NATIONAL LEVEL SPATIAL MODELING OF AGRICULTURAL PRODUCTIVITY: STUDY OF INDIAN AGROECOSYSTEM

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ABSTRACT

Traditional decision support systems based on crop simulation models are normally site-specific. In order to address the effects of spatial variability from one place/region to other of soil conditions, and weather variables on crop production, spatial model namely "Spatial-EPIC" using Geographic Information System (GIS) was developed linking with biophysical agricultural management simulation models. With the development of this model any size of agroecosystem starting from a field to a country and even bigger can be modeled. A country level Indian agroecosystem was simulated as an application of model development and have been detailed with validation in this paper. It also helped to predict spatial yield variability on a farm level, region level, state level and so on as a function of soil water conditions under various weather regimes and management practices based on their socio-economic resources they prevail. GIS-based model differing in their resolutions (~50 km grid size and ~10 km grid size) were applied to two level study respectively at whole India level and then one of the Indian province called Bihar. Results showed that at both resolution level crop yield varied significantly as a function of the data detailed due to their resolution (pixel sizes) as well as function of seasonal climatic variation, soil water holding characteristics and provided crop management time-series information.

1 INTRODUCTION

Agroecosystem are overwhelmingly a complex process of air, water, soil, plants, animals, micro-organism and everything else in a bounded area that people have modified for the purposes of agricultural production. An agroecosystem can be of any specific size. It can be a single field, household farm or it can be the agricultural landscape of a village, region or nation. Some of the most important decision in agricultural production, such as what crops to grow and on how much land to allocate depends on the existing knowledge base of current and future physical conditions like soil and climate, yields and prices. Modeling of the various processes in the system helps us to understand its flow and intricacies. An important issue in agricultural environmental modeling is that all the basic units (water, soil and chemicals) have a spatial distribution, and since this distribution does affect the processes and dynamics of their interaction considerably, geographic information system (GIS) is emerging as an important tool in modeling.

There have been a lot of studies on agricultural potential productivity but to relate actual crop productivity, however, only model-based simulations are not sufficient. Spatial biophysical model is still lacking to compute agricultural productivity at regional or national level although the estimates of farm productivity are being done using experimental/point based model. Site-specific management, or precision farming, is a strategy in which cropping inputs such as fertilizer are applied at varying rate across a field in response to variations in crop needs.

Modeling within a GIS offers a mechanism to integrate many scales of data developed in and for agricultural research. Irrespective of the scale at which various crops, agriculture environment models operate, it is known that management practices geared towards conservation and productivity are initiated at the field level. At present, however, few agricultural producers are utilizing the true analytical power of GIS and computer simulation models, partly because the loose or less linkages developed to-date between GIS and mostly public-domain modeling software are extremely cumbersome to use or are esoteric. Data access, including modeling results, expands to a "decision system" or decision tool which uses a mix of process models (where appropriate/possible) and biophysical data (growing season, climate characteristics, soils, terrain). Thus a need exists for an integrated, GIS modeling system to allow agricultural producers as well as policy makers to know the impact of differences between input and output spatially from one place/region to other from better management, productivity and profitability viewpoint.

The basic tenet associated with this goal is to facilitate the data flow and consistency between the GIS and simulated model. The specific objectives were to develop a spatial biophysical crop model from the point based process model, and then model application and its validation.

2. DEVELOPMENT OF "SPATIAL-EPIC MODEL"

To understand what these crop needs are from point to point/pixel to pixel, it is necessary to understand the relationship between crop yield and both controllable (such as fertilizer nutrients) and uncontrollable (such as soil, topography) factors. The effect of these factors on yield is complex and may change from point to point within a field. Recently, one of the many challenges facing regional, national or global agricultural research is the simple understanding of potential solutions to the constrains for achieving its solutions. Identification of opportunities and constraints is the task of characterization. Modeling within a GIS offers a mechanism to integrate the many scales of data developed in and for agricultural research. Data access, including modeling results, expands to a "decision system" or decision tool which uses a mix of process models (where appropriate/possible) and biophysical data (growing season climate characteristics, soils, terrain). An accurate spatial (and temporal) database enables the characterization of agroecosystems. This ability is vital in the developing world for efficient resource allocation in agricultural research. Agroecosystems are complex entities, which span several levels or scales, with different processes dominating each scale. Therefore, a dynamic agroecosystem characterization requires biophysical characterization integrity to be maintained by addressing particular objectives with specific information – information which may aggregate up - or down - scale (e.g. the aggregate description of a complex of soils would deliver a sensible "regional" characterization). With spatially interpolated climate data, digital elevation models, and low resolution soils data in place, agroecosystem characterization commences with simple models used to differentiate growing season and off season characteristics. Other information - usually much more difficult to acquire - becomes critical in refining target domains as resource access, land tenure, cropping system, labor availability etc. dominate the land use system at higher resolutions.

GIS based modeling of an agroecosystem is expected to give a new approach in order to provide agricultural managers with a powerful tool to assess simultaneously the effect of farm practices to crop production in addition to soil and water resources. At present, most of the crop models are location specific (point based) in nature, but to understand the impacts on the agricultural systems, it is necessary to have spatially explicit information. Therefore, development of spatially or raster based biophysical crop model took long way in helping us to understand many intricacies of modeling of large areas at coarse and fine resolution. To do this, Spatial Erosion Productivity Impact Calculator, [Spatial-EPIC] (Satya and Shibasaki,1998) was developed which gave us a new direction to simulate crop production at regional scale from microscopic simulation at each small piece of land in an efficient way, enables us to incorporate the environmental issues. "Spatial-EPIC" is a crop simulation model developed to estimate the relationship between soil erosion and crop productivity which has been implemented in GIS environment at 50km and 10 km grid size for a nation and region respectively to have spatial distribution of crop output then the classical point based method.

3. INTEGRATED SYSTEM – DESIGN AND DEVLOPMENT

As we developed "Spatial-EPIC" after integration of EPIC (Williams and Sharpley, 1989) with GIS, a brief description of "Spatial-EPIC" system files is warranted. "Spatial-EPIC" system file structure is comprised of text files, which contain estimate of parameters of different physical processes modeled by "Spatial-EPIC". These files include Basic User-Supplied Data file, Crop Parameter File, Tillage Parameter File, Pesticide Parameter File, Fertilizer Parameter File, Miscellaneous Parameter File, Multi-Run File, Output Variables File and Daily Weather Data File. In this study, a system framework was designed using ArcView 3.1a, Arc/Info as a pre and post processor for data furnishing as well as graphical display of "Spatial-EPIC". Figure 1 and 2 shows a brief schematic presentation of crop modeling and integrated model run process respectively under "Spatial-EPIC". Since the model runs outside GIS (after processing all the GIS input layers in the form of array) hence it requires an interface to link finally for its proper display query and attribute information of each cell. To do so, an in house written soft code was developed to meet their pre and post processing file format requirement. A great amount of time spent comprehending the "Spatial-EPIC" file structure and data requirements to make the model run. Also, spatial and locational databases were created to provide site-specific information of the defined cell resolution.

3.1 Development of Dynamic Adaptations cum Management Loop

The original EPIC is static with respect to management and technology. A single crop or rotation, tillage practice, conservation measure, crop planting and harvesting date, and machine sequence is specified prior to an EPIC simulation and cannot be varied during a simulation. The level of technology (such as plant genetic material and efficiency, plant varieties or cultivar, irrigation efficiencies, and so on) is also fixed. This was one of the main bottlenecks in the EPIC because it can not adopt the management as per the climatic and resources prevail in temporal time scale. Therefore, the "Spatial-EPIC" carries a component where all these management and technologies practices have been made dynamic.

3.2 Generating "Fine" Resolution Data from "Coarse" Resolution Data

As discussed before the model used for development is a field scale model hence the data requirement in terms of their resolution is a big gap. Therefore, the first question may come to readers mind is how to "spatialize" the point-based models? What data is appropriate for these models? The concept of "generators" helps to answer these questions. The weather and slope generators were used. These generators are used not to save data storage size but to provide high-resolution (temporal and spatial) data from coarse resolution data. These generators help in integration of data and knowledge to build a multi-scale GIS database. These "climate analog" models here used as a "Weather Generator" [Richardson (1981a)] serve to describe the initial domain or target area for a range of priority setting.

3.3 Biophysical Computation

The model is composed of physically based components for simulating plant growth, nutrient, erosion, and related process for assessing crop productivity, determining optimal management strategies, erosion and so on. Simultaneously and realistically, model simulates the physical processes involved using readily available inputs. Commonly used input data are weather, crop, tillage, soil-attributes and management parameters. The model runs on defined rather derived cell size data layers provided by the user depending on their availability. Figure 3 shows physical factors considered in computing a mathematical model to find the effects of crop productivity coming from different processes. How all these different processes affects overall crop productivity is being modeled while simulation is shown in figure 4. "Spatial-EPIC" is composed of physically based submodels for simulating weather, hydrology, erosion, plant nutrients, plant growth, soil tillage and management, and plant environment control. The model runs on daily time-step therefore, each model is linked subsequently and interactively with other sub models as explained in figure 4. In brief, the each sub module are dealt with their computation procedure. Weather: daily rain, maximum and minimum temperature, solar radiation, wind and relative humidity can be based on measured and data and/or generated stochastically. Hydrology: runoff, percolation, lateral subsurface flow are simulated. Erosion: it simulates soil erosion by wind and water (for this paper the erosion part has not been included). Nutrient Cycling: the model simulates, nitrogen and phosphorus fertilization, transformations, crop uptake and nutrient movement. Nutrient can be applied as mineral fertilizers, in irrigation water, or as animal manures. Soil: soil temperature responds to weather, soil water content and bulk density. It is computed daily in each soil layer. Tillage: the equipment used affects soil hydrology and nutrient cycling. The user can change the characteristics of simulated tillage equipment, if needed. Crop Growth: A single crop model capable of simulating major agronomic crops. Crop-specific parameters are available for most crops. The model also simulates crop grown in complete rotations. Plant Environment: It is capable of variety of cropping variables, management practices, and other naturally occurring processes. These include different crop characteristics, plant population, dates of planting and harvest, fertilization, irrigation, tillage and many more those are normally practiced in the field.

4. STUDY AREA AND DATA USED

The chosen study area is India, lies to the north of equator, between 8°4' and 37°6' North and 68°7' and 97°25' East. It is bounded in the south by the Indian Ocean, in the west by the Arabian Sea, in the east by Bay of Bengal, in the north-east, north and a part of the north-west by Himalayan ranges, and the rest of the north-west by the Great Indian Desert. The soil characteristics of Indian nation were obtained after digitization of survey of India soil map with many properties like soil texture, soil pH and soil depth. Slope information of the country was derived from 1km GTOPO (NGDC, 1997). Weather data were obtained and their surfaces were generated using World Meteorological Organization station falling around 230 in number scattered throughout India. Agricultural management data were obtained at state level where there numbers are more than 30 in total of entire India at 5 year interval which was used for coarse level whole country simulation of 50 km cell size. On the other hand we succeed in procuring time-series data from 1974-1994 for one of the Indian State Bihar for detailed study at finer resolution simulation of 10-km cell size.

5. RESULTS AND DISCUSSION

The model developed described in the earlier part of paper was found capable for simulating an unlimited number of crop management strategies, based on the selection and data provided by the user. In contrast to a stand-alone original EPIC crop simulation model, where the management information given in the beginning continues for the total no. of simulations year, hence the trend of output used to be more or less static and doesn't correspond to the actual farm practice. With the development of dynamic loop under "Spatial-EPIC" it got rectified. Now with this, during computation the model runs for each and every pixel following the rows and columns sequence with various multiple soil, climate, and management information provided in the form of layers. Two-year crop rotation was found appropriate for long term simulation. The crops selected in a row were maize-wheat-rice. Crop management option provided by user the model could be briefly seen from figure 1 on its right hand side given management table. Besides these there are many other information which need to be fed like start of simulation date, planting date, harvesting date, tillage time, irrigation timing its amount, fertilization time and so on. Amount of fertilizer applied used was the reported state and district level time-series data procured during the study. The crop selected in sequence for modeling was rainfed maize (without irrigation), irrigated wheat and monsoon rice with one user specified assured irrigation. All possible measures explained above were taken into account to mimic the more realistic field practice. Yield simulation of the rainfed maize varied from 0.4 to 3.5 t/ha as shown in figure described below under validation section for its spatial distribution of productivity throughout India. The maize yield shows quite high potentiality but being a third cereal it is not grown so widely like rice and wheat. Yield distribution of irrigated wheat crop varied between 0.5 to 3.5 t/ha also shown in figure described below under validation section clears that only the northern part of India is the wheat belt. Because of the fact that the Indo-Gangetic plains form the most important wheat area. The cool winters and the hot summers are very conducive to a good crop of wheat, whereas the rice is being grown throughout India but the southern part of India is found favorable from agro-climatic conditions. Similarly yield variation of monsoon rice was found to be fluctuating from 0. 3 to 3.0 t/ha.

5.1 Validation

The first approach used to evaluate "Spatial-EPIC" yield simulation was to compare the output at state level average reported data for the year 1995 values. Closeness between measured and predicted yield at state level is first and coarse level validation to see whether the simulated output is following the trend is of reported aggregate average. For doing this the simulated 0.5 degree pixel resolution falling under the state were averaged and their mean were compared with the reported state level average for maize, wheat and rice crop respectively. Again to go further ahead at same resolution validation for whole India, the output for maize, rice and wheat for the year 1990 of these growing belts were compared by overlaying the district coverage. To extract the mean value of a district simulated yield; all pixels were overlaid with all India district boundaries, which are roughly 450 in number. All the pixels following under particular district were averaged and their computed means were compared with the average reported statistical value for these three crops. All of these results can not be presented in this paper due to limited allowed volume in terms of total page no. Therefore, to see the same output spatially distributed over the country simulated vs. reported yield of maize, wheat and rice, a rough cum spatial validation map are given in figure 5 to 7 to have more explicit understanding of the area and their correspondence between productivity. Although there were some places where model has simulated more or less yields in case of maize and rice but in general it gives a very nice comparison hence one can easily identify the model performance by seeing these three maps as shown in the above said figure. The reason for getting less and more yields especially in rice crop is due to the limitation of not having district wise time series data of entire nation instead we applied state level procured management data like fertilizer and others. But, with the above validation figures it is self evident that the model was quite successful for simulating any piece of land as India could be one of the best example of showing the diversity from one place to other in terms of climate, natural, economical as well as social conditions.

Under the scope of the paper presented here country level (low-resolution) results have been explained whereas detailed state level (high resolution) could not be illustrated due to space limitation. But to give a feeling on how high-resolution results differs and gives more accurate output can be sensed seeing figure 8 comparing impact of two different resolution input data over wheat yield.

5.2 Limitations

Validation of models with a high spatial resolution is difficult and in some cases impossible, as it is impossible to validate each pixel output to a field data unless it is really being conducted under the same project. However, historic analysis gives possibilities to validate the model assuming the reported input applied in a area and validating it with simulated results. Usually in developing world all the data reported which could be fetched are not lower than the district boundaries and size of those district also varies to a greater extent. But the multi-scale approach helps in simulating the developing world where data are always a limitation. If certain grid cells, at the coarse allocation scale, have more information then accordingly a cell size can be estimated and could be applied to model the area/region more realistically.

6. CONCLUSIONS

The methodology presented found to be encouraging that provides an opportunity to plant physiologist, a modeler and GIS user a common ground to discuss simulation results and further potential research directions. Simulated crop yield and other maps generated under different scale dependencies within India and Bihar can be used to better communicate model predictions. Hence, using this methodology a region/nation can be modeled for any crop productivity, which help researchers and decision-makers understand the status and extent of climate, soils and crop cum field management effects on global processes such as rice, wheat and maize production.

To evaluate “Spatial-EPIC” yield simulation validation were carried out in different pockets of India based on the major growing reasons. Two tier validations were done at two different cell resolutions, coarse and fine for whole India (0.5 degree cell size) as well as one of the Indian states Bihar (0.1 degree cell size) respectively. Validation results was found quite successful for wheat and maize productivity whereas in case of rice it was a bit under estimated in southern most part of India whereas the other places gave better correlation between the simulated and observed values. It is believed that the model can be used in simulating any piece of land since India is one of the best example of showing the diversity from one place to other in terms of climate, natural, economical as well as social conditions from model applicability viewpoint.

Hence, the “Spatial-EPIC” possesses immense potential as a farm management tool. However, further research should be focussed on improving the model prediction, and the field level interactions within the system. Also, availability of new agricultural land-use maps with seasonal crop delineation, and other information of the management practices will help in bettering the model results.

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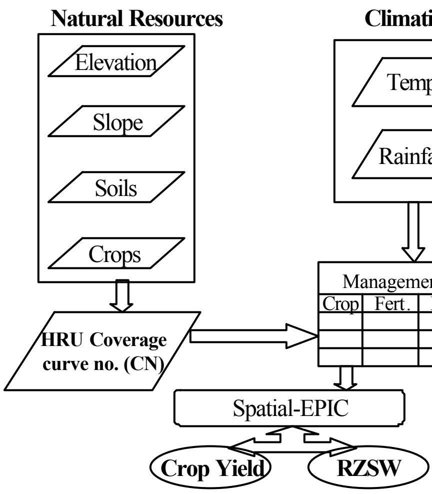


Figure 1. Brief schematic Presentation of modeling

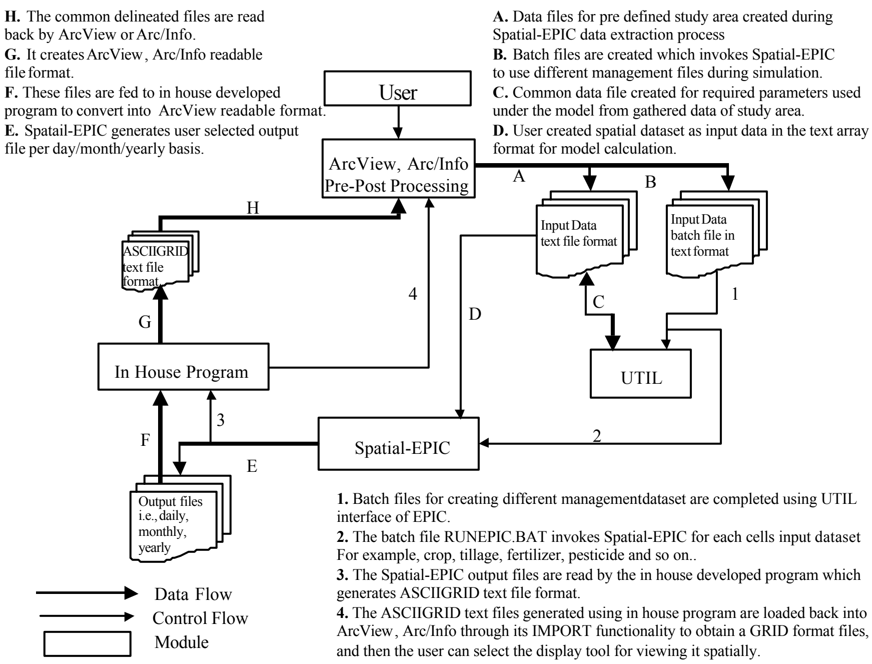


Figure 2. Integrated Model Run Process

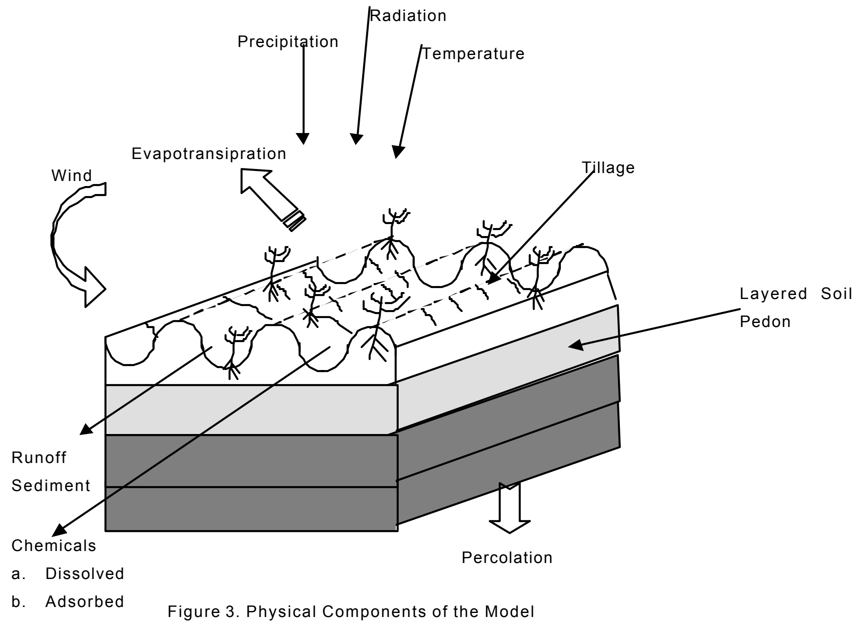


Figure 3. Physical Components of the Model

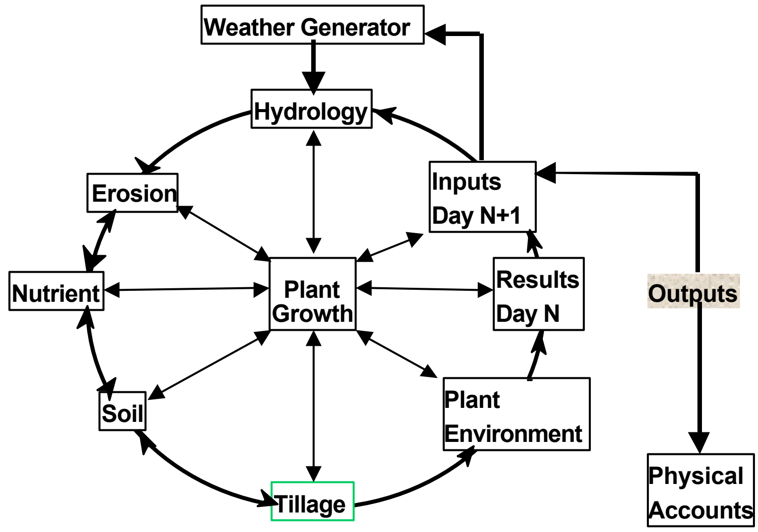
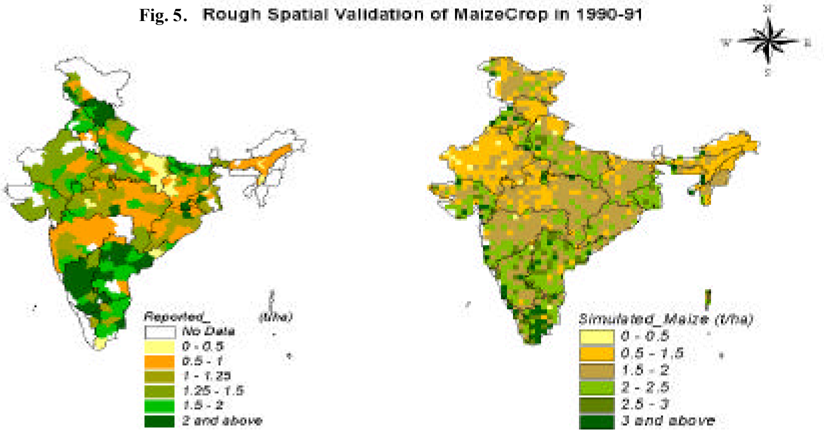


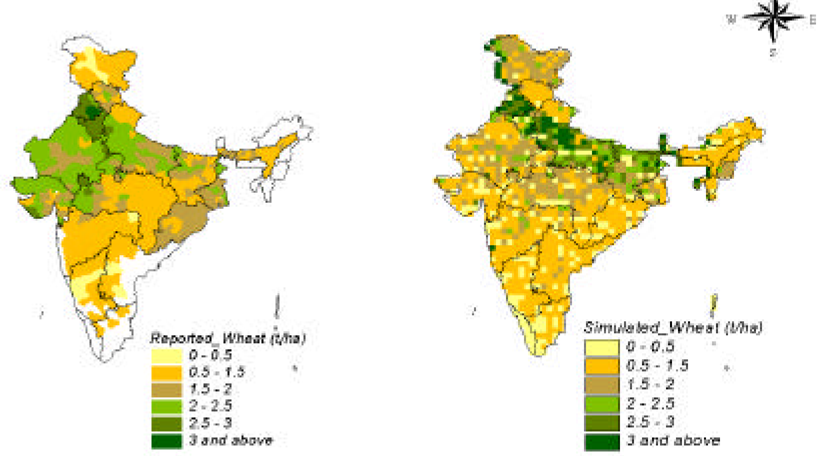
Figure 4. Modeling Linkage Diagram

Fig. 5. Rough Spatial Validation of MaizeCrop in 1990-91



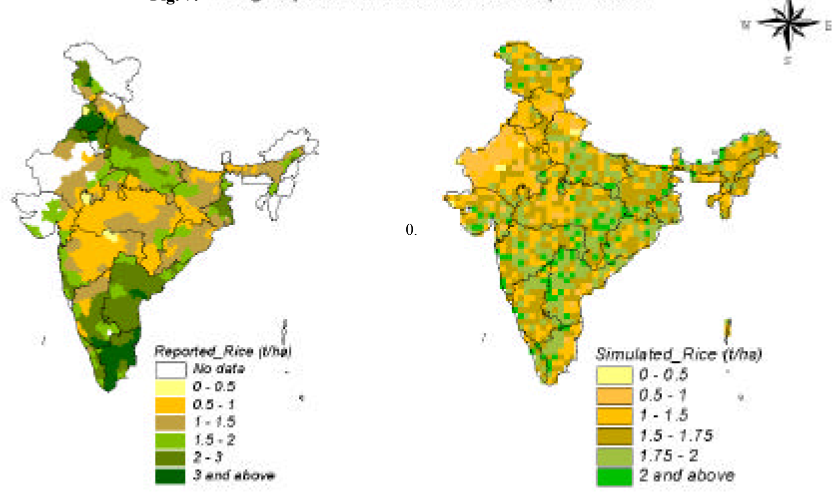
0.5 degree cell resolution, roughly 50km on ground

Fig. 6. Rough Spatial Validation of Wheat Crop in 1990-91



0.5 degree cell resolution, roughly 50km on ground

Fig. 7. Rough Spatial Validation of Rice Crop in 1990-91



0.5 degree cell resolution, roughly 50km on ground

Fig. 8 Comparision of Two Different Resolutions Impact Over Wheat Yield