INTEGRATING GIS INTO PRECISION CROP MANAGEMENT

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Abstract

Process level crop models have been shown to be effective management tools when adequate resources are available to utilize them. They have, however, been difficult to use in large scale farming operations. Recent advances in Geographical Information System (GIS) technology have provided an avenue for reducing much of the overhead associated with site-specific application of such tools. Using GIS, it is possible to develop the tools necessary to reduce the record keeping demand and implement crop simulation models in the precision farming paradigm. The first stage of a fully integrated crop model in a desktop GIS has been accomplished and shown to reduce the complexity of site-specific model implementation at farm level.

Introduction

One of the recurrent themes in American food and fiber production is the reduction in profits linked to either increasing production costs or the decrease in commodity prices. Labor, chemicals, fuel, equipment and compliance with increasingly restrictive government and environmental regulations have become so expensive that they have decreased profits for the farmer to a point where more of them are forced from the business every year. The ways for producers to survive in agriculture is to reduce input costs or improve profits. Many agriculturalists have pinned their hopes on the site-specific crop management technology that has emerged over the past few years.

Precision agriculture provides a new approach to agricultural chemical applications. This approach involves the development of tools that will regulate the amount of crop inputs applied to a field based on actual or perceived need. A key component of this approach is the utilization of GIS technology. This innovation provides visual integration of all data sources associated with an agricultural field and allows farmers to identify and describe within field variability.

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The GIS incorporates spatial information such as soil type, crop, and existing soil fertility into the chemical application process. This capability permits farmers to consider in-field variation and adjust the amount of chemical applied to what is actually needed at the sub-field level. This has the potential of eliminating waste and providing net savings to the producer (ESRI, 1997).

The problem remains as to how to determine the application rates for discrete sections of a field. Rather than relying on a labor intensive, subjective method of determining the amount of fertilizer to apply, an algorithm can be derived to calculate the value based on a series of known inputs. "Derivation of this algorithm is an agricultural research problem (ESRI, 1997)" and, indeed, industry does not have the expertise, experience or resources to develop the process level algorithms that are necessary. Industry is relying on crop modeling experts to provide the necessary components to acquire the knowledge and feedback. (ESRI, 1997; Macey, 1998)

Crop Models

Accurate crop models have demonstrated the usefulness of making management decisions that involve timing and quantity of crop inputs (McKinion, *et al.*,1989). For example, some models have the ability to predict water and nitrogen stress before it becomes evident to a producer or consultant who may be observing the plants in the field (Hodges, *et al*. 1998). Models have also been shown to be able to predict important physiological events including first square, first bloom, and first open boll (Ibid., 1998). Knowing when these types of events will occur provides additional insight for producers to be able to better schedule applications of growth regulators, fertilizer, irrigations and crop termination chemicals.

At the farm level, crop models have been useful, but require a lot of data. Initial setup involves taking soil cores for each soil type that occurs within the field. Moisture desorption tests, bulk density, and textural analysis must be run on each core for each horizon. Desorption results are then used to develop soil hydrology files necessary for soil sub-models. Additionally, soil tests must be run every season to determine initial soil nitrogen and organic matter content.

These pre-season data must be logically organized so the user can easily associate the data to the section of the field where the data were collected. This has traditionally been accomplished by placing the data in separate files and associating the name of the file with its corresponding geographical location. This scheme works well with small farming operations where a single person manages the data. Adding additional persons to the process necessitates some type of written records associating files and locations. In-season crop input records must also be managed in a similar manner. Typically, crop inputs for a given field are placed in a single file and read as the crop model is run on that field. Problems arise later in the season when perhaps one section of the field dries faster than another and requires irrigation sooner. When this happens, the file containing inputs for the field is copied, an irrigation record is added, and the new file is given a name that describes the divided field. This 'branching' effect is propagated throughout the field as the season progresses, causing the producer to maintain a 'management track' for each uniquely identified segment of his field.

In addition to model input tracking, crop models generate copious quantities of output. For a single simulation, listings are generated for plant morphological and physiological variables, weather, soil, stress, etc., for every day of the simulation. Charts and graphs can be generated to display these output data as well. Similarly, management branching makes model output difficult to organize and analyze, especially over large, disjoint farming operations.

When the Agricultural Research Service's cotton model was first released, it required about 20 minutes on an AT class computer to simulate a season. In fields with multiple soil types, an attempt to simulate every soil type added another 20 minutes per run to analysis time, likewise, differences in the field due to irrigation, fertilizer, plant density, etc. also required additional processing time. The recommendation was made to select the dominant soil type in the field and use it's soil physical properties for the entire field. Soil fertility was also averaged across a field and simulations and recommendations were made based on the average need of the field. Decisions about irrigation management caused problems as well. For example, if the majority of a field is covered by a center pivot, the edges and corners are, of course, not irrigated. In an effort to reduce analysis time, the field was averaged and the pivot was assumed to cover the entire field.

Field averaging of this sort reduced input requirements for running the cotton model; thus, at the time, averaging was a common practice. Similarly, extension recommendations for crop inputs were based upon average conditions because application equipment was not available to account for variations in field requirements. To receive the highest return on the dollar invested, the farmer's best strategy was to apply what was considered the mean requirements of the field. It was generally understood that some sections of a field would receive more than necessary inputs, while other sections would be deficient. Averaging reduced the management intensity of the necessary inputs, however, it also reduced the scope and resolution of model predictions. Natural variability had been 'smoothed' in order to capture general trends in crop growth.

As computers have become cheaper and more powerful, field averaging is slowly being abandoned. Producers are now able to run an entire season's simulation in a few seconds. The increased speed enables managers to run increased numbers of simulations, thereby allowing them to simulate crop inputs on an increasingly site-specific fashion. Thus, the use of computers to refine management practices is becoming site-specific. At first, this was done by running simulations on every soil type. Irrigated and unirrigated sections of the fields were eventually treated separately. Simulations can be done on separate sections of fields based upon the natural and induced variations in initial soil fertility. However, expansion of the management track by adding resolution to model implementation increases the record keeping and storage requirements for model input and output. When the model was released with a graphical user interface, record management became easier, but was still burdensome.

Geographical Information Systems

An Information System is defined as a chain of operations ranging from planning the observation and collection of data, to storage and analysis of data, to the use of derived information in some decision making process. It naturally follows that a map is a type of information system. Maps are collections of analyzed and stored data. Information derived from map 'collections' is useful in making decisions. A Geographical Information System is an information system designed to work with data that are registered by spatial or geographical coordinates.

GIS's have been around for many years, although only relatively recently have they been recognized as such. For example, an early GIS might have consisted of elements that included maps, sheets of transparent overlays, aerial photographs, statistical reports, etc. These elements are often referred to as data layers. The transparent overlays would be placed over an aerial photograph or topographic map to see how proposed structures, streets, light posts, etc., might relate to other surrounding features. Topographic maps, in turn, display several different kinds of information about a given geographical area. For example, different types of land cover are often represented by different colors, blue for water, green for vegetation, or by different textures for farmland or wetlands. The different types of information on a single map are referred to as themes. Automated GIS, those based on digital computers, consist of both spatially registered and non-registered databases (contour lines, streams, railroads, etc.) and a set of operations that act on these data (distance measurements, intersections, buffer zones, etc.). In a sense, a GIS can be thought of as a 'high-ordered' map (Star & Estes, 1990).

GIS software has been in existence for a number of years, although it has historically required large mainframe computers or high end computer workstations. Additionally, GIS software has been notoriously difficult to learn, use, and maintain. However, recent advances in microcomputer technology has made GIS functionality available on desktop computers. Similar advances in software design and implementation has given novice users access to tests and analysis methods that were formerly out of reach.

GIS is very appropriate for agricultural applications because agricultural land is itself, highly variable. Sections of a single field may differ in slope, aspect, elevation, drainage, soil type, fertility, and other field properties. GIS is inherently able to store and display these patterns of variability.

Global Positioning System and Variable Rate Equipment

In the early 1980's, the Department of Defense (DoD) conducted an experiment to determine the feasibility of using satellites to determine position on the face of the earth. The experiment was a success and has turned into what is today known as the Global Positioning System (GPS), a system of 24 plus operational satellites with 12 hour orbital periods divided into six orbital planes. The DoD has chosen to introduce error into the signals known as 'selective availability'. With inexpensive, civilian receivers, one's position can be determined within 100 meters, 95% of the time. Necessity being the mother of invention, new techniques were quickly developed to apply real time corrections to the dithered signals. Differential GPS (DGPS) will remove the effect of selective availability and improve positional accuracy by an average of 80%. Using mapping grade equipment, positional accuracies in the range of 1 to 5 meters can be expected (Dye, 1997).

With the GPS technology readily available and becoming less expensive, agricultural equipment manufacturers have seized an opportunity previously unavailable. GPS receivers were fitted to application equipment that had been built with metering equipment. The Variable Rate Technology (VRT) equipment allowed producers to vary application rates for fertilizers and other agricultural chemicals. When fully integrated with GPS receivers and microcomputer controllers, application rates could be automatically changed to match the requirements of the particular locations in the field.

Integrated Systems

Until recently, it made little practical sense to use a crop model to simulate discrete sections of the field. We could formerly invest the time and effort into simulating the field on a site specific basis. It would have been, however, strictly an academic exercise because variable rate equipment was not available to make prescription applications. Only recently has the technology and application equipment become available where we could actually manage the field on a site specific basis. The next logical step in the development of in-season crop management tools is to attempt to utilize GIS and GPS for crop management. Since GIS has inherent capability to store, manage, and display spatially varying factors, it makes perfect sense to take advantage of it. In a crop management GIS, spatial data such as soil hydrology, topography, and initial fertility are stored in separate data layers. For any point in the field, a simple mouse click can retrieve any or all this data.

Crop input records can also be kept in a spatial database. Whenever an input is applied to a field, it would be simply a matter of selecting the areas on the map and entering the type and amount applied. When crop records are accessed by location, they need only be recorded one time. Again, a mouse click on any point in the field can retrieve all management practices applied at that point, whether they were applied to a whole field or simply a small section. Obviously, this type of input management will eliminate the need to duplicate crop input records or maintain distinct management tracks when practices diverge for different sections of a field; a clear solution to numerous problems mentioned earlier.

GIS allows the farm manager to fully utilize crop models by eliminating much of the error sources associated with merely 'averaging' a field. Crop models coupled with GIS can readily reflect the natural variations within a given field and allow exploration of future effects. For example, different simulation runs can be made for each soil type by simply selecting the regions of the field uniquely defined by soil type boundaries. The necessary data can be entered once, without having to maintain separate record sets for each soil type. Additionally, output from integrated crop models can be spatially registered and displayed visibly on a map generated without using paper printouts of tabular data.

Initial stages of a fully integrated GIS and cotton crop model were completed in the summer of 1998. The ArcView 3.0 Desktop GIS package was used to develop the relationships between the GIS and the current ARS Cotton Model. The first stage involved removing the existing crop model's user interface and modifying the cotton model to operate as a dynamic link library (DLL). Computer code was written in Avenue, ArcView's scripting language, that linked and accessed the cotton model's functions available in the DLL. Additional code was written that allowed ArcView and the cotton model to communicate, pass data and variables back and forth. Next, database management routines were implemented using Delphi and Visual Basic. These, however, proved to be rather difficult to seamlessly integrate into ArcView. Fortunately, ESRI then released the Dialog Designer, an ArcView extension that allowed programmers to write code in Avenue that uses common dialog boxes. Using the Dialog Designer, data management routines could respond directly to messages from the GIS, thus allowing ArcView to serve directly as the user interface to the cotton model.

Precision Applications

Initial applications of the geo-referenced cotton model involve the Levingston Field, a 500 acre field in Bolivar County, Mississippi, near the Mississippi River. The field had been divided into one hectare grids. Soil samples were taken and soil tests were run for each grid section. The results were 209 distinct areas with unique soil hydraulic properties. The locations were plotted using the GIS and the field was subdivided into 209 uniquely identifiable simulation units (Figure 1), a step that is well beyond the practical scope of the non geo-referenced version of the cotton model. Remember, in the previous applications that involved the use of a management model, the results would be averaged and the field would be treated as a homogeneous unit.

Soil fertility sampling is typically done on a 2½ acre grid as well. For this application, however, we relied on soil fertility tests which were done on 72 one-acre grid sections located in the east half of the field (Figure 2.). In this grid, the test results varied from as little as 35 pounds of residual nitrogen to as much as 95 pounds per acre. These results, also, would have been averaged for previous versions of the model. Combining the soil physical tests with the soil fertility tests resulted in 146 unique combinations of soil hydrology and fertility (Figure 3.). This is obviously a level of resolution much more precise than an assumption that dictates the use of a larger homogenous unit.

Further defining the unique areas within the field was the coverage area of the center pivot. For this example, the pivot was assumed to traverse the entire field in three days. For the study area, the pivot could cover the field in less than two days. However, the cotton model is sensitive to irrigation effects (Stevens, *et.a*l. 1996) and the field plots needed to be divided again (Figure 4). The study area now contained 158 unique management units.

Model Results

The integrated model was developed and tested during the Spring and early Summer, 1998, and was used by the authors to monitor a variable rate nitrogen test conducted on the Kenneth Hood farm in Bolivar County, Mississippi. The objective here is not to describe the results of the variable rate fertilizer tests, but to demonstrate the effectiveness of the integrated model in maintaining the prescription records and in visualizing the prescribed applications and predicted results.

Using the embedded cotton model, nitrogen prescriptions were developed corresponding to the one acre grid sampled for residual nitrogen (see Figure 2.). These recommendations were added as a feature theme to the map of the test field. Farm management practices included two additional nitrogen and three PIX applications. These were applied to the entire field and were maintained as field level inputs by the geo-referenced model. Irrigations were applied using the center pivot. In the integrated system, the pivot is assumed to be capable of applying variable rate irrigations, however, in practice and for the results of this study only, uniform applications of water were made. Each pivot application was maintained as a separate feature theme.

By modulating the agricultural inputs, a map of the field could be generated that showed the predicted effects distributed over the entire field (Figure 5.). Researchers were now able to visualize the effects of a management practice. The effects could be seen distributed across a geographical area where as previously they were only available as a plot from a single simulated plant. Plots for the single plant simulations were still available and were quite useful in determining the timing and extent of water and nitrogen stress. Following a simulation of the entire field, single plant charts can be retrieved for any location in the field by clicking an area and selecting a menu option. The results of multiple runs can be succinctly described and visualized by the GIS generated map.

Conclusion

Management for the field was efficiently done using the integrated software, a process far too cumbersome for any previously released management model. Results of the simulations with the prescribed variable rate nitrogen applications showed a yield variation in the field from 0.76 to more than 1.87 bales per acre (Figure 5.). Questions remain, however, that require additional study. For example, what resolution or scale is actually necessary or sufficient for precision management? At what scale does the cost of acquiring additional input data become greater than the expected return? Additional work also needs to be done on methods to display model results that are sufficient for decision support. Eventually, decision support software needs to be written to fully utilize the spatial variability and automatically generate recommendations that take advantage of the available application technology.

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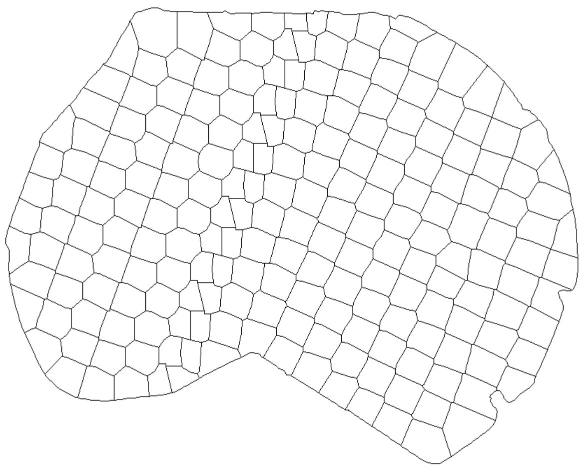


Figure 1. Levingston Field on the Kenneth Hood Farm in Bolivar County, Mississippi. The field is divided into 209 units based on soil sampling and tests.

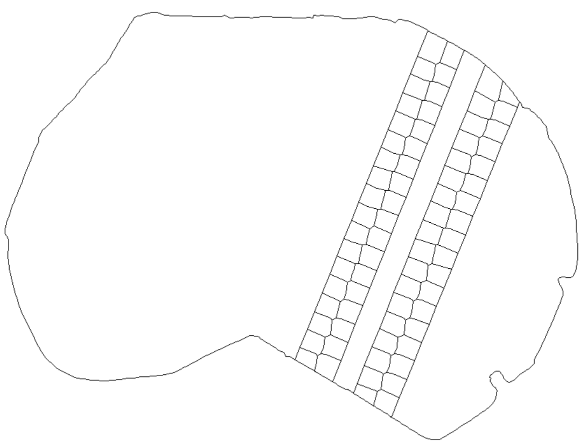
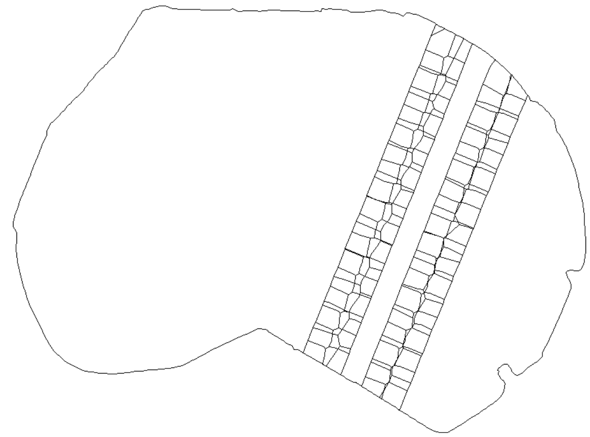


Figure 2. The Levingston Field showing the one acre grid used to collect initial soil fertility.



Ficure 3. Levingston field showing 146 unique sub plots within the initial test area.

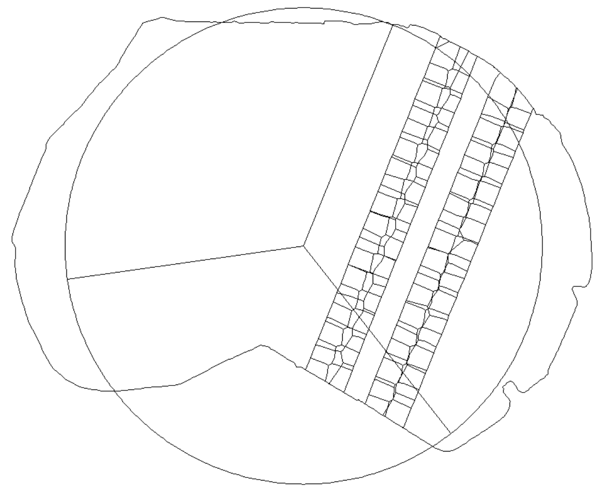


Figure 4 Levingston field showing the extent of the center pivot. It took two days to water the irrigated sections of the study area.

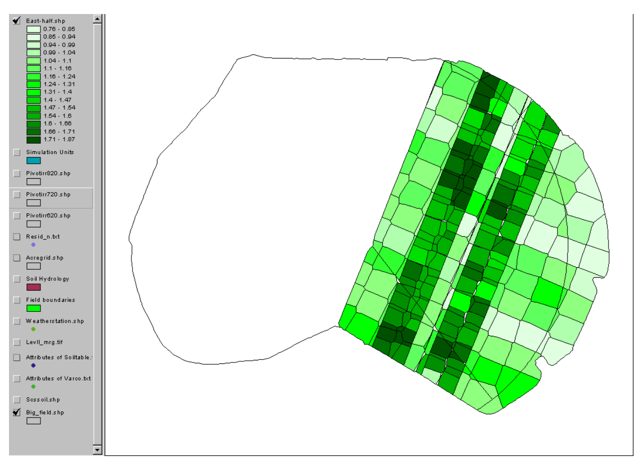


Figure 5. Results of simulations on east half of the Levingston Field showing the effects of site specific fertilizer applications.