Fostering Undergraduate Research by using GIS technology in Precision Agriculture

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Abstract

Precision agriculture is a unique agricultural management practice through which, crop productivity can be improved. The technologies that promote this modern agricultural practice include GIS (Geographical Information System) and GPS (Global Positioning System).

Farmers all over the world have always struggled with the availability of information about their land. Without proper information and guidance they have been forced to apply input parameters such as pesticides, fertilizers, etc, uniformly, which causes a lot of wastage and a decrease in profit margins. The information that would lead to a proper decision making is usually in the form of spatial data such as soil/plant properties and conditions.

The paper describes a precision model created using GIS software for a soybean crop that can be used as a learning tool for agriculture students. The model is used as a case study to develop crop management skills related to analysis and reasoning for students interested in pursuing careers in agriculture.

Introduction

Precision agriculture or site specific management is a strategy that optimizes the crop productivity on farm land with the help of technologies such as Global Positioning System (GPS) and Geographic Information Systems (GIS) along with principles of management. Using spatial information related to soil properties, fertilizer requirements, soil moisture availability, etc. for a specified parcel of farm land, producers will be in a better position to choose appropriate treatments for their land with optimal input parameters. This spatial information is usually stored in the form of a database. When the database is analyzed for crop productivity over several production cycles it will reveal any deficiencies of the spatial input parameters across the farm land. With a good understanding of these deficiencies, the uncertainty of decision making that most of today's farmers have to face can be minimized. According to Morgan (1995), the five broad objectives of precision agriculture are:

A. Increased production efficiency
B. Improved product quality
C. Efficient chemical use
D. Energy conservation and
E. Soil and ground water protection

Of these five, objectives A and C were incorporated in the project model in measurable terms.

For a successful implementation of a precision based model three elements are essential

A. Information
B. Management and
C. Technology

These three elements are interrelated in a closed loop cycle as depicted in Figure 1.

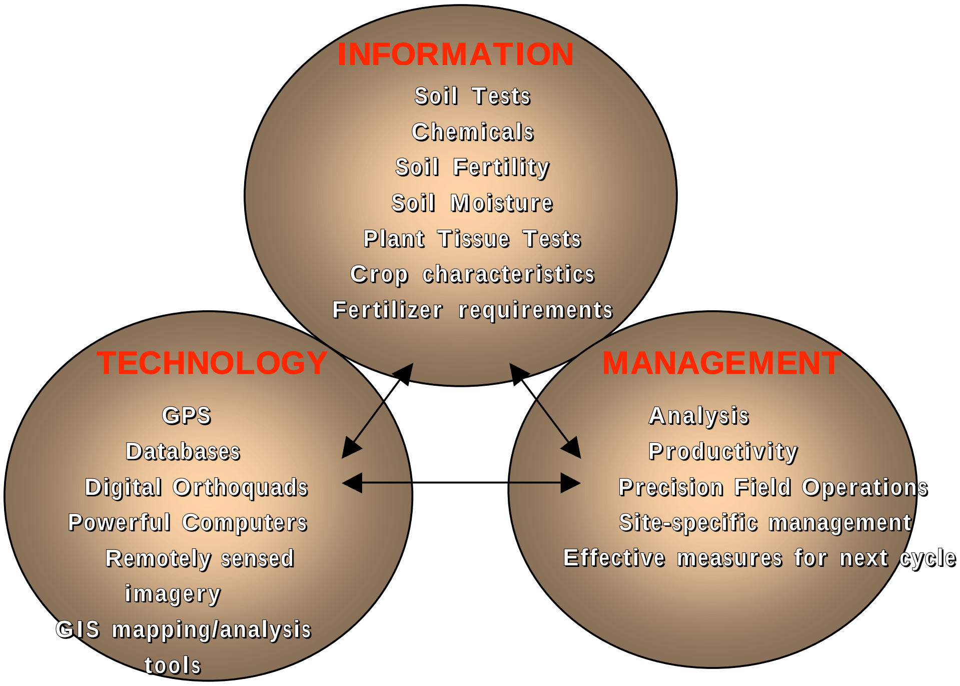

Figure 1: Elements of precision model

History and Theory of Precision Agriculture

In the early part of the 20th century, scholars were already studying variability in soil properties such as nutrient status and organic matter levels, and documenting spatial variations in crop yields (National Research Council, 1997). In the United States, the University of Illinois was even advising farmers to map soil acidity variations within their fields and vary application rates of lime accordingly (Linsley and Bauer, 1929). Although, researchers have continued to report on soil and yield variability through the years, the mechanization of agriculture and the trend toward larger implements led agricultural production to treat larger and larger areas as homogeneous. In the early 1980's, agricultural engineers began to write about control systems that would respond to variations in field conditions and apply varying amounts of inputs such as herbicides or fertilizers. For example, Krishnan et al. (1981) worked to develop a soil organic matter sensor that could be used as part of a variable rate herbicide application system. Rudolph (1983) speculated that future equipment would control application rates of fertilizers, herbicides, and insecticides based on field condition maps stored in an onboard computer. This prediction soon became reality, when Ortlip (1986) was issued a U.S. patent for such an invention. In the intervening years, technological advances and the increasing pressure of environmental concerns have increased interest in the concept of defining smaller management units and applying inputs based on the individual characteristics of those units, in the concept now generally referred to as precision farming. Ever increasing acceptance of information technology in everyday life has also had a significant impact on agriculture, and this will only grow with increased technological accessibility.

There are two methodologies for implementing precision or site-specific farming. Each method has unique benefits and could even be used in a complementary or combined fashion: (Morgan, 1995)

1. The first method, Map-based, includes the following steps: grid sampling a field, performing laboratory analyses of soil samples, generating a site-specific map of the properties and finally using this map to control a variable-rate applicator. During both the sampling and application steps, a positioning system, usually DGPS (Differential Global Positioning System), is used to identify the current location in the field. This method was adopted for the project and is discussed in detail later.
2. The second method, Sensor-based, utilizes real-time sensors and feedback control to measure the soil properties or crop characteristics on-the-go. The signal from the

feedback is used to control the variable-rate applicator. This second method does not necessarily require the use of GPS technology.

Map-based Technologies/Yield mapping (Morgan, 1995)

Currently, the majority of available technologies and applications in site-specific farming utilize the Map-based method of pre-sampling, map generation and variable-rate application. This method is most popular due to the lack of sufficient sensors for monitoring the soil conditions. Also, laboratory analysis is still the trusted and reliable method for determining most soil properties. However, the cost of the soil testing limits the number of samples that a farmer is willing to secure. Thus, the usual practice of precision agriculture is to grid sample a field approximately every 2 acres (There are currently ongoing discussions on the optimum number of acres represented by each sample and the location of those samples.) Detailed mapping of fields is easily performed using computer software systems such as GIS. Some GIS's can even use algorithms for interpolating the data between sampling points, others use a constant value for the measured property over the entire area, i.e. 2 acres for example. In either case, the mapping facilitates long term planning and analysis. It provides an opportunity to make decisions regarding the selection and purchase of seed and chemicals well in advance of their time of use.

Problem Domain

Although, agriculturalists have long known that fields are heterogeneous, only recently have technologies become available that allow production practices to efficiently take this variability into account. Key technologies include GPS, GIS, electronic sensors, and high end computing for within-field data acquisition and operation control (Sudduth et al., 1998).

Although, it is now relatively easy to collect geospatial data for precision agriculture, it is more difficult to know how to most effectively use that data in making crop management decisions (Sudduth et al., 1997). The key factor in making these management decisions is to recognize that there are spatial relations between a variety of agricultural production factors and the harvest yield. This project examined a GPS approach to spatial data collection and the use of GIS software (ArcGIS) along with its extensions for creating a predictive crop growth model for soybeans using map based methodology that relates spatial grain yields to various factors that affect yield. The yield obtained in the first crop cycle will act as a benchmark for subsequent cycles that should register an improvement in the yield and economic outcomes over time as a result of modification of input parameters. This project culminated in finding individual cell rankings based on an objective function that optimizes the productivity by showing high yields and less wastage, thus forming the basis for cell statistics and time series analysis for the future.

Project Objectives

The two objectives of this project were to:

- Learn GIS methodology that is being used in the field of precision agriculture
- Create a project prototype on a sample plot that can be used as a resource in student learning

Project Prototype

For a successful implementation of a precision agriculture project, it is essential to understand the interaction amongst the multiple factors that affect crop growth. The precision farming approach to crop production may be viewed as a four-step process (Figure 2). An initial step in this process is the spatial measurement of those factors that limit or otherwise affect crop production and yield outcomes. These variability data are then used to develop a management plan for the variable application of inputs such as fertilizers and herbicides. Inputs are applied through precision field operations. The farmer collects the consequential data for evaluation and finally, the effectiveness of the precision farming system is assessed with respect to economics and environmental impacts. This assessment becomes a part of the management/planning process for the next cropping season. Multiple iterations through the cycle allow for refinement of the precision management plan in succeeding seasons (Sudduth, 1999)

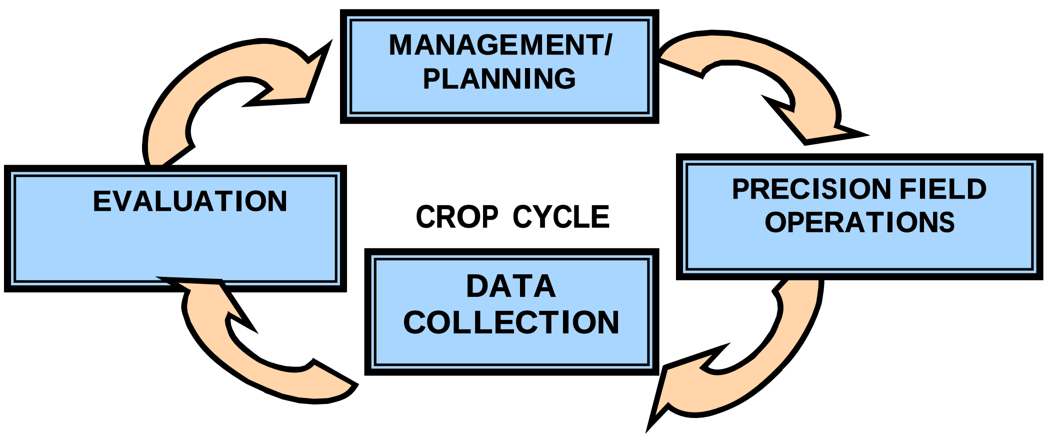

Figure 2: Precision Crop Cycle

A predictive model was used as a project prototype, these types of models are used to predict and correct the predictions over a period of time after additional data becomes available. In the case of crop growth a similar scenario occurs, after a yield is predicted based on the data available in one crop cycle, the model can be improved by obtaining more data that reflects the current needs of the crop. The model can be corrected over time to record the best objective function that yields maximum economical crop productivity. The model generates scenarios based on accurate site-specific variations in application of inputs to create yield maps for a soybean crop with the help of GIS/GPS technology. The project model was tested on an 80 acre plot[1] of land (Figure 3), using grid sampling method. Grid sampling is one of the methods of sampling in which soil information is collected from the field that is divided into square sections of about 2.5 acres in size. The project experimental plot was divided into equal grid cells (32 total) of 2.4 acres for sampling purposes, which was based on a typical soybean cropping system with low soil variability. Future crop cycles will incorporate the studies related with the *modifiable areal unit problem* (MAUP), which states that the relations between variables change with the selection of different areal units for sampling purposes, and that the analysis can be affected by the selection of areal units. After various input parameters including soil characteristics, land topography, crop needs, etc. were added to the model in the form of feature classes, objects (tables), and joined classes of a geodatabase, they were analyzed with various map algebra, spatial analyst and criterion weighting functions (available through extensions of ArcGIS). The resulting output maps revealed the deficiencies and yields at various locations on the experimental plot.

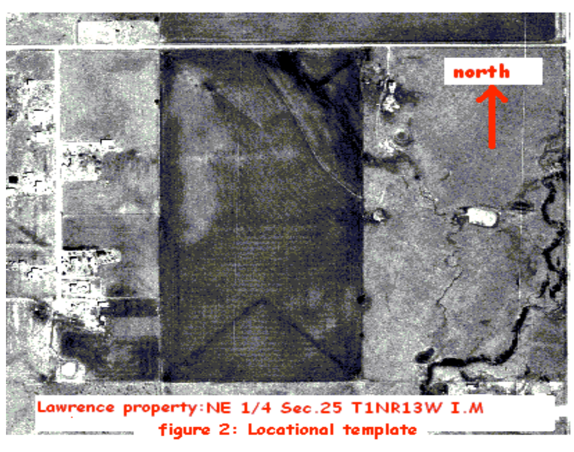

Figure 3: Experimental plot DOOQ

[1] Lawrence property is owned by the Cameron University Foundation and is located 4 miles south of Lee Blvd. on SW 82nd St. and 1 mile west. Legal description is NE 1/4 Sec. 25 T1N R13W I.M.

Following list details the tasks performed throughout the project timeline:

Task 1: Data Collection:

A. Topography

Field surveying was done using both, traditional and GPS tools. After identifying control points on the plot, the transit and cross staff helped measure elevations at various points within the grid cells, whereas GPS locations and their elevations were measured across the length and breadth of the plot to get a realistic topography for the field. The unit of measurement for traditional surveying was feet, whereas, GPS readings were recorded in meters.

B. Soil Mositure

Time-domain reflectometry (TDR) measuring techniques quickly and accurately determine soil volumetric water content in percentage. Approximately, 960 pieces of data from 32 cells were collected using a soil moisture meter.

C. Soil Test

Grid samples for 32 cells were collected and sent for soil testing. The results indicate pH, topsoil nitrogen, phosphorus, potassium, sulphur, calcium, magnesium, buffer index and organic matter (OM%) as well as interpretations and recommendations of the test.

D. Soil Compaction Test

The DICKEY-john Soil Compaction instrument is a simple penetrometer designed for farm use as an aid in soil management. It uses a 28 inch probe attached to a strain gauge that measures in pounds per square inch of force. When the probe is pushed into the ground the strain gauge reveals the force required for the depth of penetration. Deeper penetration by plant roots is usually highly desirable. A reading of 100 psi at a depth of 9 inches would indicate an uncompacted soil. Readings over 200 but less than 300 psi are fairly compacted but readings over 300 psi usually indicate poor root growth.

E. Harvest Yield

A Hege 125 combine harvester with a swath size of 4.5 ft. was used to collect yield samples from 32 cells on the experimental plot. The yield was measured in bushels/acre.

F. Miscellaneous (Rainfall, Fertilizers, Herbicides)

Since these factors were more or less uniformly distributed over the experimental plot, they were not used while studying the spatial variability for this project.

Task 2: Overlay:

The data obtained in Task 1 was overlaid on an aerial Orthoquad and a geodatabase structure was created using ESRI ArcGIS (Figure 4).

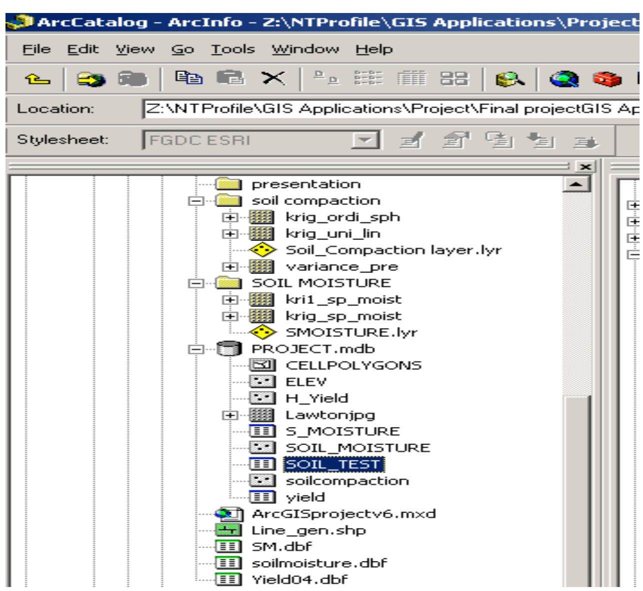

Figure 4: Geodatabase structure for the project

Task 3: Analysis:

A. Spatial analysis (Interpolation, Slope and Drainage)

B. Criteria weighting (Ranking)

C. Conditional Analysis

Raster based analyses were performed, since for an application such as this, the measurement of the spatial variability across the plot of land was important.

A) Spatial Analysis:

Spatial interpolation was performed on three data layers namely elevation, soil moisture and soil compaction. Since the elevation data was collected using a GPS that recorded the Z values inherently, an IDW algorithm in 3-D/spatial analyst extension was used to interpolate the values. An IDW algorithm was used because there was relatively less variation across the data points. Also, considering that near points are weighed more than the ones that are farther away helps calculate reasonably accurate values. The interpolated elevation data obtained gave an idea of the topography of the plot, which along with a TIN elevation model revealed the slope and drainage characteristics of the field (Figure 5). Although, the experiment did not incorporate any irrigation system for the first crop cycle, future cycles may see the benefit of the elevation data, when used in designing the irrigation system.

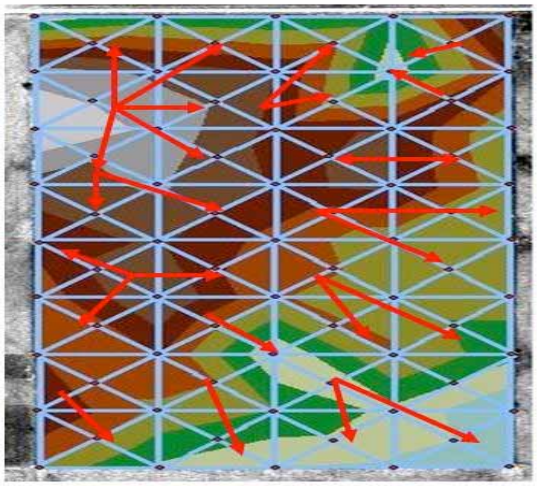

Figure 5. Drainage across the grid cells

A universal Kriging interpolation method was used to calculate the values for soil moisture and soil compaction. Kriging algorithm was used for two reasons, firstly there was a significant variation in the data obtained for these two layers, and secondly it incorporates some randomness in calculating the values, which was helpful especially for soil moisture data, considering that there were few unrecorded data points on the plot. A universal method was used because it assumes no knowledge of the dataset and assumes unknown trend through the calculation process of interpolated points.

As can be seen from Figure 6, the northeast and most of mid-west sections of the plot have good average penetration values (6-18 inches), beneficial for root growth, but also noting that most of the grid cells in the experimental plot showed poor penetration values (0-6 inches), which affects the plant development. Figure 7 shows the soil moisture across the plot, which is, except for some unrecorded points in south and south west at its average for soybean crop growth (15% - 45%)

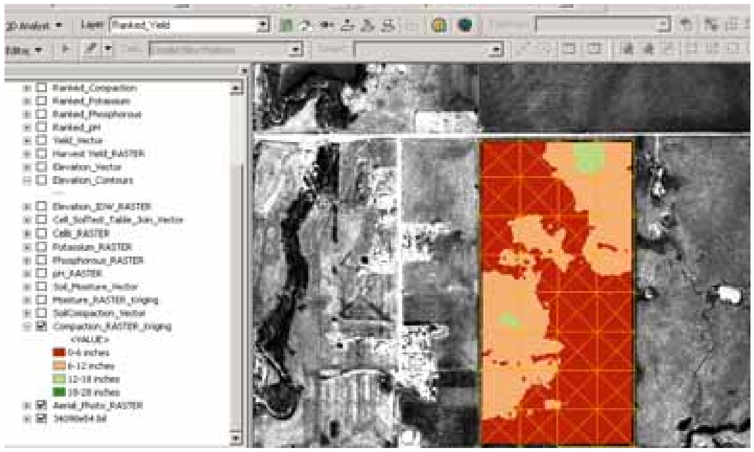

Figure 6. Universal Kriging Interpolation for soil compaction data

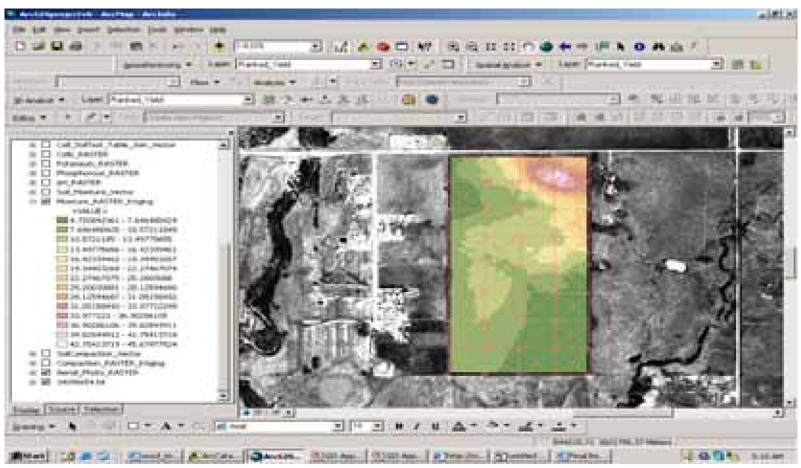

Figure 7. Universal Kriging Interpolation for soil moisture data

Before objective function or criteria was set, all the soil test data had to be converted as raster classes in the geodatabase. This was done using a *Join* function, since the soil test data was in a table format. A new raster polygon feature class was created that would facilitate the join and was used as a mask for creating the raster layers of K, P & Ph, from the table (Figures 8a, b, c.)

Figure 8a. Potassium 'K' variability

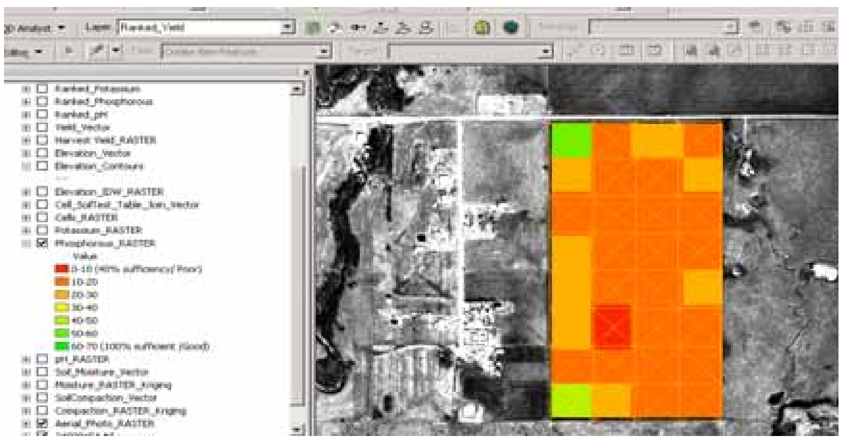

Figure 8b. Phosphorous 'P' variability

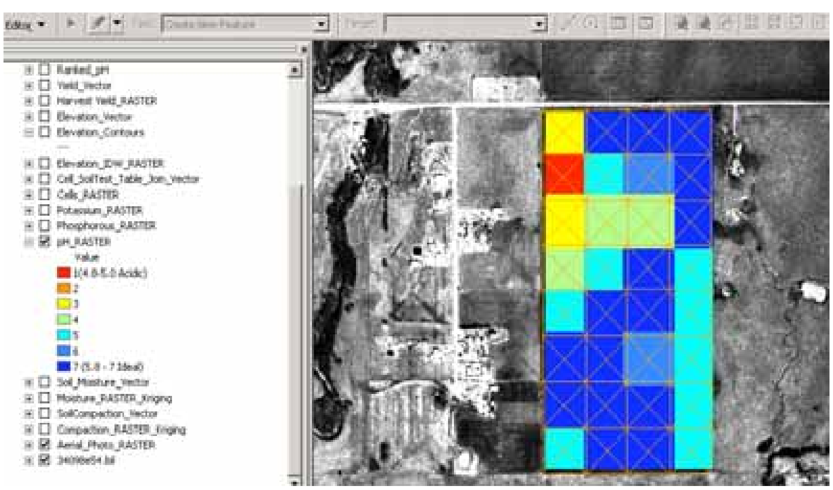

Figure 8c. pH variability

B) Criteria Weighting:

The objective function was selected to rank (Figure 9) the cells based on the following criteria a.) increase in yield, b.) pH between 5.8 – 7.0, c.) Phosphorous index near 65, d.) Potassium index near 250, e.) Penetration depth between 6 -12 inches, f.) Soil moisture VWC(Volumetric water content) closer to 50 %.

Of these, all except Potassium is a constraint to the objective function because of its excess and hence wastage, and is assigned a negative sign. Weighted ranks were calculated based on their importance (Straight Ranking: The most important = 1, Second important = 2, etc) revealing the ranks (Rank 1: Yield; 2: P; 3: pH; 4: Moisture; 5: Compaction; Rank 6: K). Overall cell rank was calculated using the Rank Sum procedure (Malczewski, 1999):

$$w_j = \frac{n - r_j + 1}{\Sigma (n - r_k + 1)}$$

where:

w_j is the normalized weight for the jth criteria

n is the number of criteria under consideration (k = 1, 2, . . . n)

r_j is the rank position of the criteria

After reclassifying and ranking all the raster layers that are part of the objective function, a raster overlay was done, which computed the total score on a cell by cell basis to reveal the cell rankings and hence the location on the plot that is closer to the objective function (optimal productivity) (Figure 10).

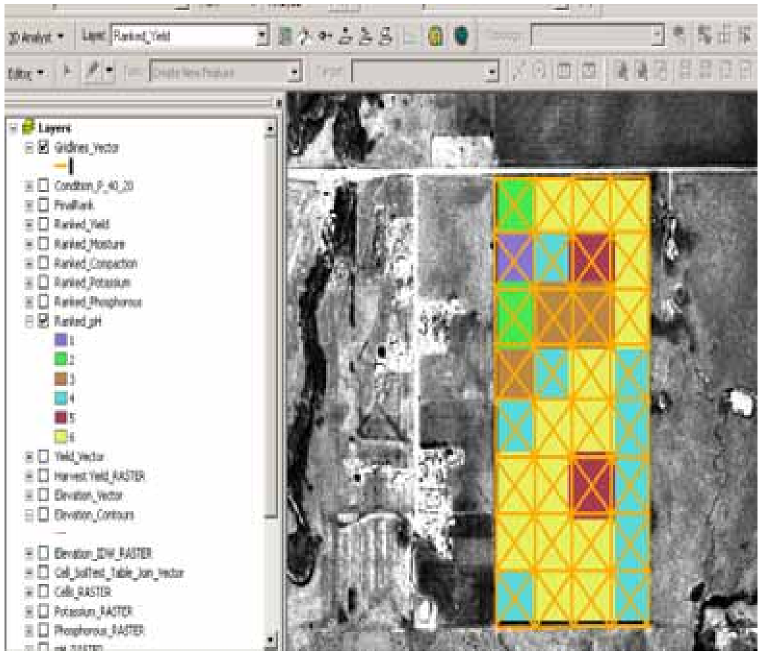

Figure 9. Example: Ranked pH

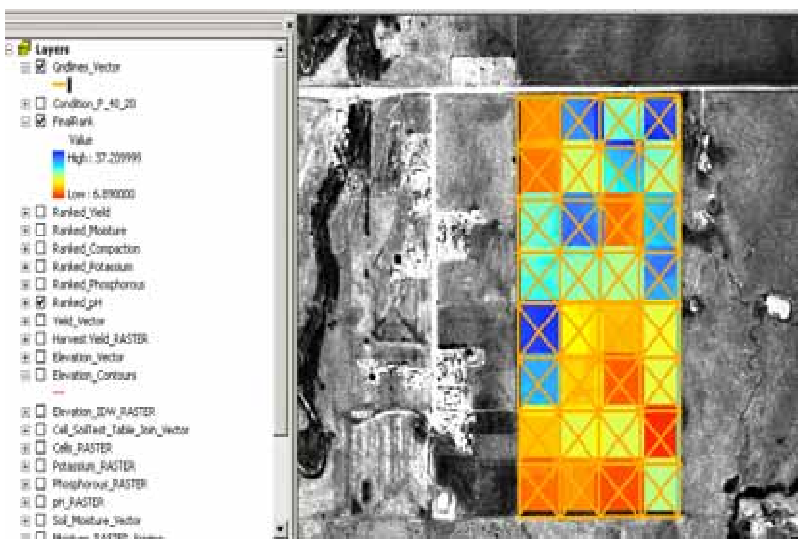

Figure 10. Overall Cell Ranks

C) Conditional Analysis:

Conditional analysis was performed to help the user identify requirements of the plot. This was done to give some kind of feedback to the user, as to what needed to be done if a particular location was deficient in certain input parameter. As an example, a conditional function was used that created a layer with certain cells having values of 30 lbs/acre and other cells with 0 lbs/acre, where 30 lbs/acre reveals the amount of phosphorous that needs to be input at the highlighted cell locations. This was a suggested dosage of phosphorous, if the soil sufficiency level for phosphorous (as revealed in soil test) was between 20 and 40. (Figure 11) (Zhang *et al.,* 2004*)*

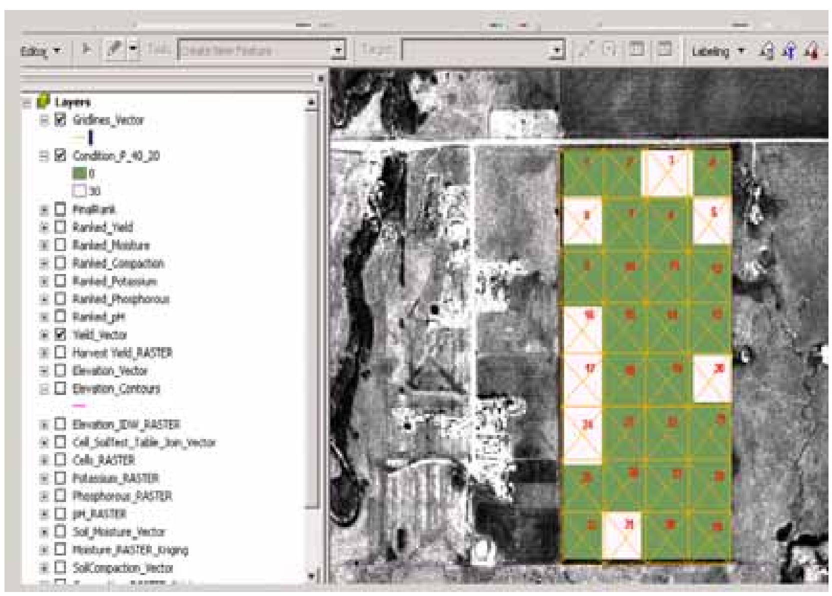

Figure 11. Conditional Function 20<Pindex < 40

Conclusions

1. Based on the interpolated maps that reveal the variability of data, the algorithms worked well in all the cases (except Kriging for soil moisture). When known points were deselected and interpolation algorithms applied to the selection, the known points were interpolated quite accurately. The soil moisture data was missing from 9 cells out of 32, and hence Kriging algorithm found the interpolated values with some degree of error. To downplay this error, soil moisture weightage during the ranking for criteria analysis was reduced to rank 4 out of 6 criteria.
2. Based on the overall rankings map, range: 6.89 -37.20 (Figure 10) the cells (counted from 1 to 32 from NW to SW corners of the plot in a 'serpentine' pattern) that were ranked low had poor scores towards the objective function. The best scored cells 4 and 17 were optimal and an effort to bring other cells to the same level by comparing the characteristics of optimal cells would be beneficial for higher productivity in those poorly performing cells.
3. Thus, the yield alone did not matter for a better score of a cell, but a collective parameter score helped certain cells reach optimal productivity (cells 10: *pH deficient* and 24: *Phosphorous deficient*)
4. A basis for time series analysis and cell statistics was laid because of the rankings of the individual cells. Thus, with each of the subsequent crop cycle, a similar ranking technique can be employed to measure the improvements of the deficient cell locations from the previous cycle.

5. A Yield map depicting harvest yield in bushels/acre along with a 3-D ArcScene rendering (Figure 12 and 13) helps the user get a visual display of the yield across the plot.

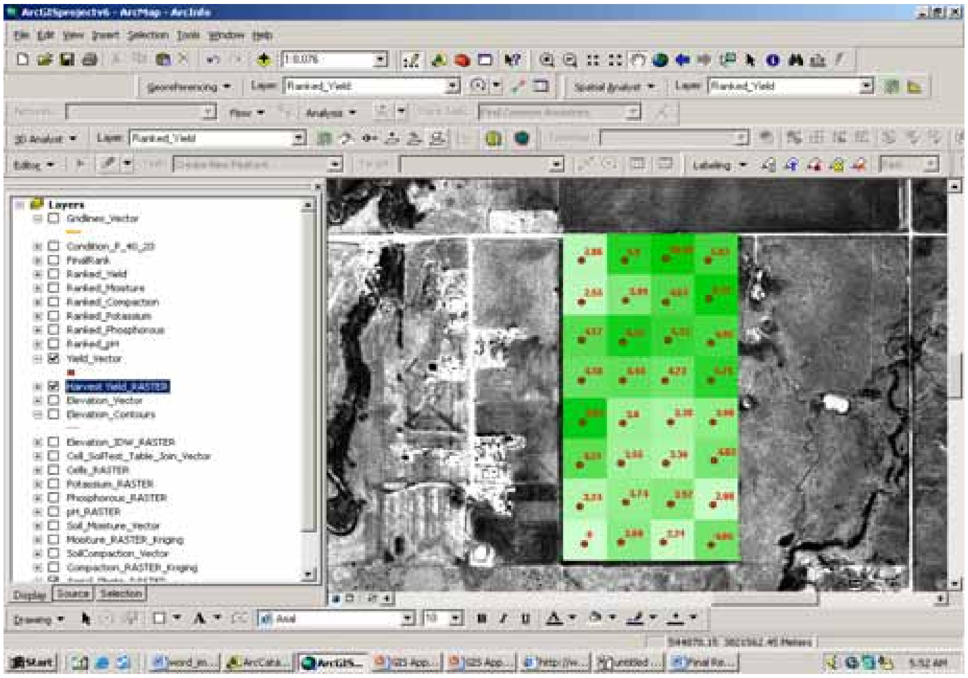

Figure 12. Yield Map

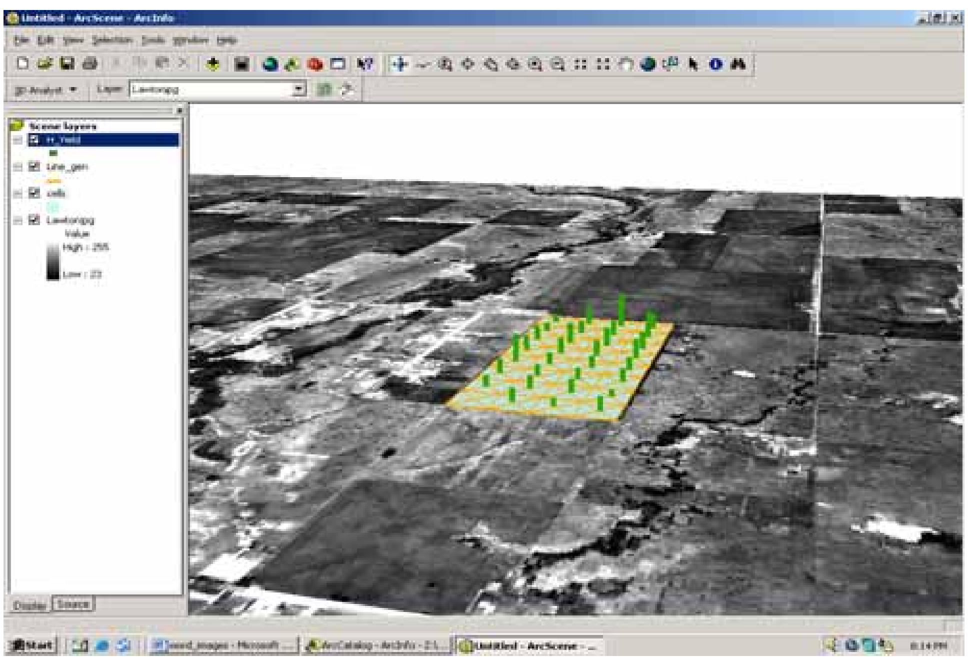

Figure 13. Yield Map in ArcScene

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