficients for an additional eleven sites for the weather generator using kriging, a spatial interpolation technique. Kriging, a general technique that produces optimal least-squares estimates of a function's value, is often used to interpolate over a grid when data do not exist for some of the grid points, as well as to smooth noisy data (Delfiner and Delhomme, 1975). The long-term mean monthly rainfall and standard deviation for two interpolated sites are shown in Figure 12 in relation to historical data from nearby sites.

Simulation runs for the crop models can be carried out with historical or simulated weather data. In order to save space on the hard disk of the computer, it was decided to use simulated data for all weather stations to run all simulations.

The sixteen (five historical and eleven interpolated) weather station points were positioned on the relief map according to their geographic location, producing a coverage with twenty-two polygons (Maps 2 and 3). This coverage was then overlaid with the soil coverage (Map 1). The crop model input data were then loaded into each of these coverages. (Note that each coverage may have between one and five soil types associated with it, depending on the occurrence of the various soil types within that coverage.) Data were not loaded into six of the coverages because there was a change in the elevation within the area and no weather data were available for that area. These coverages can be identified in Map 3 as the polygons with the "omitted sites" legend. After the data were loaded into the coverages (using a program written in Simple Macro Language, PC-ARC/INFO's programming language), the twenty-two coverages were then combined to make one coverage.

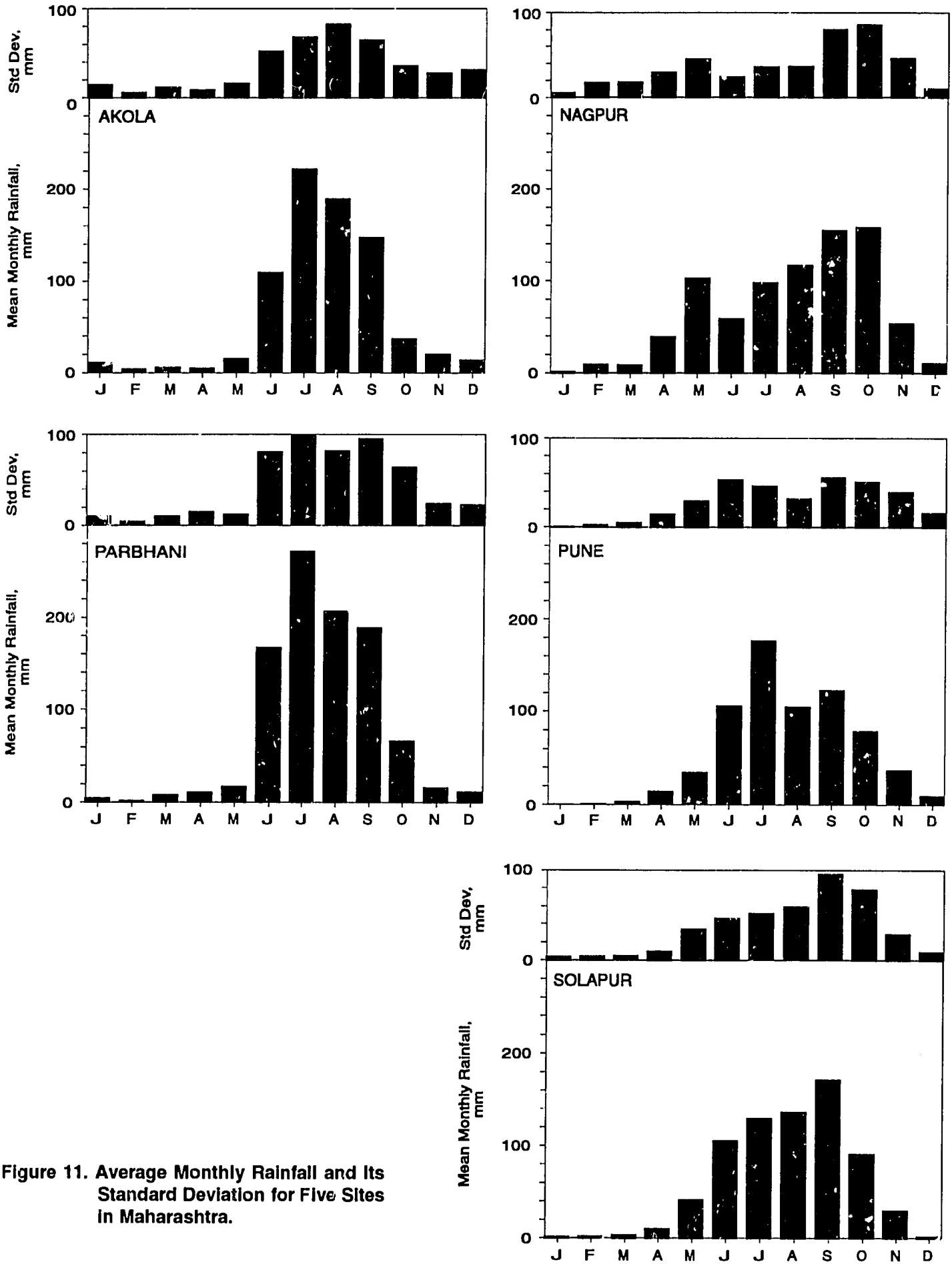

Figure 11. Average Monthly Rainfall and Its Standard Deviation for Five Sites in Maharashtra.

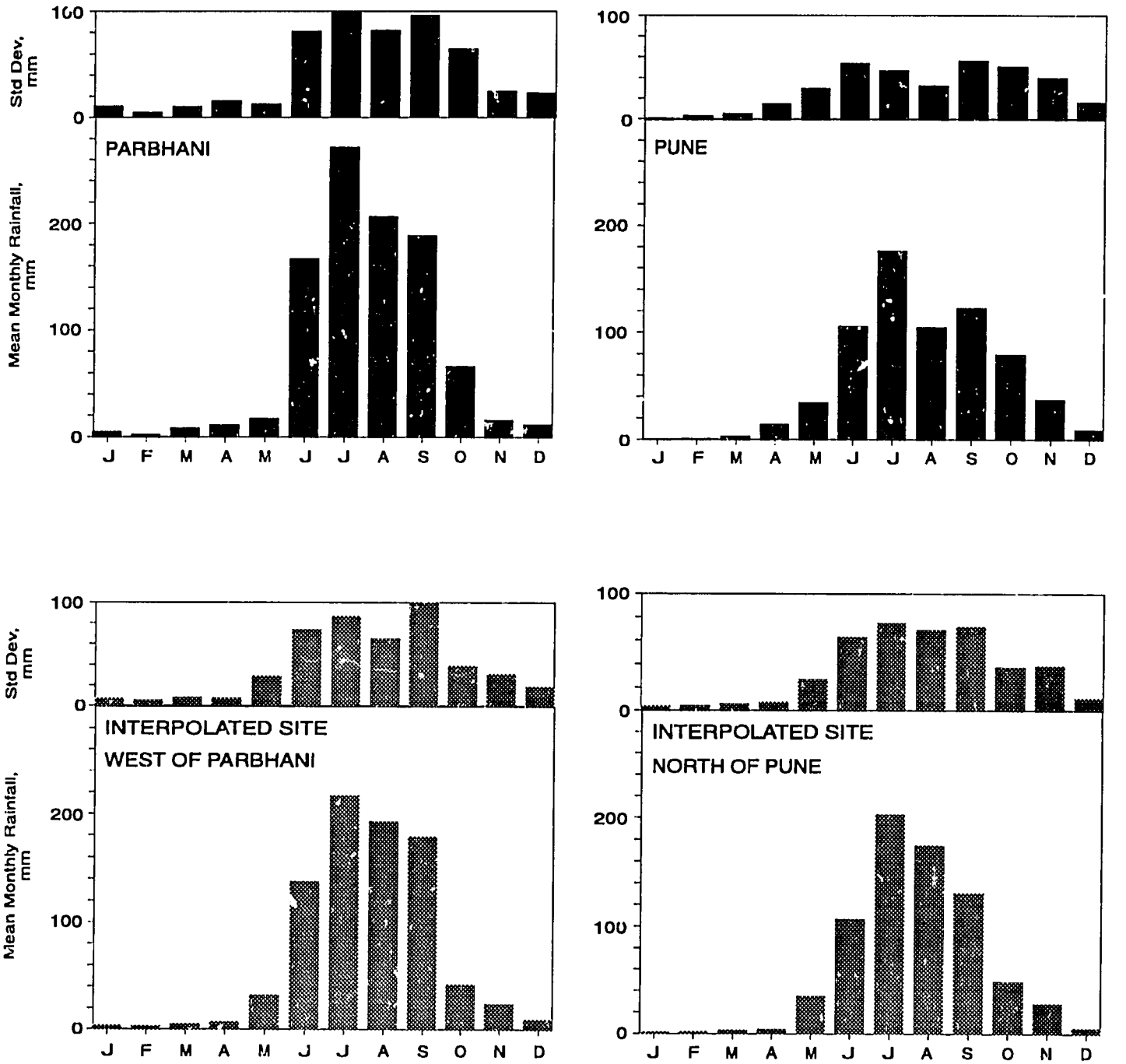

Figure 12. Average Monthly Rainfall and Its Standard Deviation for Two Interpolated Weather Sites and Nearby Historical Sites in Maharashtra.

Running the Simulations

The next step was to take the weather, soils, crop management, and geographic coordinate data and run the model simulations for sorghum growth and yield. A factorial simulation experiment was designed to investigate a number of planting dates and fertilizer application strategies. The experimental variables are listed in Table 3. For each site, there were four planting dates, ranging from mid-May to mid-October, and four rates of nitrogen fertilizer application. Soil depth was another experimental factor; the original profile depths (see Table 2) were modified to represent shallow and deep soils of the same types. All treatments were "replicated" over 25 weather season types. Batch processing files were set up to run CERES-Sorghum; the version used was CERES-Generic version 2.0. Each batch processing file was set up to run 6,000 simulations (4 planting dates by 4 nitrogen application levels by 3 soil depths by 25 replications (years) by 5 soil types). With a 386/25 MHz PC, this process takes 8 to 10 hours; with a 486/50 MHz PC, it takes between 2 and 3 hours.

The summary output files created by the CERES-Sorghum model, illustrated in Table 4, occupy about 1.5 megabytes for each site, or 25 megabytes for the 16 locations. In the first version of the crop model GIS, a text editor was used to modify the batch processing file to run the simulations for the next location (in particular, to modify the location name). In addition, the daily weather data files had to be loaded manually for the new location.

A FORTRAN program was written to read the summary output file for each site and to calculate a variety of statistics for the output variables of interest. These were then written to attribute files to allow analysis and mapping of the crop model outputs. An example of the resultant attribute file is shown in Table 5.

Table 3. Experimental Variables for the CERES-Sorghum GIS Study

Planting Date	Nitrogen Fertilizer Applied (kg/ha)	Soil Depth[a]
15 May	0	shallow
15 June	30	medium
15 July	60	deep
15 October	90	

4 x 4 x 3 = 48 treatments, replicated over 25 seasons, per soil type

a. See Table 2; medium depth is the depth as measured.

Results

Some general trends observed during this simulation experiment can be distilled with regard to a consideration of sorghum yields from one particular polygon located in the Nagpur area (Map 3); the soil type in this polygon is a chromic Vertisol, the most common soil type in the state (Vc 43-3ab, see Map 1). Mean yields are plotted against their standard deviation in Figure 13 for each combination of planting date and fertilizer application rate, by soil depth. The general trends that can be observed are as follows:

- Mean yields tended to increase as the rate of nitrogen fertilizer application increased, for all planting dates and soil depths; the mean-standard deviation curves slope upwards, towards the left or right. Decreasing marginal yield benefits to increasing fertilizer applications were observable on the medium and deep soils, but not on the shallow soil. Yield standard deviations tended to decrease as more fertilizer was applied (the curves slope to the left), except for the October planting on all soil depths and for the May and July plantings in the shallow soil.
- To some extent, mean grain yields tended to decrease as planting date was delayed. Yield standard deviations tended to decrease as planting dates were delayed from May to July on the deep soil, but not for the other soil depths.
- Mean grain yields tended to increase only slightly as the soil became deeper, and yield standard deviations tended to increase concomitantly.

These trends are generally what would be expected: the greatest yield benefits occur when the growing season coincides with adequate rainfall on soils of greatest depth with adequate nitrogen fertilization. It is interesting to observe that fertilizer application tends to decrease yield risk in situations where the soils are deep and water supply to the crop is adequate; where water supply is not adequate in all years (such as the October planting traces in Figure 13), then fertilizer application can be expected to increase the risks of economic returns to fertilizer use. Even a 20% risk that economic returns to an investment in fertilizer will not be realized in any year constitutes a compelling reason for a small-holder farmer in a highly variable environment not to use fertilizer (see Keating et al., 1991, for example).

Table 4. Example Simulation Summary Output File From CERES-Sorghum

Columns 1 - 101

	A-M	E-M	NLOSS	NIT STRS 3	NIT STRS 5	NUPTK	NIRR	TOT IRR	WAT STRS 1	WAT STRS 5	CET	RAIN	BIOMASS	YIELD	YIELD	PLANTS	NFT	NRATE
SG:	70	102	0.	36	.64	52.3	0	0.	.00	.00	394.	418.	8.72	1.86	1.86	18.00	0	0.
SG:	73	105	5.	.38	.66	48.9	0	0.	.00	.00	359.	497.	8.19	1.80	1.80	18.00	0	0.
SG:	72	106	6.	.29	.65	51.9	0	0.	.00	.00	342.	539.	8.57	1.99	1.99	18.00	0	0.
SG:	74	106	12.	.29	.68	48.2	0	0.	.00	.00	366.	629.	8.57	1.74	1.74	18.00	0	0.
SG:	70	102	2.	.36	.64	53.4	0	0.	.00	.00	391.	460.	8.85	1.81	1.81	18.00	0	0.
SG:	73	102	4.	.33	.65	49.5	0	0.	.00	.00	373.	465.	8.52	1.80	1.80	18.00	0	0.
SG:	70	102	9.	.36	.63	46.2	0	0.	.00	.00	407.	561.	7.86	1.59	1.59	18.00	0	0.
SG:	68	103	0.	.33	.66	48.4	0	0.	.00	.00	371.	378.	8.25	1.65	1.65	18.00	0	0.
SG:	73	105	5.	.35	.65	49.6	0	0.	.00	.00	357.	508.	8.37	1.71	1.71	18.00	0	0.
SG:	72	104	13.	.35	.68	45.0	0	0.	.00	.00	348.	727.	7.65	1.56	1.56	18.00	0	0.
SG:	72	104	2.	.35	.64	50.8	0	0.	.00	.00	370.	455.	8.43	1.86	1.86	18.00	0	0.
SG:	72	105	11.	.36	.67	47.1	0	0.	.00	.00	383.	615.	8.06	1.73	1.73	18.00	0	0.
SG:	71	101	7.	.33	.63	49.2	0	0.	.00	.00	375.	530.	8.24	1.83	1.83	18.00	0	0.
SG:	71	105	13.	.35	.70	44.3	0	0.	.00	.00	400.	702.	7.81	1.50	1.50	18.00	0	0.
SG:	73	106	14.	.42	.70	44.8	0	0.	.00	.00	367.	805.	7.50	1.73	1.73	18.00	0	0.

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:
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Columns 102 - 208

TITLE	RUN	IN	SI	YEAR	EX	TR	IRR	VARIETY	FILE1	SOIL	ROW SPACE
AKOLA NOF VP 60INT M	1	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	2	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	3	WG	WG	198	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	4	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	5	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	6	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	7	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	8	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	9	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	10	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	11	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	12	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	13	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	14	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450
AKOLA NOF VP 60INT M	15	WG	WG	1981	01	1	1	CSH-6	WGEN0112.W10	SIRPURO,IND	.450

:
:
:

Key

A-M	Days, anthesis to maturity	PLANTS	Planting density /m^2
E-M	Days, emergence to maturity	NFT	Number of N fertilizer applications
NLOSS	Nitrogen loss kg/ha	NRATE	N applied, kg/ha
NIT STRS 3	N stress factor, growth stage 3	TITLE	Title of simulation run
NIT STRS 5	N stress factor, growth stage 5	RUN	Run number
NUPTK	Total N uptake, kg/ha	IN	Institute code
NIRR	Number of irrigation applications	SI	Site code
TOT IRR	Total irrigation water applied	YEAR	Year of simulation
WAT STRS 1	Water stress factor, growth stage 1	EX	Experiment number
WAT STRS 5	Water stress factor, growth stage 5	TR	Treatment number
CET	Cumulative evapotranspiration, mm	IRR	Irrigation switch (1=rainfed)
RAIN	Cumulative rainfall, mm	VARIETY	Variety grown
BIOMASS	Total plant biomass, t/ha	FILE1	Name of initial weather file
YIELD	Yield at maturity, t/ha	SOIL	Soil description
YIELD	Harvested yield, t/ha	ROW SPACE	Row spacing, m

Table 5. Example Polygon Attribute File

$RECNO	2	Record number
AREA	761581800.0	Area of polygon, m^2
PERIMETER	131563.1	Perimeter of polygon, m
STAT2_	2	ID number 1
STAT2_ID	1	ID number 2
SOIL_TYPE	Be 66-2c	Soil type
SOIL_CODE	6	Soil code
SOIL_CONNE	4	Soil connector code
YPROB10	3.68	#10% yield, t/ha
YPROB90	5.41	#90% yield, t/ha
YIELD	4.41	Mean yield, t/ha
YIELD_STD	0.59	Yield standard deviation
BIOMASS	13.01	Mean biomass, t/ha
BIOMASS_ST	0.84	Biomass standard deviation
N_UPTAKE	93.43	Mean total N uptake, kg/ha
N_UP_STD	5.55	N uptake standard deviation
APP_RECOVE	0.86	Mean apparent N recovery rate
APP_STD	0.03	N recovery standard deviation
EFFICIENCY	48.59	*Mean N use efficiency
EFF_STD	6.57	N use efficiency standard deviation
N_LOSS	8.52	Mean N loss, kg/ha
N_LOSS_STD	5.83	N loss standard deviation
NET_RETURN	5068.12	Mean net return, rupees/ha
NET_STD	742.96	Net return standard deviation
$RECNO	3	
AREA	4612545000.00	
PERIMETER	736733.0000	
STAT2_	3	
STAT2_ID	2	
SOIL_TYPE	Hh 11-2bc	
SOIL_CODE	11	

The 10th and 90th percentiles of the simulated yield probability distribution.

* Defined as the ratio $(Y_x-Y_o)/x$, where Y_x is yield with x kg N applied and Y_o is yield in the absence of N fertilizer.

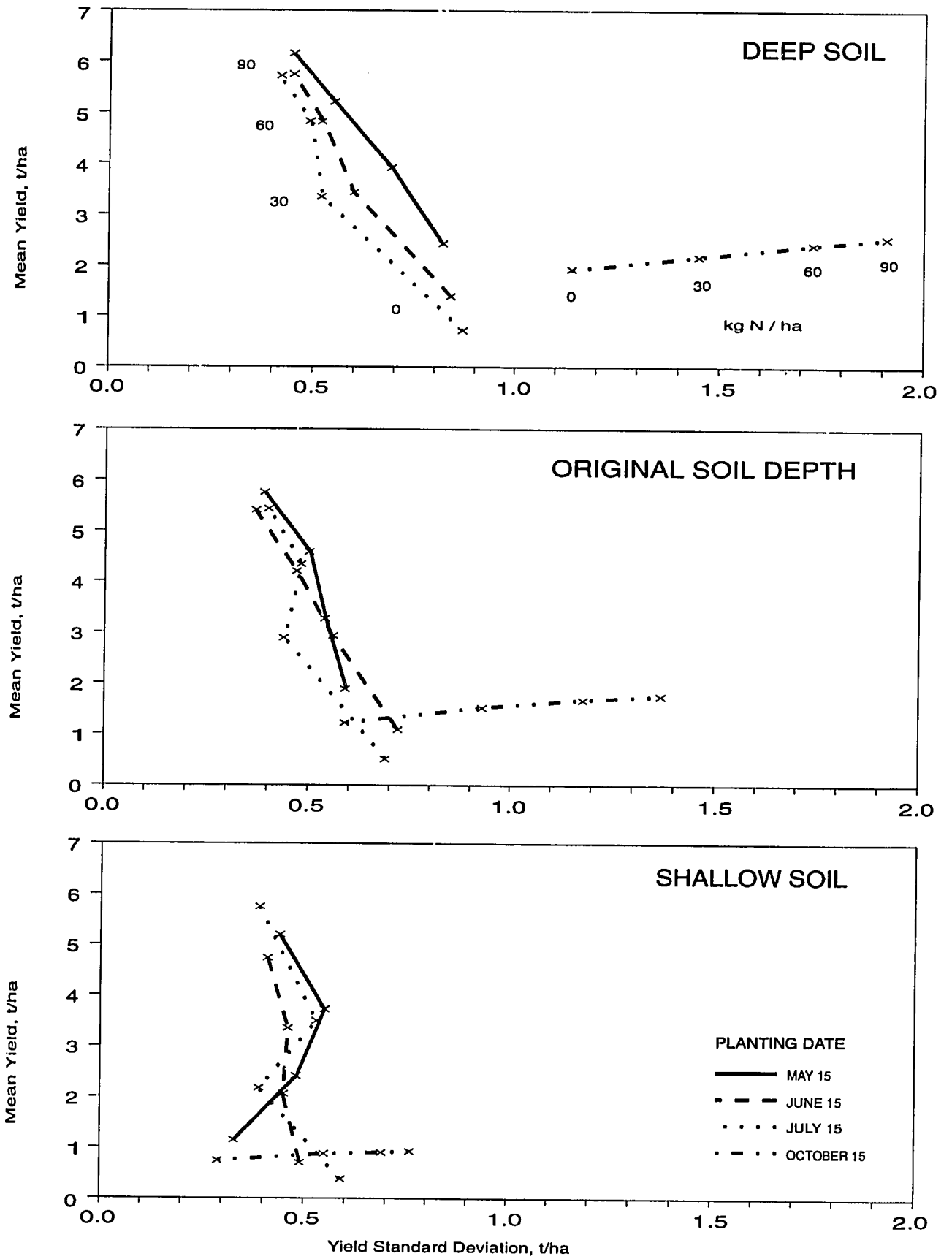

Figure 13. Summary Sorghum Yield Responses (Means and Standard Deviations) to Soil Depth, Planting Date, and Nitrogen Fertilizer Additions, Simulated Using CERES-Sorghum on a Chromic Vertisol, for a Polygon Near Nagpur, Maharashtra.

To illustrate the ways in which simulation outputs can be assembled in map form for ease of assimilation, nine maps are presented (Maps 4-12). A comparison of mean yield response to fertilizer applications on soils of the original depth (Table 2) for the four planting dates can be seen in Maps 4 (May planting), 5 (June planting), 6 (July planting) and 7 (October planting). These figures help to indicate the areas where maximum benefit can be achieved from the use of fertilizer, and they allow an estimation of the mean yield potential of the region under differing management strategies. The reason that yields tend to be greater for the earlier planting dates (mid-May and mid-June) compared with the later planting dates is obvious from the rainfall distribution histograms in Figure 11: a crop planted in July and October is more likely to run into water stress. In addition, sorghum planted in July is more prone to shoot fly damage, although this effect is not taken into account by the model.

Map 8 illustrates the spatial yield variability associated with fertilizer use for the May planting with 60 kg N applied per hectare on soils of original depth. The mean, standard deviation and the 10th and 90th percentiles of the yield distributions are shown. Such information helps to identify regions where yield risk is particularly high (and where, it might be inferred, N fertilizer will not be economic for sorghum production in most years).

Map 9 shows a spatial assessment of mean economic net return, nitrogen uptake, nitrogen loss, and nitrogen use efficiency (defined as the marginal increase of grain yield in kilograms for every kilogram of N fertilizer applied) for 25 years across Maharashtra, for the May planting and 60 kg N fertilizer. Regions in the state that could benefit most from fertilizer use in terms of N efficiency (the additional amount of grain produced per kilogram of fertilizer applied) can be quickly identified. Thus, if only limited supplies of fertilizer are available, such information would indicate where scarce resources should be allocated during, for example, a year of average rainfall (there are a number of ways of identifying whether any particular year is likely to exhibit average rainfall amounts). When maps showing nitrogen loss are superimposed on maps showing nitrogen use efficiency, regions with the highest use efficiency with least loss can easily be identified.

Similarly, when the price for grain and the cost of fertilizer are known, estimates of the relative profits associated with fertilizer use can be determined, allowing general inferences to be made about likely fertilizer use in a region. Long-term simulations incorporate the variability of rainfall and thus facilitate an assessment of the economic risk associated with fertilizer use. If it appears that fertilizer use will increase yields and profits significantly in only 5 years out of 10, a farmer may be reluctant to use it. As noted above, farmers with a very limited resource base may simply not be in a position to bear the expense of fertilizer inputs unless positive economic returns to fertilizer use accrue in almost all years. Such analyses can have important policy implications for government, industry, and farmers alike.

A final set of maps (Maps 10, 11, and 12) shows spatial nitrogen use efficiency by the sorghum crop at the various application rates for the June planting on soils of different depths.

Limitations of the Example Analysis

Maps 4-12 indicate the substantial improvements in yield that can be expected from even moderate applications of nitrogen fertilizer in most years. However, they should be interpreted with caution. By no means do the soils and climate data used to construct the maps give a comprehensive coverage of Maharashtra State. Comparatively few soil units (five) and weather stations (16) were used in the analysis; the polygons used were large, and the variation between them, for a given level of nitrogen fertilization, was not great. An analysis with more complete coverage could be expected to result in much more yield variation within a particular subregion. Simulations with maize rather than sorghum indicated that, even at the level of detail used, there was much more variability between polygons at given levels of nitrogen application; this is presumably related to the fact that sorghum is well adapted to the semiarid environment of Maharashtra, whereas maize production is marginal in the state as a whole.

Another reason for caution in inferring too much from such maps is that nothing is said concerning pest and disease effects, production systems, and socioeconomic constraints at the farm level. Analyses based on single cropping enterprises and biophysical production constraints have an important role, but they do not present a complete picture. This highlights the need for further development of such tools, a topic addressed in the following section.

Despite these caveats for what, after all, was intended to be a prototype study, the maps clearly illustrate the capability of integrating crop simulation models and GIS to provide information for a wide variety of uses.

PROSPECTS AND CONCLUSIONS

The simulation results of the prototype study indicate that fertilizer response varies greatly from year to year and among

soil types. Running the model over many years with different weather patterns allows the quantification of this temporal variability in yield and response to fertilizer. When nitrogen losses from the system occur, the frequency and nature of those losses, which also lead to poor fertilizer efficiency, can be identified and their relative significance evaluated. Simulated results indicate that nitrogen losses by leaching may even be reduced by fertilization; nitrogen application could lead to increased root density, thereby improving the utilization of soil nitrogen by the crop.

The development of this computer system is being taken a number of stages further. The linkages between the GIS and the crop models are now fully automated, and coverages from other regions of Latin America, Europe, and Africa are being incorporated into the system. This Locational Crop Modeling System (LCMS) has been built around the shell of IBSNAT's DSSAT software (IBSNAT, 1989). On running the system, the user selects a continent or country from those listed (Map 13). The computer displays the continent or country that is selected, those having sufficient data to run the models being shaded in green. Once the user has selected a shaded area, the program displays a menu that lists the planting dates and the fertilizer rates. After these are selected, the program loads the previously simulated summary output files and builds a file that is then loaded into the GIS data base. The program then displays a menu with a list of output variables that the user may choose for displaying in map form. Once the output variable has been selected, the appropriate map is drawn. Work is currently underway to allow crop simulations to be run interactively. This will allow the user to choose from a wide range of management strategies and initial conditions, perform the appropriate simulations, and analyze and map the desired outputs.

In addition to an interactive modelling GIS system, work is in progress to allow socioeconomic and farming system data to be incorporated into the data base. This work is still in its infancy, but GIS provides a highly suitable framework for integrating biophysical and socioeconomic data to produce information of a descriptive and prescriptive nature concerning the evaluation of technology and the impact this may have. Much work remains to be done, but the potential exists for this tool to be used for forecasting and, with suitable socioeconomic models, for adoption studies and impact assessment at the regional level.

More sophisticated crop modelling GIS software is being developed at a number of other institutions under the IBSNAT umbrella, notably at the Universities of Florida, Puerto Rico, and Georgia. Collaborative efforts with these institutions over the next few years can be expected to make significant headway in finding solutions to some of the methodological problems, so that truly integrative and flexible information systems can be produced.

The contributions that such an information system could make are substantial. The system could be used in a number of ways:

- To act as a store of information on farming systems, which can be updated, mainly by survey, to produce timely statistics indicating current land use patterns and production levels and how these are changing over time.
- As a short-term policy tool, in relation to forecasting for the coming year or the current season; here, regional simulations of yield and resource use would give an estimate of requirements for imports of agricultural inputs and exports of commodities, any aid requirements in response to a bad season, and likely international loan requirements, for example.
- As a longer term policy tool, to investigate the effects of change on regional production and resource requirements, be it economic, technological, or climatic change, or substantial policy or trade changes to the economic environment within which farmers operate.

The crop models can be used within such a GIS framework to investigate a whole range of effects; the limits of the experimental domain are imposed by the capability of the model to simulate accurately the response of the crop to biological and management inputs and by the quality of the data in the data bases. The integration of the crop models, spatial physical data bases, and representative farm socioeconomic models poses considerable problems, but one potential payback is the ability to model adoption patterns of particular agrotechnology packages over time and to identify feasible pathways for step-wise farming system development where substantial changes are proposed. One of the major problems to be resolved is how to make use of the enormous quantity of socioeconomic and biophysical information that already exists. Data are usually collected for a particular purpose, which often imposes constraints on the use of the data for other analyses. Much work is needed to ensure that data base structures are flexible enough to hold and make use of information collected at different scales, in different ways, and for different purposes, if the best use is to be made of the existing knowledge base.

Another problem that should be mentioned relates to the vast quantities of information that can be produced in a comparatively short time. It is clear that, in such a complex chain of analysis, the ultimate quality of the information produced is

dependent on the quality of all the links, be they process-oriented models or soils data, for instance. Making sense of the large quantities of information produced by the model can be very difficult, but the process of extracting the important pieces of information is critical to potential use. GIS provides a vehicle for the display of complex data in a form that is simple to understand, and it greatly facilitates the task of extracting essential results.

Despite the problems, many of which still have to be resolved, the implications of regional modelling are profound: not only can biophysical and socioeconomic feasibility be assessed, but also likely impacts on the resource inputs and outputs of the region can be judged, in response to a new agrotechnology package or a changing physical or economic farming environment. An information system comprising crop modelling and a GIS offers considerable potential in providing easily assimilable information to decisionmakers throughout the agricultural sector.

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APPENDIX: A BRIEF DESCRIPTION OF CERES-SORGHUM

Phasic Development

To simulate crop growth successfully, it is fundamental that phasic development be accurately described. Phasic development in CERES-Sorghum quantifies the physiological age of the plant and describes the duration of nine growth stages (Appendix Table 1). With the exception of fallow duration (stage 7), which is user-specified, the model simulates the duration of all growth stages. Crop development cannot be expressed in terms of chronological age because crop cultivar, ambient temperature, day length, and water and nutrient stresses can speed up or reduce the rate of phenological development (Warrington and Kanemasu, 1983; Angus et al., 1981). Cultivar-specific characteristics required as inputs to the sorghum model are as follows: thermal requirements (°C) for the juvenile and the post-anthesis (flowering) phase, photoperiod sensitivity, critical day length, and a leaf width coefficient (Singh et al., 1989).

Appendix Table 1. Growth Stages of Crops as Defined in the CERES Cereal Models

Stage[a]	Duration	Output	Growth
7	Fallow	Water, N, P	
8	Sowing to Germination	Germination day, water, N, P	
9	Germination to Emergence	Emergence day, water, N, P	Root
1	Emergence to End of Juvenile or Terminal Spikelet Initiation	All[b]	Root, leaf
2	End of Juvenile to Floral Initiation, or Terminal Spikelet to End Leaf Growth	All	Root, leaf, stem
3	Floral Induction to End of Leaf Growth/Anthesis (flowering) or End of Leaf Growth to End of Pre-Anthesis Ear Growth	All	Root, leaf, stem, panicle
4	Anthesis to End of Panicle Growth/Beginning of Grain Filling or End of Pre-Anthesis Ear Growth to Grain Filling	All	Root, stem, panicle
5	Grain Filling	All grain	Root, stem
6	End of Grain Fill to Physiological Maturity	Water, N (tiller growth), P	Tiller, grain

a. Stages 9 and 1 are vegetative phase; 2-4, reproductive; and 5-6, grain filling or ripening phase.
b. Simulates growth. development, water balance, nitrogen balance, and phosphorus balance.

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Growth

The crop growth submodel has four main functions: leaf area development, dry matter production, assimilate partitioning, and tiller growth and development. Leaf area development in the model is a function of leaf tip appearance rate (which is temperature-driven) and leaf expansion growth. Leaf expansion growth in the model is highly sensitive to unfavorable temperatures, soil water deficit, and nitrogen and phosphorus deficiency. Under these conditions, leaf expansion is reduced before photosynthesis, resulting in biased partitioning of assimilates in favor of the roots or storage organs.

Potential growth is dependent on photosynthetically active radiation and its interception as influenced by leaf area index (LAI) or area of leaves per unit land area, row spacing, plant population, and photosynthetic conversion efficiency of the crop. Actual biomass production is further constrained by suboptimal temperatures, soil water deficit, nitrogen deficiency, and phosphorus stress. The crop's development phase dictates assimilate partitioning on a per-plant basis for the growth of roots, leaves, stems, panicles (ears), and grains (Appendix Table 1). Potential tiller growth and development are controlled by leaf appearance rate while actual growth is limited by assimilate availability, unfavorable temperatures, and water, nitrogen, and phosphorus stresses.

Soil Water Balance

The soil water balance, the nitrogen balance, and the phosphorus balance submodels are optional. These may be bypassed if one or more are assumed to be nonlimiting for a given simulation. All three submodels operate on a soil layer basis.

The soil water balance component simulates surface runoff, evaporation, drainage, automatic irrigation, and water extraction by the plant. Water input in any layer may occur as a result of infiltration of rain, irrigation water, or flow from adjacent layers. Water content can decrease in a given layer because of surface evaporation, root absorption, or flow to an adjoining layer. Nitrate and urea movement in the nitrogen balance submodel is simulated as a function of water flux through the soil layers.

Plant water extraction is calculated as a function of root length density, available water to the maximum rooting depth, and potential transpiration. The distribution of root growth among soil layers is simulated as a process that is very sensitive to the prevailing water and nutrient conditions in each layer. In environments where timing and placement of fertilizer applications may be critical, the simulation of root distribution in this manner enables the model to have sensitivity to fertilizer management.

Nitrogen Dynamics

The nitrogen submodel is coupled to the water balance and plant growth routines. The submodel simulates the processes of turnover of organic matter with the associated mineralization and/or immobilization of N, nitrification, denitrification, hydrolysis of urea, and ammonia volatilization (Godwin et al., 1990). Many of the nitrogen transformation processes involve first-order rate kinetics. Fluxes of nitrate and urea associated with water movement are also simulated. Nitrogen uptake is simulated as a process that is sensitive to soil nitrogen concentrations, root length density, soil water availability, and plant nitrogen demand. (In addition to these processes, the nitrogen submodel of the CERES-Rice model simulates floodwater and paddy soil transformations affecting the supply of nitrogen to the plant.) The model simulates the effects of nitrogen deficiency on photosynthesis, leaf area development, tillering, senescence, and remobilization of nitrogen during grain filling. The nitrogen submodel can simulate transformations of different nitrogen sources, including chemical fertilizers, green manure, and other organic nitrogen sources.

Soil and Plant Phosphorus Dynamics

A phosphorus submodel for the CERES models is currently under development at IFDC. It will be closely coupled to the water balance, nitrogen balance, and plant growth routines. The submodel simulates the processes of adsorption and desorption of phosphorus, organic phosphorus turnover, and the dissolution of rock and fertilizer phosphate. The rates of each of the soil phosphorus processes are assumed to be affected by the size of the labile phosphorus pool and the prevailing soil, water, and temperature conditions. Organic phosphorus turnover is also controlled by the C:N:P ratio of the organic matter.

Model Inputs

The following data are required for running the simulation model:

- Weather data: Daily values are required of maximum and minimum temperature (°C), rainfall (mm day^{-1}), and solar radiation (MJ m^{-2} day^{-1}).
- Soil characterization data: The soil component uses a layered model. Layers can be natural horizons in the profile. The model uses a surface layer of 5 cm thickness and a variable number (up to 15) of lower layers. The number and thickness of layers are user-specified inputs. All layers should be less than 30 cm thick. For each layer in the soil profile, the following are required: layer depth, pH, organic carbon, volumetric moisture content at various

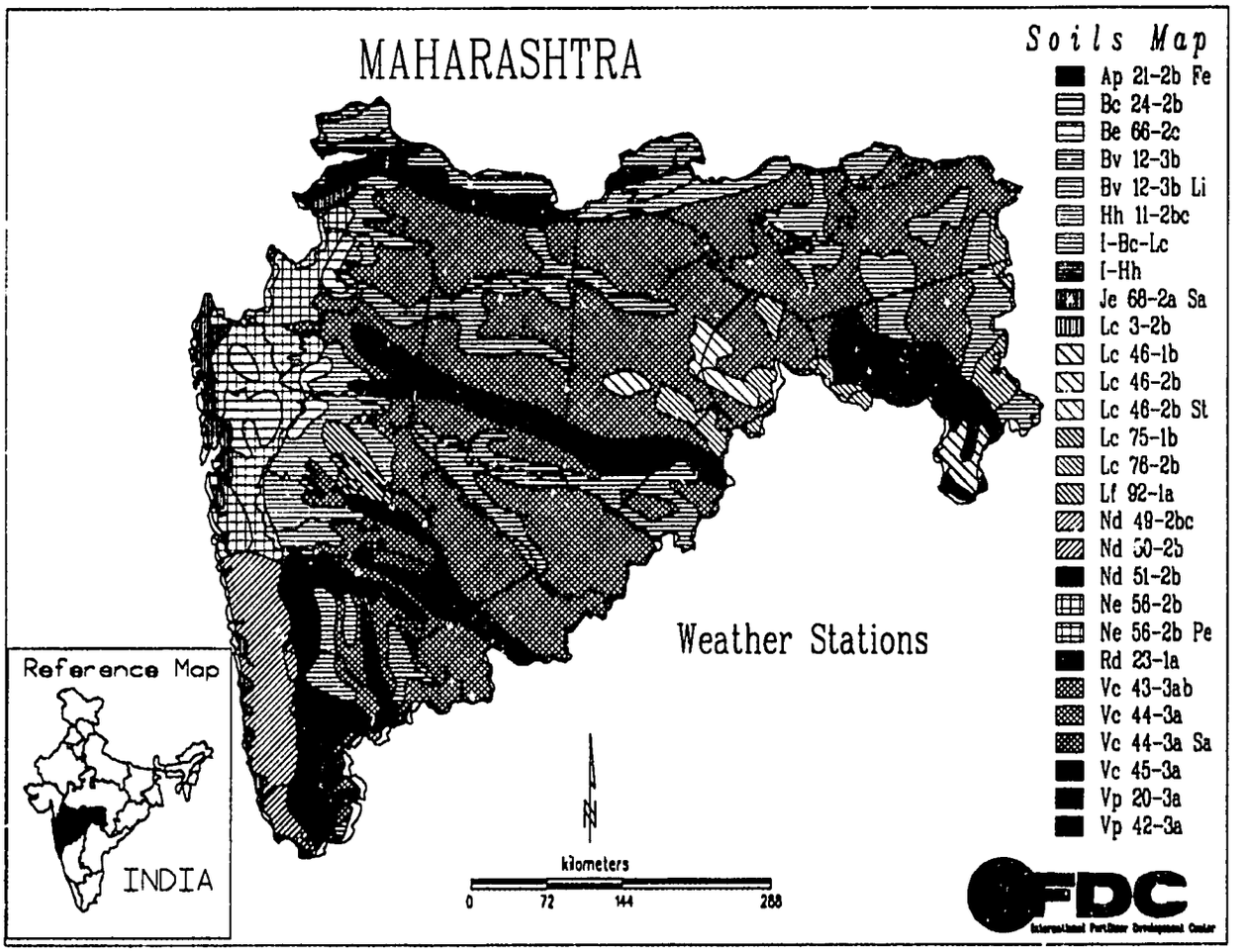
moisture levels (the lower limit, the drained upper limit, and field saturation; these levels can normally be estimated when the percentages of sand, silt, and clay are known); bulk density; and cation exchange capacity. If the phosphorus submodel is run, then other inputs are required, such as pH in KCl, extractable Fe and Al, $CaCO_3$ content, organic P, and P isotherm values.

- Crop residue and/or green manure information: Estimates are required of the following: the date of incorporation of residue, the amount of residue (kg per ha), the C:N:P ratio of residue or percent N and P of residue, and a description of the type of residue and method and depth of incorporation.
- Soil fertility and soil water variables: For each layer in the soil profile, extractable ammonium-N and extractable nitrate-N are required, together with volumetric soil water content, at some point before the commencement of the experiment.
- Crop management variables: Crop variety, emerged plant population, row spacing, and seeding depth are required.
- Fertilizer data: Dates, amounts, sources, method of incorporation or placement of all fertilizer applications, and depth of placement, where appropriate, are needed.
- Irrigation management: Method of irrigation, amounts, and schedule are required.

Model Outputs and Data for Model Validation

The model produces outputs that provide information concerning water balance, soil and plant nitrogen balance, and crop growth and development. The following are typical field observations that can be used to test the model:

- Crop phenological observations: Dates of emergence, floral initiation, 50% anthesis, and physiological maturity.
- Crop growth and nutrient uptake observations: Samples for biomass and nitrogen concentrations at floral initiation, flowering, and maturity; yield components (panicles or ears per square meter, grains per square meter, grain weight). Additional observations of biomass accumulation at other times are also valuable.
- Soil fertility and fertilizer fate observations: Where appropriate, soil analyses for extractable nitrate-, ammonium-, and urea-nitrogen. Direct measurements of denitrification, leaching, and ammonia losses can also be used to test various components of the nitrogen model.



Map 1. FAO Soils Map for the State of Maharashtra, India. For legend, see UNESCO (1977).

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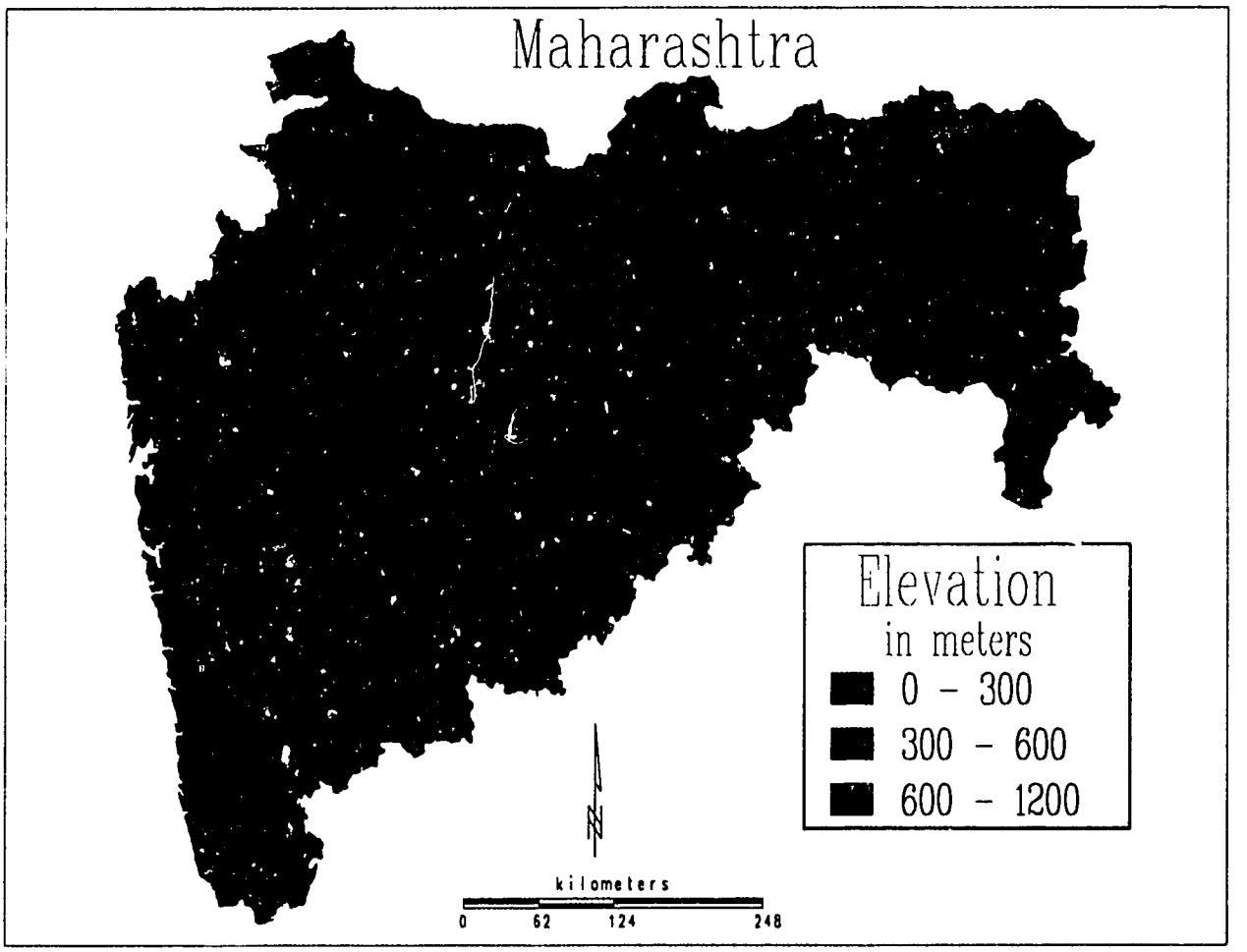
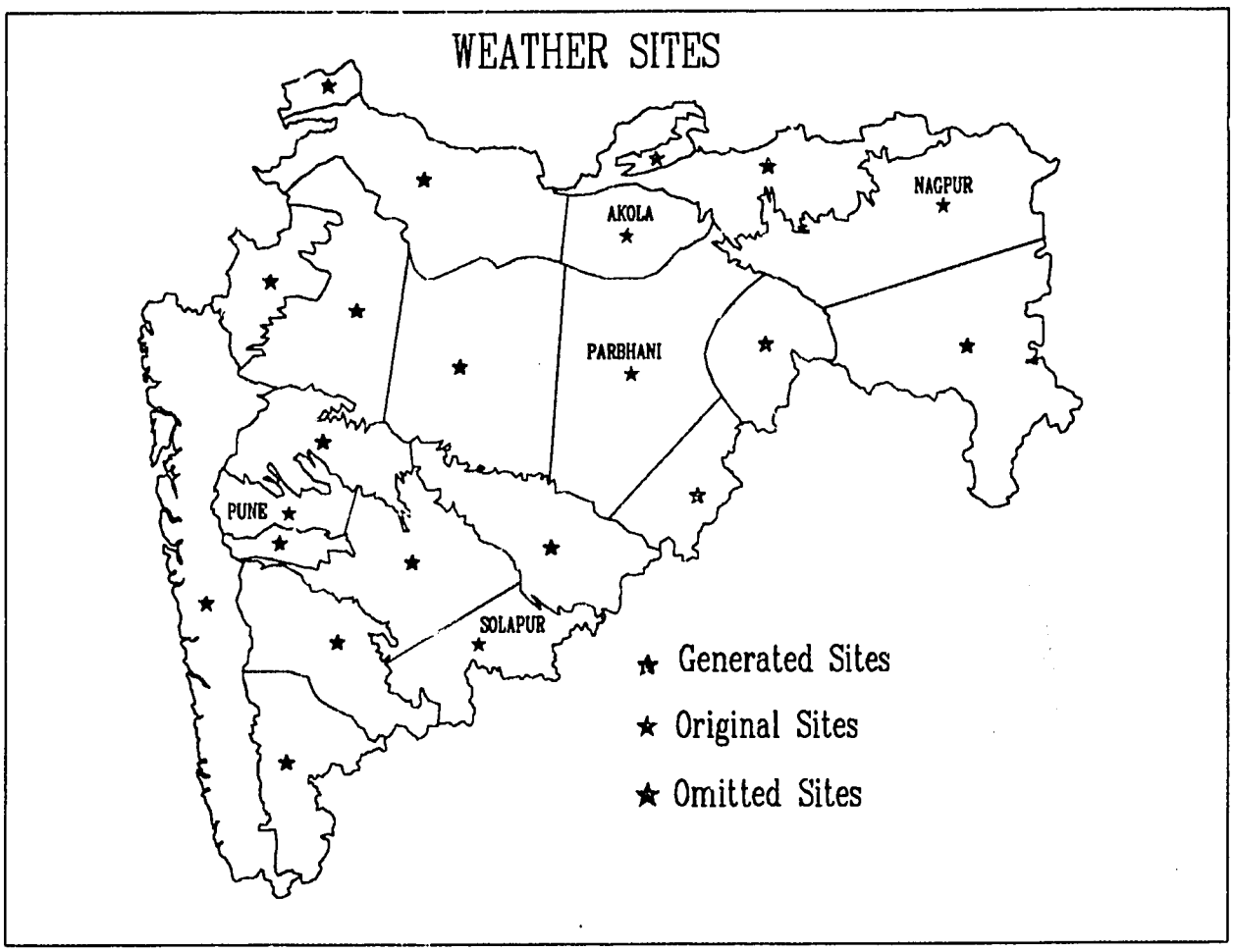
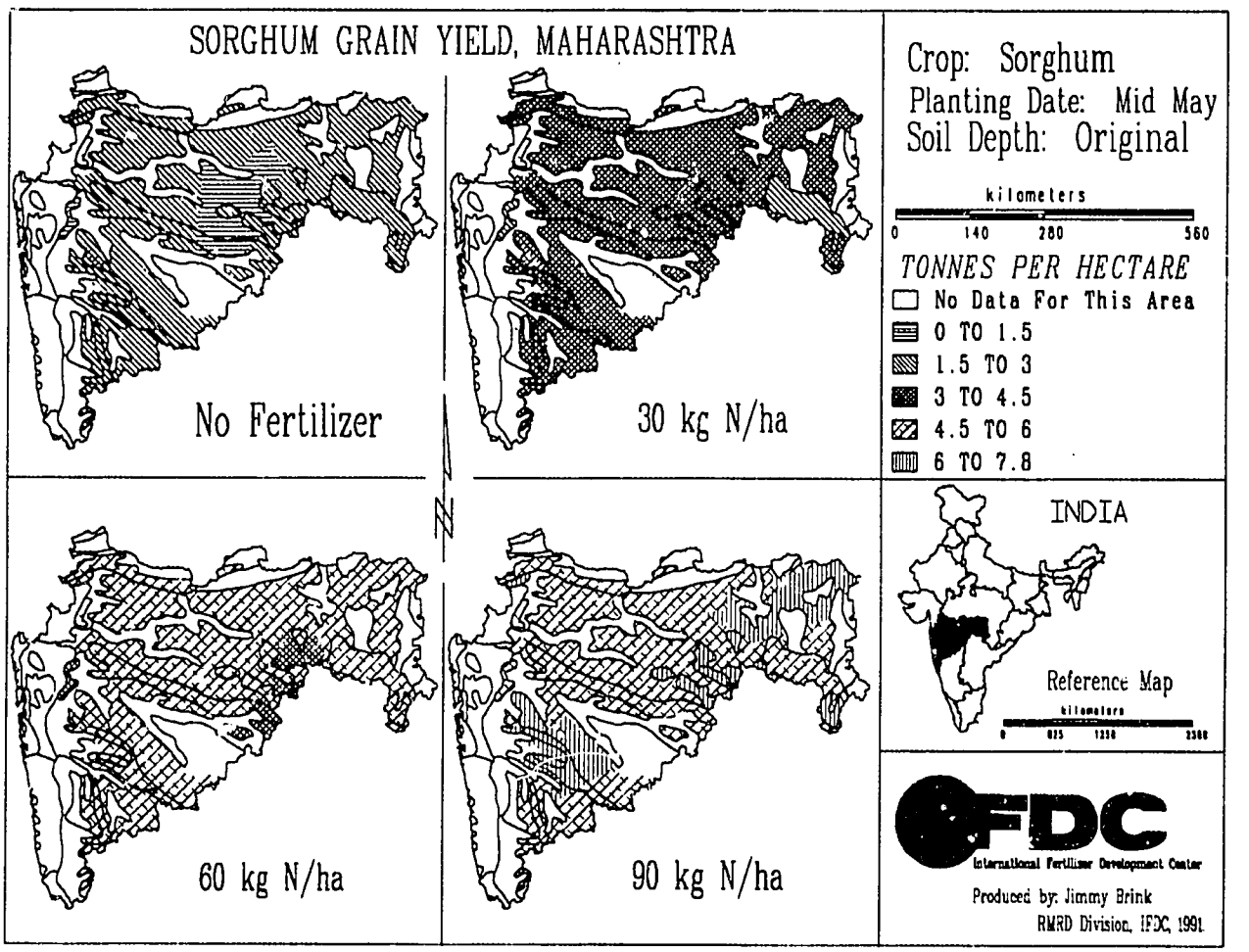


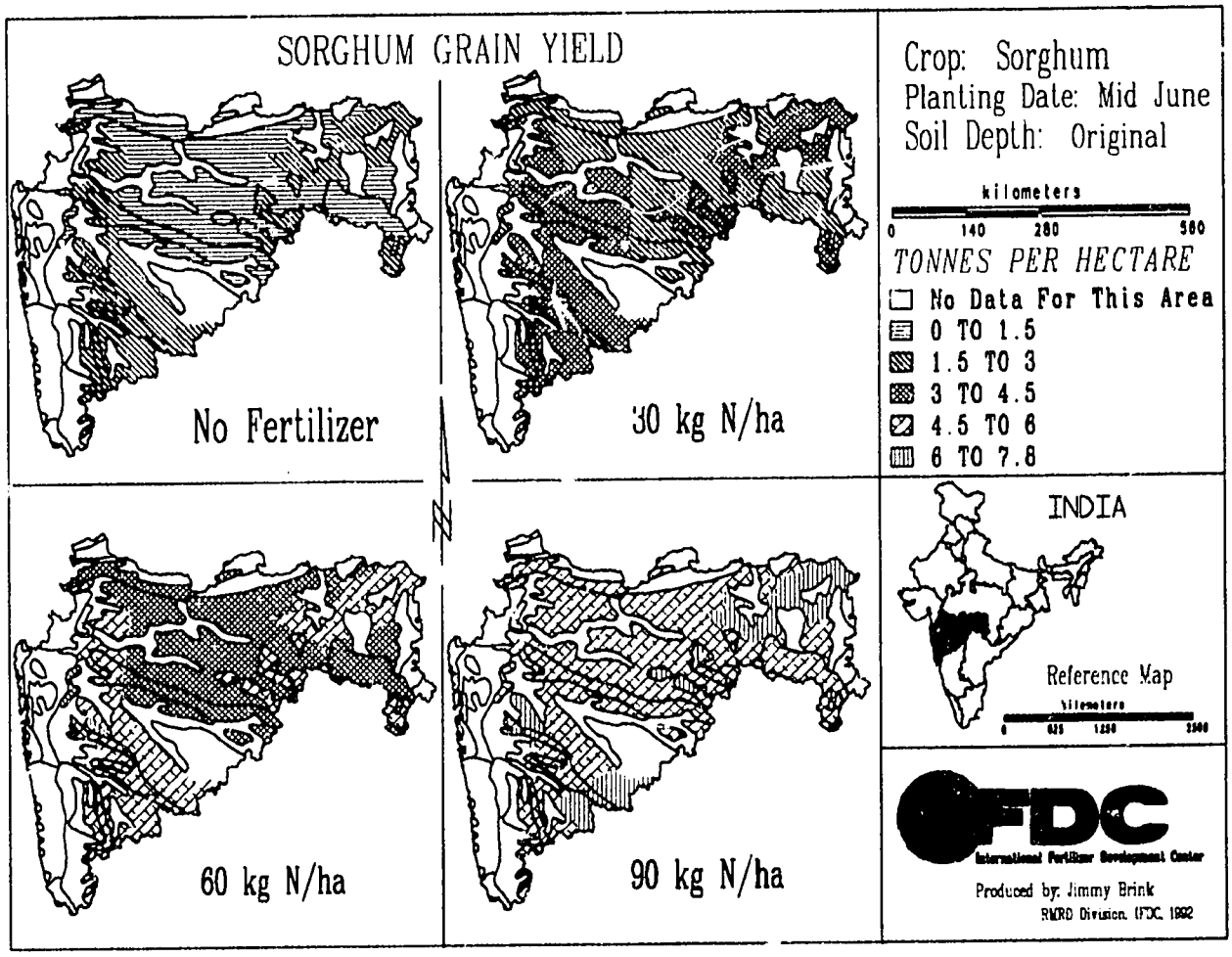
Map 2. Elevation Map for the State of Maharashtra, India.



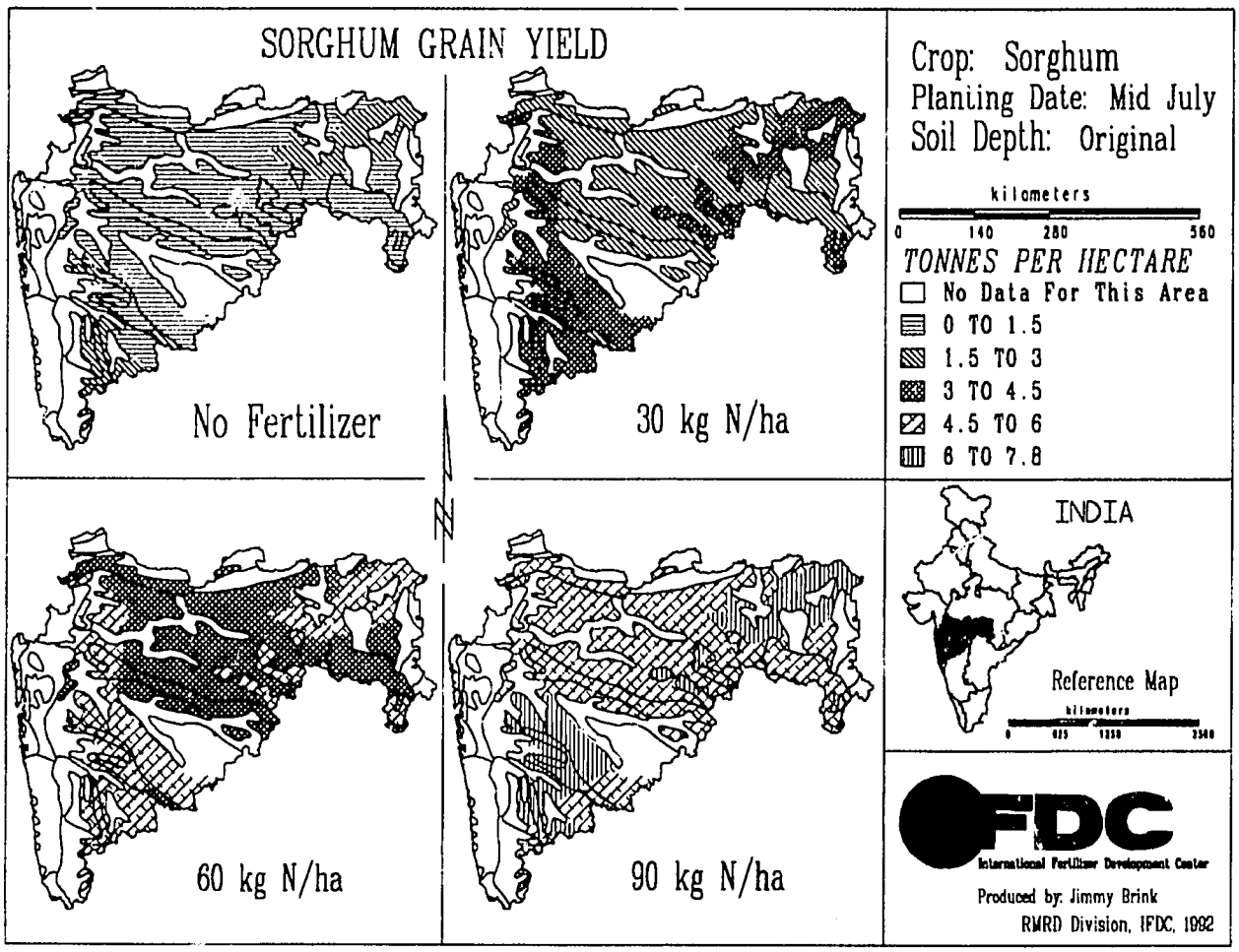
Map 3. Weather Sites in Maharashtra Used in the Study.



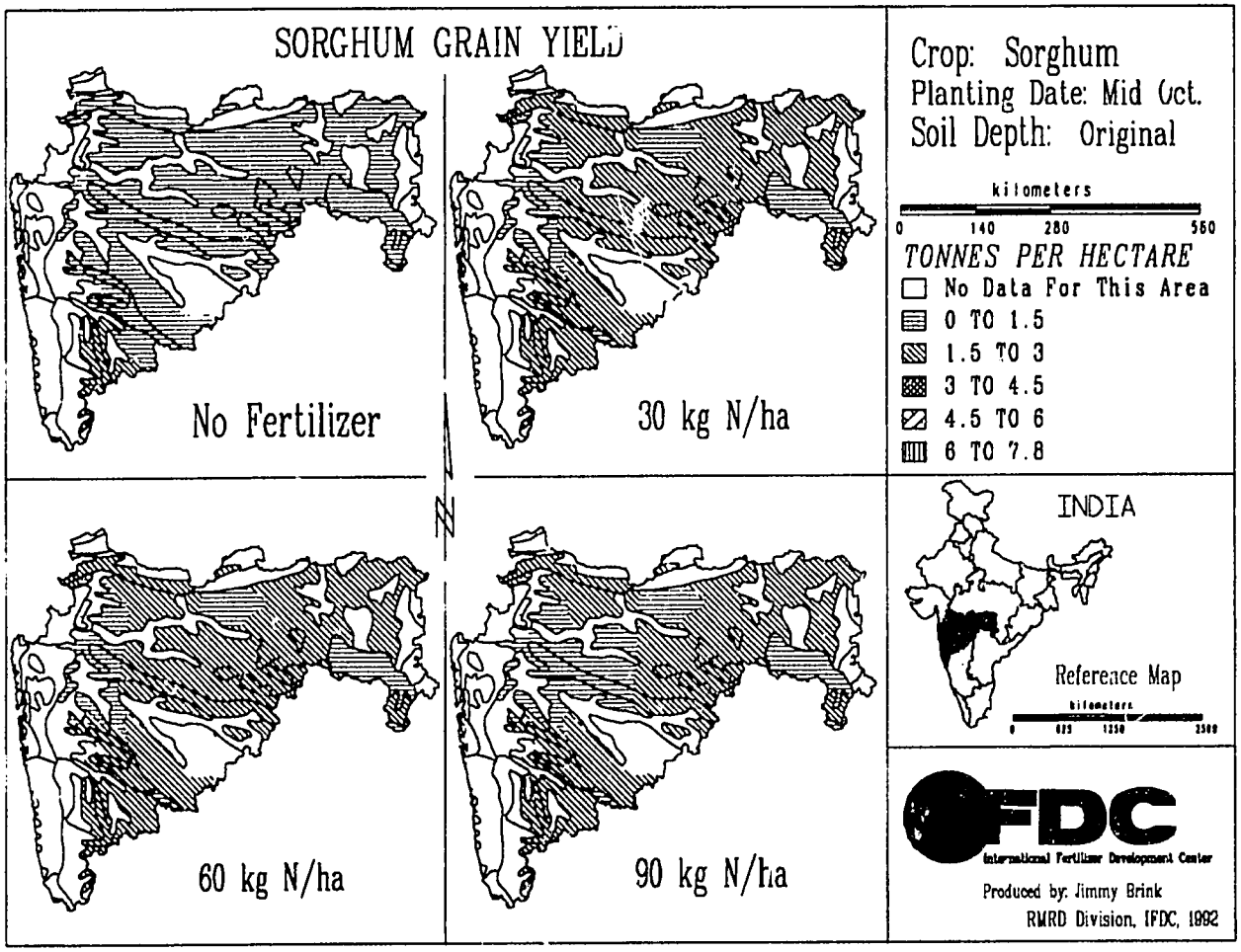
Map 4. Mean Sorghum Grain Yield in Maharashtra at Four Levels of Nitrogen Fertilization, Planted in Mid-May.



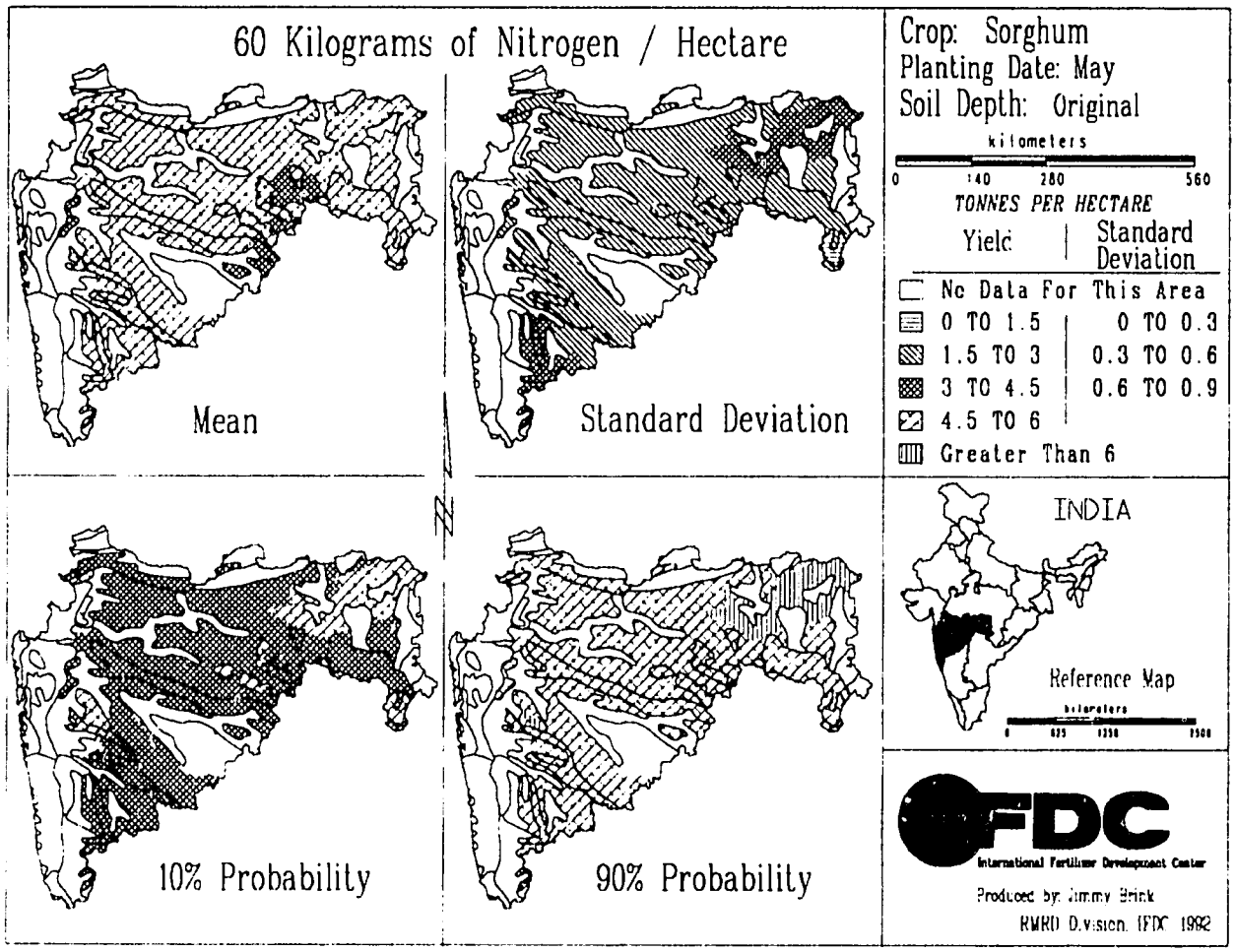
Map 5. Mean Sorghum Grain Yield in Maharashtra at Four Levels of Nitrogen Fertilization, Planted in Mid-June.



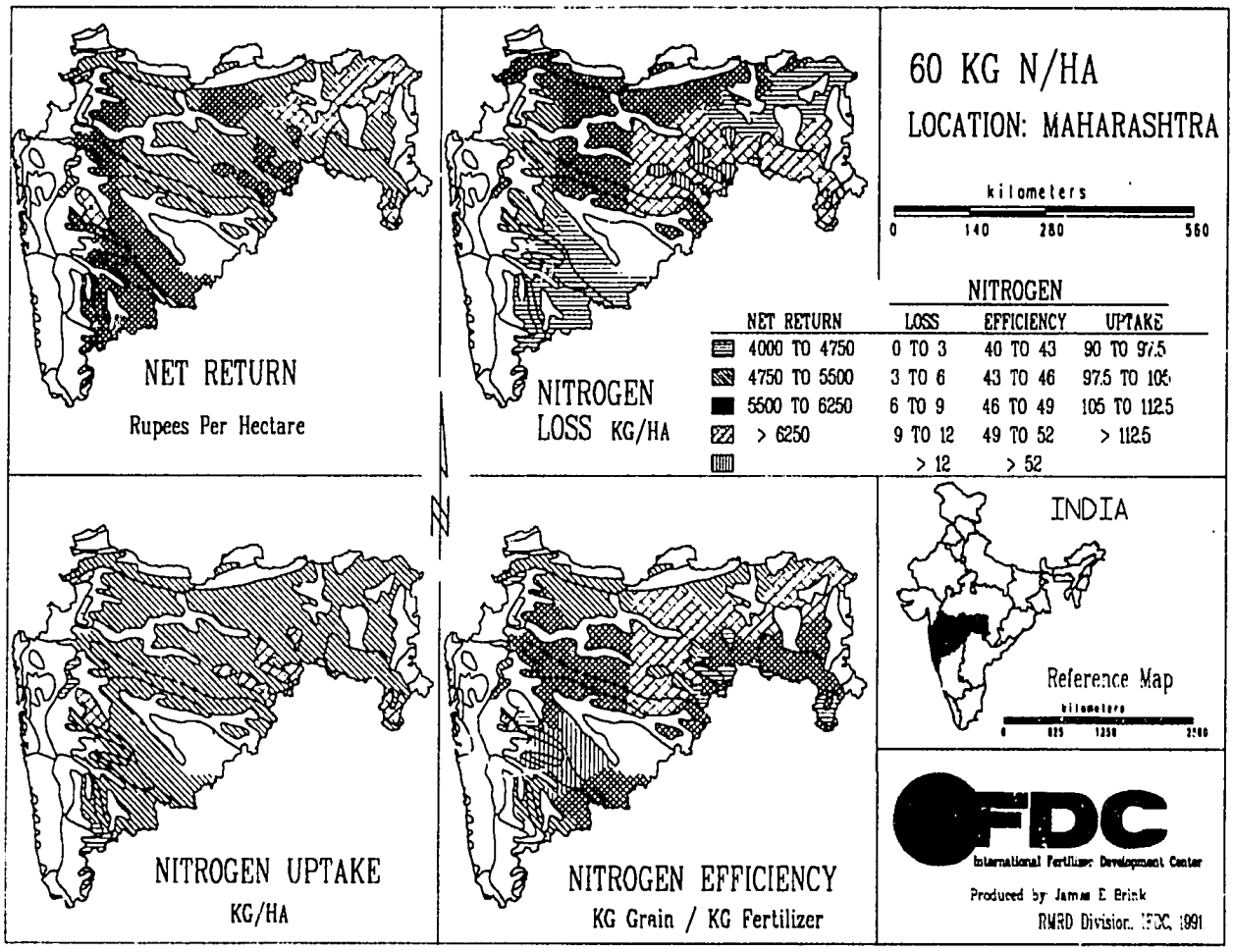
Map 6. Mean Sorghum Grain Yield in Maharashtra at Four Levels of Nitrogen Fertilization, Planted in Mid-July.



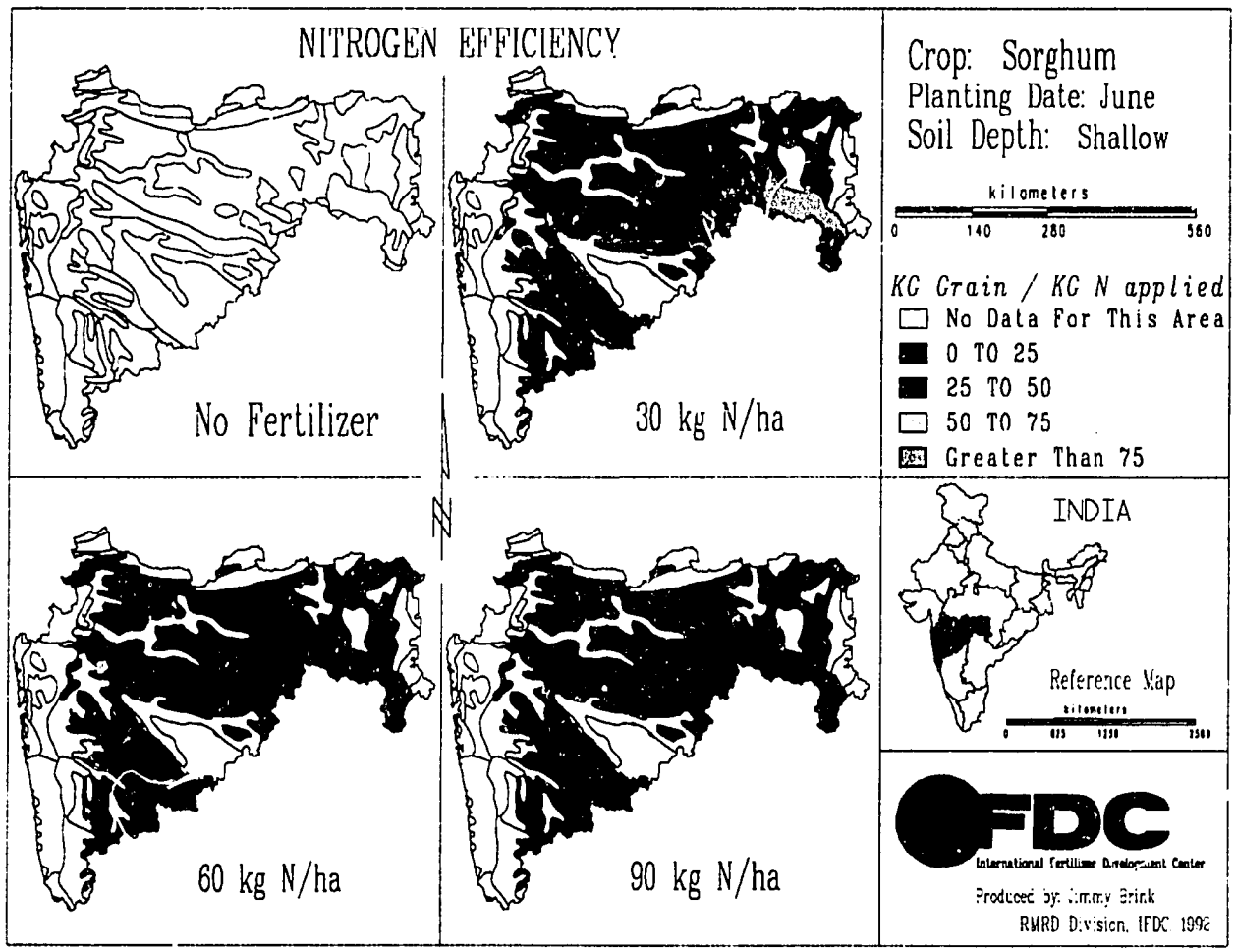
Map 7. Mean Sorghum Grain Yield in Maharashtra at Four Levels of Nitrogen Fertilization, Planted in Mid-October.



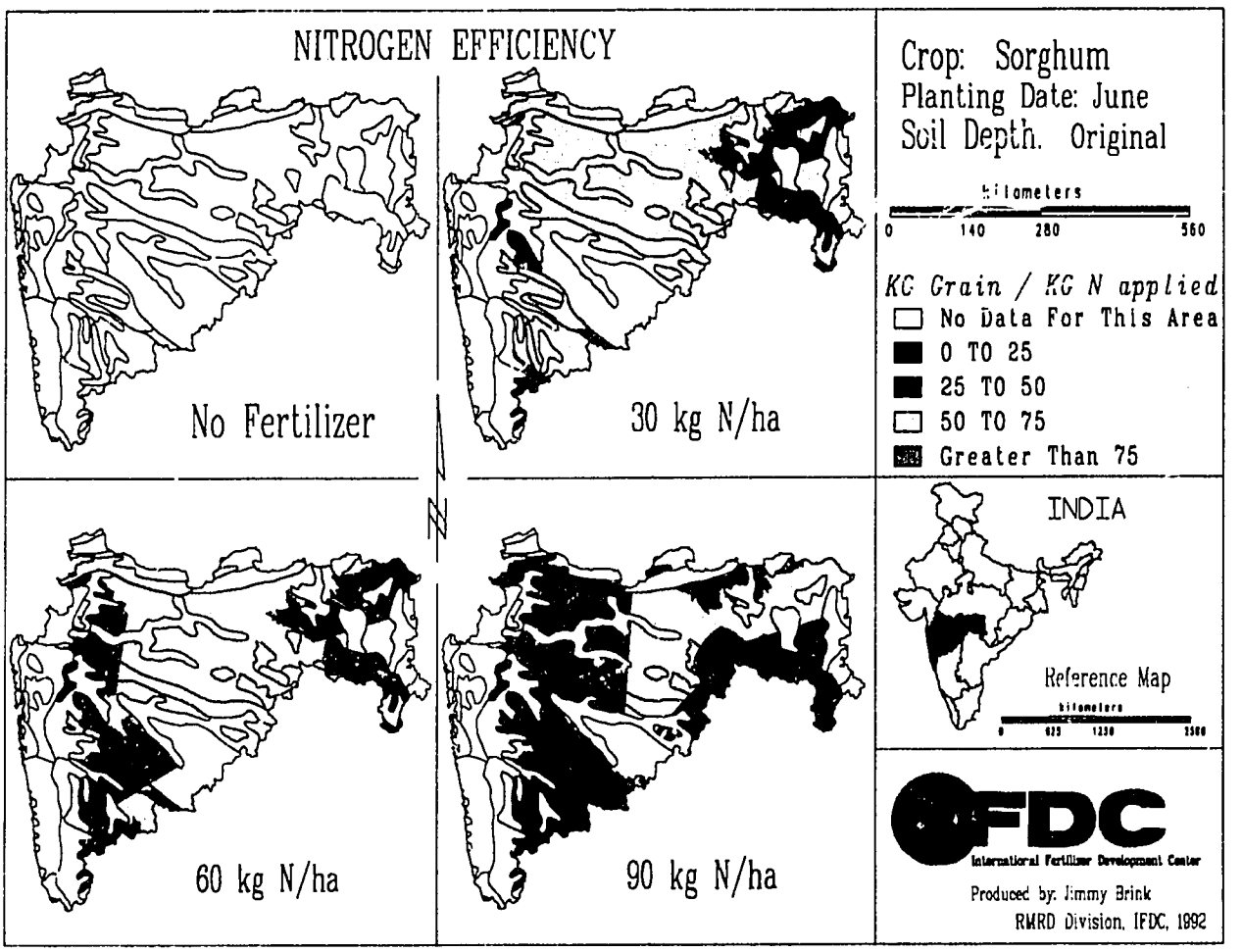
Map 8. Mean, Standard Deviation, and 10th and 90th Percentiles of the Sorghum Grain Yield Distribution in Maharashtra in Response to Four Levels of Nitrogen Fertilization, Planted in Mid-May.



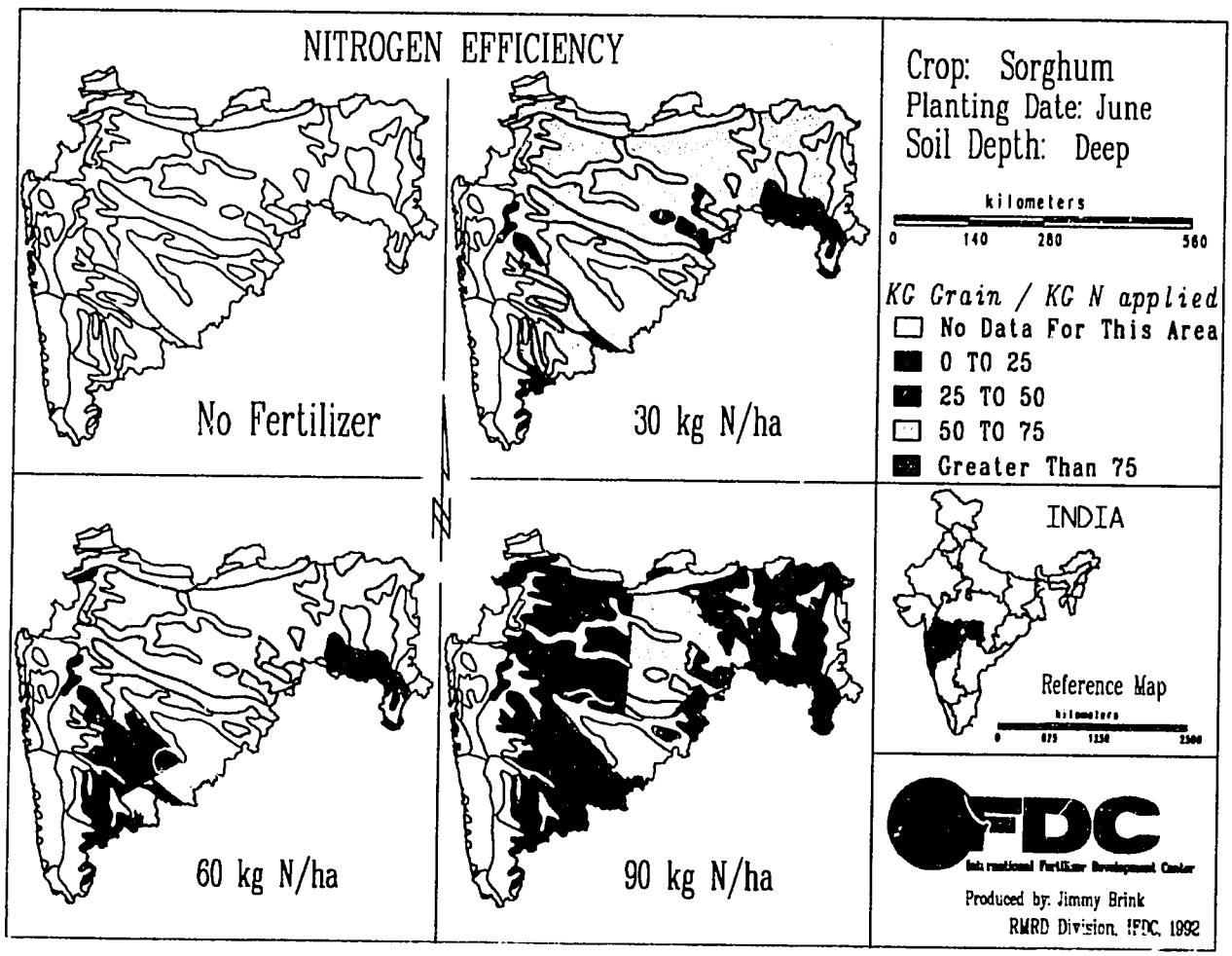
Map 9. Mean Net Return, Nitrogen Loss, Nitrogen Uptake, and Nitrogen Use Efficiency for Sorghum Planted in Mid-May in Maharashtra With 60 kg N Applied.



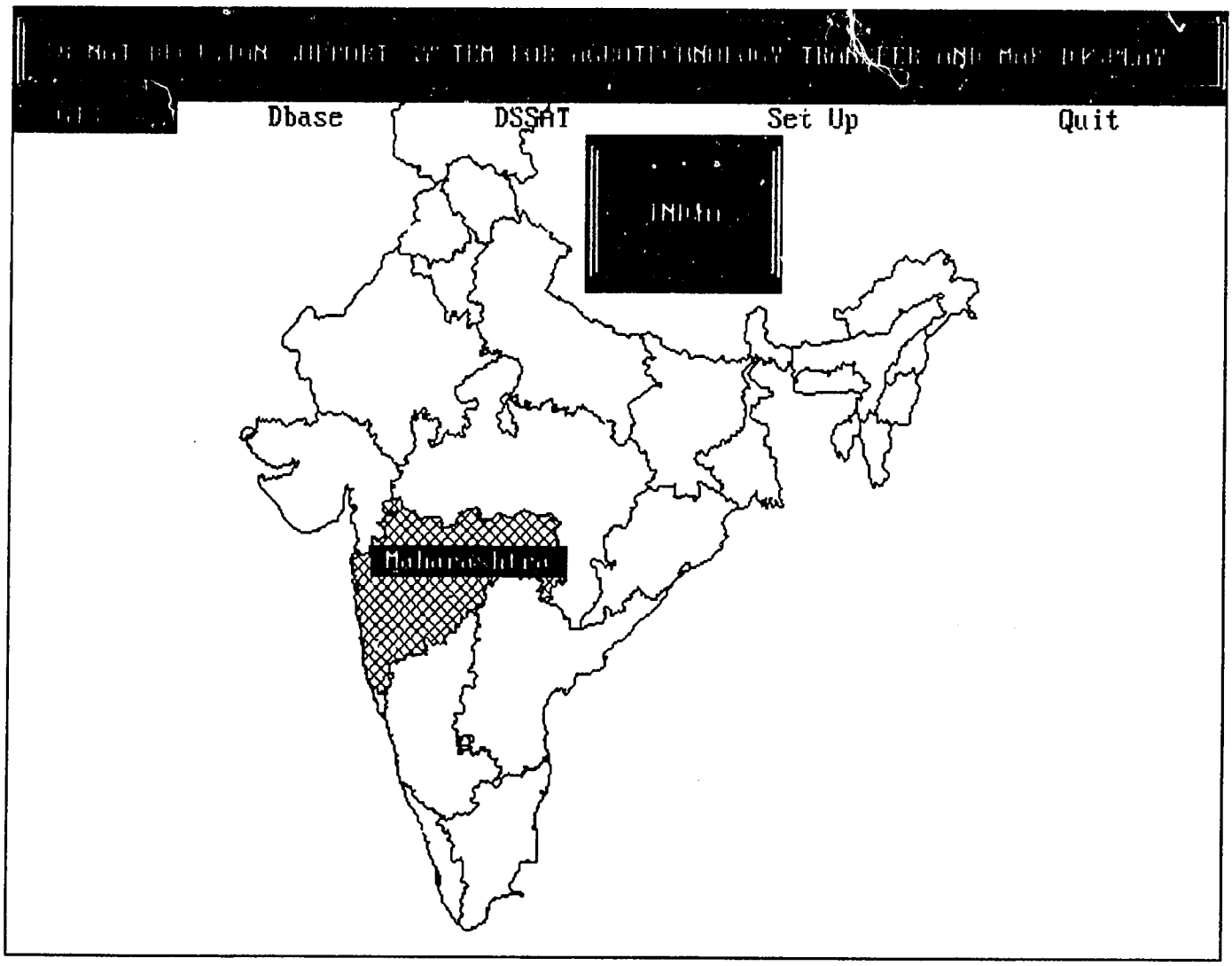
Map 10. Sorghum Nitrogen Use Efficiency in Maharashtra at Three Levels of Nitrogen Fertilization, Planted in Mid-June on Shallow Soils.



Map 11. Sorghum Nitrogen Use Efficiency in Maharashtra at Three Levels of Nitrogen Fertilization, Planted in Mid-June on Medium Depth Soils.



Map 12. Sorghum Nitrogen Use Efficiency in Maharashtra at Three Levels of Nitrogen Fertilization, Planted in Mid-June on Deep Soils.



Map 13. Main Menu of the Locational Crop Modeling System (LCMS) Being Developed at IFDC as an Adjunct to IBSNAT's Decision Support System for Agrotechnology Transfer (DSSAT).