Precision Farming Data Management Using Geographic Information Systems

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Abstract
Agricultural ecosystems are inherently variable entities. To manage spatial variability, modern farmers are looking for advanced technological solutions. Management strategies incorporating remote sensing, the Global Positioning System (GPS), and variable rate treatment (VRT) offer the possibility of positioning inputs exactly in order to optimize farm returns and minimize chemical inputs and environmental hazards. The use of geographic information systems (GIS) is essential for such a management paradigm. This paper introduces the concept of precision farming and discusses the role of GIS as a centralized data management and analysis tool. Results from a survey of the use of GIS in precision farming are included in order to determine strengths and weaknesses of the technology and to provide impetus for improvements in GIS to support agricultural applications.

Introduction
Innovative agricultural techniques known as site-specific farming, prescription farming, or precision farming, the term to be used in the remainder of this paper, apply a combination of new technologies to improve production and reduce environmental pollution. Taking advantage of recent developments including the Global Positioning System (GPS), remote sensing, geographic information systems (GIS) and variable rate treatment (VRT), precision farming is used to manage spatial variability in fields through determination of spatially referenced inputs, such as nutrients which affect soil fertility and chemical applications which control insect and weed pests (Chancellor and Goronea, 1994). The result is optimized production with minimum inputs of chemicals and a corresponding minimum impact on the environment. The precision farming approach has been used in the U.S. Midwest to measure yield variations in wheat and corn (Pringle *et al.*, 1993) while the National Environmentally Sound Production Agriculture Laboratory (NESPAL) in Georgia has developed technology for making similar yield measurements for peanuts and cotton in the Southeast. The potential to use GIS to integrate the various types of information needed to manage and control crop production on a site-specific or within-field approach is rapidly being researched and developed (Schueller, 1992). The potential benefit of the integration of these technologies to improve agricultural production while simultaneously reducing environmental degradation may be one of the greatest contributions of GIS to human populations.

It is the purpose of this paper to explore GIS as a tool for integration and analysis of precision farming data and to present a brief survey of the use of GIS in precision-farming research and applications. The next section of this paper provides a brief review of developments in the major technologies associated with precision farming, i.e., GPS, continuous-yield sensors, remote sensing, VRT, and GIS. The third section provides an examination of GIS as the hub of precision-farming data management and analysis as being implemented by the authors and others at NESPAL. The fourth section presents results of a questionnaire survey of precision-farming researchers and practitioners concerning their use of GIS, its strengths and its weaknesses. The final section draws conclusions concerning precision-farming applications of GIS and presents areas for future work by GIS researchers to better serve this growing application area.

Precision Farming
Ideas of within-field variability, which are the basis of precision farming, surfaced as early as 1929 with approaches to measuring the spatial variability of soil acidity (Linsley and Bauer, 1929). The modern manifestation of the concept is a result of environmental awareness and economically viable technological innovations which allow global positioning, precision application of variable inputs, and measurement of variable yields (Goering, 1993). Precision farming can be represented as incorporating three main areas of management (Figure 1). Data pertaining to yield and potential yield-affecting factors are initially collected. These data are then analyzed to determine whether or not yield is affected by the factors studied. If yield is being affected, a farm manager decides the type, distribution, and amount of treatment to apply. Remedial measures can then be undertaken in such a way that the correct treatment is applied at the required rate and to the appropriate area within a field. Evaluation of treatment effects can then begin and this essentially brings the manager back to the start of the cycle. Economic analysis of treatment measures and yields is critical to successful management. Variable application of inputs may not increase yields but simply hold them constant while reducing input costs. Thus, the farmer reaps increased profit through better management and application of less chemical treatment which also helps preserve the environment. An immense volume of information is collected and interpreted during

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Figure 1. The conceptual components of precision farming.

this process. If this management method is to be successful, a suitable data storage, analysis, and decision support system must be implemented.

Key Technologies
Technologies that have advanced the introduction of precision farming include GPS, continuous data sensors, remote sensing, VRT, and GIS. Each of these technologies is briefly examined below.

GPS
Location expressed in geographic coordinates — latitude and longitude — can be determined with GPS to accuracies better than ± 100 m. By using a known base source position and signal, differential positioning (DGPS) can attain accuracies in real time of ± 1 m and with sufficient time — several minutes to several hours at a collection point — accuracies of a few centimetres are attainable. Precision farming has many operations that rely on immediate and precise knowledge of field location and DGPS is an ideal approach to acquiring that knowledge. For example, to link VRT of fertility to a desired geo-referenced fertilizer application map, the operator must know field location and map location simultaneously. From the map location the operator can identify the correct application rate for the current field position (Delcourt and Baerdemaker, 1994). Similarly, spatially variable treatments have been tested for control of pests from pest maps (Schueller and Wang, 1994a). Yield mapping combines the accurate location information of DGPS with the results of a variable-flow rate (yield) sensor. The resulting yield-variability map can then be used to spatially locate high- and low-yielding areas of managerial interest for further investigation (Aurenhammer *et al.*, 1994).

Data Collection
Precision farming relies on the collection of geo-referenced environmental data to provide relevant information for use in management planning. Direct field attribute measurement and remote sensing are the two most common forms of data collection. Although direct measurement techniques are very accurate, their cost and intense labor requirements may restrict the precision of sampling. For example, the manual grid soil sampling of a field to determine spatial variability of fertility is both costly and time consuming and the sample analysis results may take days to return. In an effort to reduce the cost of obtaining spatially referenced data and at the same time increase data resolution, farmers are turning to continuous measurement techniques and remote sensing for more accurate within-field variability information.

Continuous-Yield Sensors
The development of continuous-yield sensors and their subsequent linking to DGPS-provided location information has been perhaps the most important and influential development in precision farming data collection. Yield rates which vary spatially require different sensing techniques depending on the type of crop being monitored. The greatest progress has been achieved with grain flow measurements for corn and wheat (Schueller and Bae, 1987; Searcy *et al.*, 1989; Pang and Zoreb, 1990; Schueller and Wang, 1994a; Guitjens, 1992). Continuous sensors for cotton yields have been tested by Hunsaker (1992) and Wilkerson *et al.* (1994). Recently, personnel from NESPAL developed and tested sensors for measuring yield variation in peanuts (Figure 2) and tested commercial grain flow monitors in low-yielding conditions in Australia (Figure 3). Maps produced from these systems are hardcopy evidence of the degree of within-field variability. The magnitude of this variability is a good indication of the suitability of implementing a spatially variable management plan.

Remote Sensing
Remote sensing of environmental factors important to crop growth, both from long range, such as aerial photography and satellite images, and short range, such as ground-penetrating radar (GPR) and electromagnetic induction, provide accurate information of field variability with geopositioning. The ability to collect a large amount of data rapidly and cheaply fits with precision farming requirements. Examples of long-range sensing include determination of soil type variability from aerial photographs to estimate spatial relations of soil fertility (Gerberman *et al.*, 1988), detecting soil surface conditions with multispectral video (Everitt *et al.*, 1989), use of aerial video images to identify vegetal condition and discriminate between crop and weed species (Nixon *et al.*, 1985; Richardson *et al.*, 1985; Everitt *et al.*, 1992; Brown *et al.*, 1994), and detection of plant stress and insect infestation from video images (Everitt and Nixon, 1986; Everitt *et al.*, 1994). Short-range sensing with GPR has been used to measure soil characteristics such as location and attributes of hardpans in clay soils (Raper *et al.*, 1990) and depth to bedrock (Schellentrager and Doolittle, 1991). Electromagnetic induction is a short-range sensor used to determine soil conductivity, and to estimate salt content, soil texture, water content, and yield potential across the field (Kachanoski *et al.*, 1988; Suddeth *et al.*, 1994).

VRT
Variable rate treatment provides the precision farmer with the ability to accept information pertaining to within-field variability and plan management operations to best release the potential of a field. Examples where VRTs have been implemented include the use of multiple flow-rate fertilizer spreaders that vary application across the field to match the local requirements and the management of weeds with flow-rate controlled sprayers to match previously collected weed incidence maps. VRT herbicide applicators have been developed by Shearer and Jones (1991) and sprayer design examined by Schueller and Wang (1994b).

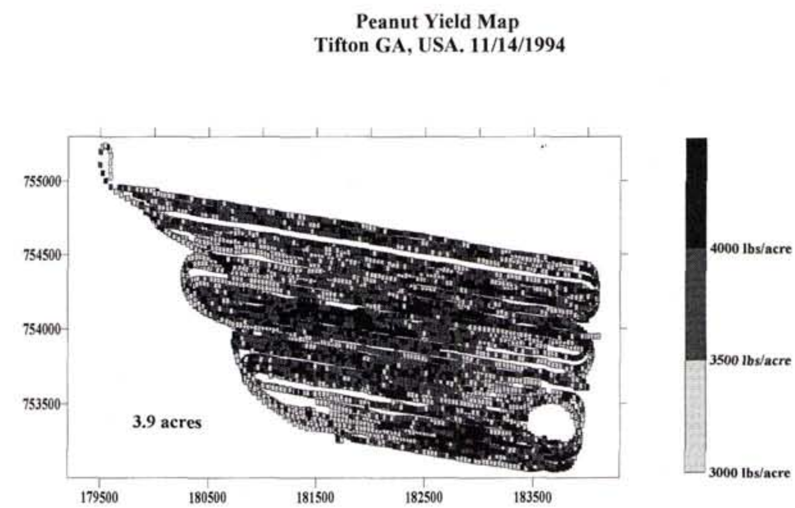

Figure 2. Variable peanut yield map constructed from data gathered with yield sensors and GPS.

GIS

The use of GIS in farm related matters is not new. GIS techniques have been used for agricultural management in many areas but primarily on a whole-field approach, that is, management by application of fertility and pest-control inputs by an average value for an entire field. For example, Wylie *et al.* (1994) used a GIS combined with a nitrate-leaching modeling package to describe the distribution of leached nitrates in groundwater. Everitt *et al.* (1994) used GIS to develop a map of blackfly infestations of citrus crops in southern Texas. A street map from U.S. Census Bureau Topologically Integrated Geographic Encoding and Referencing (TIGER) files was combined in the Atlas*GIS software with GPS locations of the citrus blackfly locations. In attempts at weed eradication, Lass and Callihan (1993) and Prather and Callihan (1993) recorded weed-infested areas in a GIS with data from U.S. Geological Survey topographic maps to development management areas by treatment methods and environmental and health requirements for controlled spraying. Wilson *et al.* (1993) coupled GIS with models of weed control to determine groundwater pollution by herbicides. Swindell (1995) used GIS along with GPS to study data quality and generate yield-surface maps.

Schueller (1992) presents a case for using a GIS as the hub of an integrated system for precision-farming data management. Such a model is a logical choice because of the data management and integrating capabilities of GIS. Increased implementation of continuous-data collection techniques and remote sensing coupled with new applications of these technologies could rapidly lead to information overload. Several companies have recognized the unique ability of GIS to organize these types of information and present them in a form useful for management decisions and have begun to develop GIS software to specifically support the precision farming application. Examples of these software packages include SOILECTION™ from Ag Chem (1994) of Minnetonka, Minnesota, for VRT planning and control; CROP-SIGHT™ from Applications Mapping (1994) of Frankfort, Illinois, which has GIS layering capabilities and can associate farming records such as seed type, equipment use, weather conditions, and fertilizer; and the VISION SYSTEM™ from Rockwell (1994) which is a whole-farm multiseason GIS capable of data collection, presentation for management assistance, and map generation to control VRT equipment.

GIS Data Management Approach

As suggested by Schueller (1992), GIS is the logical hub for precision-farming data management. At NESPAL, GIS forms the core of three activities: data collection, data analysis and decision-making, and variable application treatment (Figure 4). While the process is cyclic with the output of one crop season used as the input to the next season, some variables are monitored and controlled within a single season. For example, several photographic missions may be used to measure weed infestation and results of herbicide applications within a single crop season, whereas the final yield will be measured at harvest to provide data for analysis and prediction to help determine nutrient and pest control inputs for the next season.

Data Collection

For precision farming, the GIS database must consist of many layers of spatial data, each of which has precise control of ground position in the field. Among the layers are physically measured inputs such as field boundaries, slope and aspect of the terrain, water content, particle size distribution, rooting volume, and drainage. While some of these inputs can be interpreted from soil maps, conventional soil survey maps from the Soil Conservation Service are not accurate enough for precision farming, thus requiring intensive soil sampling and soil map generation for each field to be managed. Layers with chemical inputs such as nutrient levels, cation exchange capacity, pH, salinity, pollution potential, and plant tissue element levels are also collected but all with a cost. Measured biological data may include layers of yield quantity,

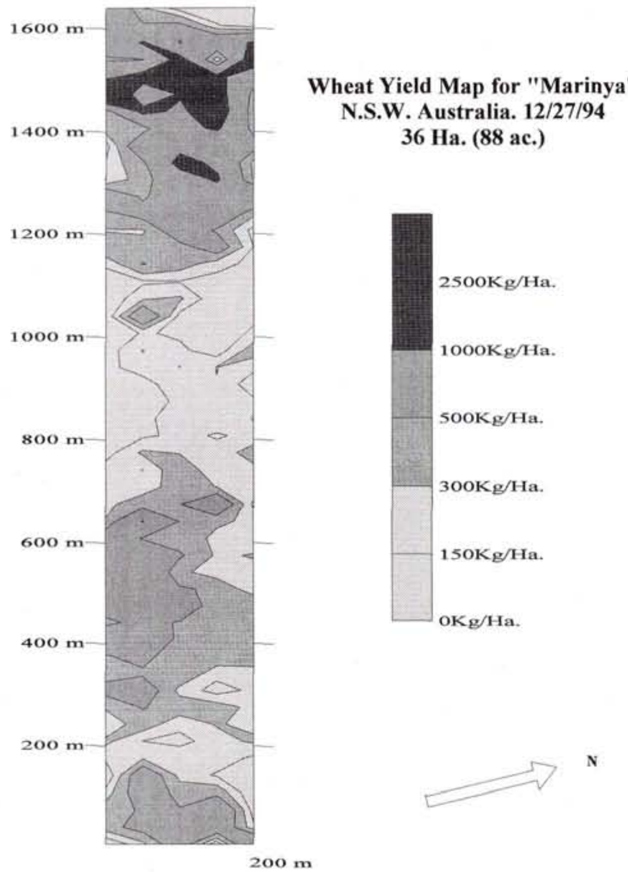

Figure 3. Variable yield of wheat from a field in New South Wales, Australia.

yield quality, disease distribution, insect distribution, weed distribution, and organic matter content.

Data Analysis and Decision-Making

Data manipulation includes rectification functions to correct the geometry of the digital image data such as scanned aerial photography and digital video images. To aid image interpretation, both spatial and spectral enhancement are performed. Classification of the digital images, using statistical classifiers, in both supervised and unsupervised modes yields information on weed or insect infestations, soil types, vegetation types, and plant stress.

Visualization of images, including multiple image display and linking, allows NESPAL scientists, including ecologists, agro-economists, consultants, state extension agents, and others, to use their discipline-specific knowledge and unique human abilities to spot important data characteristics. It also provides a well-defined and appropriate tool to link these sciences for a better understanding of the complex biological systems. Using GIS analytical functions such as Boolean overlay, cluster analysis, clumping functions, reclassification, indexing, and spatial searching, analysts can create new data layers which reflect particular characteristics deemed to be important.

Modeling capability, including expert systems, linear programming, and statistical and economic tools, allows scientists and consultants to develop decisions concerning application of inputs and effects on yields. Development of spatial models allows eventual production of maps of fertility and pests which are used to drive VRT applications. The models include raster, vector, and tabular data, as well as scalars, matrices, and a variety of analytical functions from simple arithmetic to eigenvalues and principal components. Developing landscape assessments requires examining areas broader than the field itself. The GIS modeling functions are used to develop pollution and habitat models and to integrate these with the GIS data layers.

The precise positioning of the data layers allows an analyst using GIS to determine locational coincidence among the yield rates and the various fertility and pest-control inputs. The locational coincidence can then be used to create maps which guide VRT applicators to enhance production and reduce investment. For some inputs and yield measurements resulting in VRT, the process is cyclic, using the yield maps from one crop season as input with the fertilizer, pesticide, herbicide, and soil fertility from the GIS to predict required inputs to increase yields for the next crop season.

Data Management

As shown in Figure 4, GIS provides the capability to integrate diverse datasets, but, because precision farming requires data of many different types from different sources, a process is needed to insure compatibility of the various data sources. One approach being used at NESPAL concentrates on four data aspects: control, sampling, resolution, and generalization.

Control

Because location in the field is the key to precision farming data management, each collected data set must be precisely registered to a standard set of control. The approach is to establish ground control points (GCPs) within each field and to use these GCPs to establish the locational coordinates for each data layer gathered. The GCPs are established by precise DGPS techniques to a horizontal and vertical accuracy ≤ 0.1 m. A minimum number of GCPs are determined based on field size and shape with an absolute minimum of four points. The GCPs are targeted to appear in all aerial photographs and video images. The GCPs form the starting point for units using on-the-go DGPS determination.

Sampling

Once established, the GCPs are used by all NESPAL scientists to collect precise data which are introduced into the common GIS database. While the GCPs account for locational correspondence among data layers, other factors such as precision of the collected data and variable types and rates of data can introduce inaccuracy. To facilitate management, standard sampling methods are being developed to insure that point data collected for one layer can be effectively combined with point data from another layer. Interpolation is critical but only produces results adequate for overlay in a GIS if the original samples are representative. For data requiring random samples over a field, a procedure called systematic stratified unaligned random sampling is used (Berry and Baker, 1968; Congalton, 1988; Wollenhaupt *et al.*, 1994). This procedure has been demonstrated to maintain systematic coverage of a target area while providing randomness in subareas, allowing statistical testing to be used.

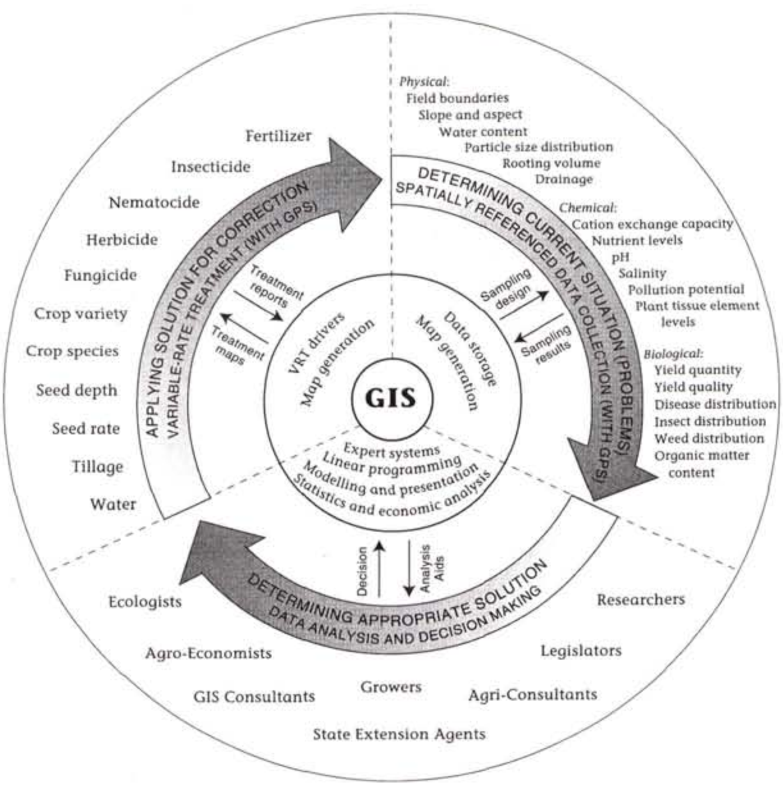

Figure 4. The components of precision farming organized with a GIS as a central hub and GPS as the correlating base for geographic reference.

Resolution

The resolution of data collection for different data types is established to facilitate data management and analysis. Ultimately, the resolution is a product of the crop being managed, but various types require different scales of analysis. For example, insect pests may cause crop damage with small infestations while, to cause equivalent damage, weed pests or soil infertility may need to cover much larger areas. Collecting the data at the appropriate resolution facilitates use in the GIS in which all data layers are eventually reconciled to a common resolution.

Generalization

Many of the data layers are collected on a grid or raster pattern. These datasets are directly used in raster-based GIS software requiring only resampling to a common raster cell size. The layers are maintained in their initial form for manipulation and analysis. Other data, such as point samples, are entered directly in vector-based GIS software, but are interpolated to provide correspondence with the raster data model. While the interpolated data are used in some analysis and presentation procedures, the original points are maintained in the GIS databases. Data collected as lines of attribute or response values, such as yield rates, also require interpolation to yield raster cells matching the other datasets. Data collected by interpretation of aerial photographs require digitizing and processing to convert to a raster format. In essence, all datasets undergo transformation to support analysis in a GIS in raster or vector formats, and conversion between the forms is essential.

Integrating Precision Farming Data Using Commercial Software

At NESPAL data integration is managed through application of standard functions in commercially available GIS software. The GIS software must be suited to a wide range of users, permitting the precision-farming specialists to interact with the system and analyze their own data. To assess the applicability of generic GIS software packages to precision-farming needs, a study was conducted.

This study consisted of a survey of precision-farming workers. One hundred and eighty questionnaires were mailed to individuals across the U.S. based on a mailing list compiled from past precision-farming conferences. All surveys were sent with a cover letter, instructions, and a stamped return envelope. The survey was written in two sections, one section for those who use a GIS and one for those who don't. The survey comprised a variety of short answer and multiple choice questions. A copy of the survey is available from the authors.

Of the 180 questionnaires mailed, 82 were returned. Of these, eight were unread because of relocation of the intended recipients. Of the remaining 74, a further 13 were determined to have been received from individuals outside of the target field and were disregarded. Thus, a total of 61 valid survey responses from 18 different states was received. Of the respondents, 82 percent are researchers, defined as

TABLE 1. SOFTWARE PACKAGES USED FOR PRECISION FARMING

Software Package	Percentage of Respondents
GIS Software	
Arc/Info	37
GRASS	20
Idrisi	17
MapInfo	13
Non-GIS Software	
Surfer	36
Sigma-Plot	29
SAS	50
Other	57

people primarily engaged in investigating improvements in agricultural methods and production, 3 percent are farmers, 10 percent are suppliers of equipment or software, and 16 percent are involved in some other way with precision farming. These percentages do not total to 100 percent because several researchers also consider themselves to be involved in precision-farming activities other than research. Because the majority of responses came from researchers, it was decided that this group would be made the focus of the analysis. The percentage time spent by the respondent researchers in precision farming-related research ranges from 2 percent to 100 percent with an average of 32 percent. Precision farming is still a relatively small field of research despite rapid growth over the past few years. It is probably reasonable to assume that 52 researchers from 18 states comprises a representative sample of all researchers in the field. Tables 1 through 4 summarize responses to the questionnaire.

GIS Users

Three-fifths of the respondents utilize GIS in their research. These researchers spend roughly double the amount of time (40 percent) than non-GIS users spend on precision farming research (18 percent). The GIS software packages in use vary greatly. By far the most prevalent is Arc/Info with 37 percent of respondents listing this as one of the packages used. Next most prevalent is GRASS (20 percent) followed by IDRISI (17 percent) and MapInfo (13 percent) (Table 1). Other products used include PC_MAPS (Texas A&M), EPPL7 (University of Minnesota), MapsII, Arcview2, FIS (University of Illinois), Grouper (Soil Teq), SGIS (AG Chem), and ERDAS Imagine. By far the most widely used operating system is MS-DOS (77 percent) followed by Unix (33 percent), OS/2 (20 percent), and Macintosh operating systems (10 percent).

GIS are currently used mostly for soil parameter mapping and yield mapping (Table 2). It is rare that a GIS is utilized for only one purpose. In 89 percent of cases, researchers indicated that they use GIS to map more than one factor within a field. This is perhaps to be expected because researchers often seek correlation and coincidence among observed factors. Only 59 percent of respondents, however, indicated that they performed correlation analysis between maps of different factors. This large discrepancy may indicate that the GIS used does not have the ability to correlate different factors. It may also indicate that, if the GIS is capable of performing this operation, the researcher has not yet been able to fully utilize this option.

Forty-six percent of respondent researchers use their GIS to perform advanced statistical analysis on their data. For a research community this is a low percentage and may indicate a shortcoming in many of the GIS packages used. Alternatively, it may be indicative of the newness of this research or a tendency for researchers to perform statistical analysis outside the GIS environment. Many researchers may simply not be cognizant of the features available to them in their GIS beyond the simpler functions. Nearly half of the respondents suggested forms of statistics that they would like to see incorporated into their GIS. The desire for kriging-related geostatistics was highly prevalent. Statistical tests to perform multivariate analysis, linking yield response to other measured factors, was also an obvious priority. Other requirements include trend analysis, clustering, principal components analysis, and fuzzy-logic statistics as well as such simple statistical tests as t-tests and F-tests. Obviously, there is concern among the research community that the statistical functions currently available to them in GIS packages are inadequate.

A GIS which incorporates and manipulates data in real time would be useful for instantaneous viewing of results because data are gathered in the field. It would also be required for instantaneous application of amendments in response to gathered site data. Only 17 percent of the respondents are using a GIS capable of performing real-time manipulations. For most research applications it is probable that post-processed data are quite adequate. For some of the spatial-relationship research, linking factors which cannot be measured simultaneously requires post-processing. However, 48 percent of researchers do consider that incorporation and manipulation of data in real time is necessary (Table 2). There is probably some conflict between responses dealing with fundamental agronomic research and responses related more directly to applied precision-farming research in this answer. The lack of sensors reliable enough to be used in real-time treatment is probably another reason for the lack of appreciation for this feature; however, the future in pest management appears to be in real-time sensing and treatment.

Incorporation of some form of economic analysis was regarded, almost unanimously, as essential for precision-farming purposes (Table 2). Again, however, practice is lagging behind the theory, probably a result of the early stage of VRT, and only 36 percent of the respondents have actually attempted incorporation of economics into their GIS applications.

Despite apparent deficiencies in current GIS, more than 75 percent of the respondents scored their GIS a 3 or above on a suitability scale of 0 to 5 (Table 3). There was much less satisfaction in terms of user-friendliness of GIS software,

TABLE 2. SUMMARY OF QUESTIONNAIRE RESPONSES

	Percentage of Respondents	
Software Use	GIS-Users	Non-GIS Users
Yield Mapping	75	92
Soil Parameter Mapping	89	75
Insect/Weed Mapping	39	17
Aspect/Elevation Mapping	43	33
Correlation of Data Layers	14	42
Real-Time Analysis	17	8
Advanced Statistics	46	–
Economic Analysis	36	–
GIS Software Needs		
Real-Time Analysis	48	46
Economic Analysis	96	–

TABLE 3. SUITABILITY AND USER-FRIENDLINESS OF GIS

Low	0	1	2	3	4	5	High
GIS Suitability	0	7	15	30	30	18	
GIS User-Friendliness	10	10	21	21	28	10	

although there are obviously systems available which are very friendly. Among the respondents, Arc/Info was viewed as the system considered most unfriendly. No single package was viewed as being particularly user-friendly, although Macintosh and Windows-based systems fared best.

There appears to be quite some variability in the expectations of useful lifetimes of current GIS (Table 4). Nearly 50 percent of researchers think that their systems are already obsolete or will be within two years. Thirty-two percent of researchers said their GIS will not become obsolete in the immediate future (within two years) and 19 percent were unable to say. This variability is probably to be expected, given the different aims and GIS of the respondents. It is striking that nearly a third of researchers believe that their GIS is *already* inadequate for their needs.

A major concern communicated about GIS is the complexity of most of the GIS software. There are many functions on the large GIS packages which are superfluous for precision-farming work and hence only contribute to complexity and result in user confusion. Ease of use is also a major concern. Some of the smaller customized packages in use had much better reviews with respect to ease of use. One respondent stated another major concern: "[it is] difficult for end-users to perform complex analysis with real understanding. Knowledge of theory and principles of GIS is required for real agility with the software to be acquired."

Lack of a soils database at a scale appropriate for precision farming is another problem. This particular concern probably holds for most of the yield-determining factors within a field. Other failings recorded repeatedly included difficulties in interfacing particular GIS data with other systems, slow speed, lack of statistics, high cost, and long training time.

Positive features of GIS for use with precision-farming research varied with the particular GIS used. There were, however, a number of recurring positive general features. The mapping abilities of most GIS are highly valued, as are layering and overlay features. A good user interface and compatibility with other software and databases is highly prized as is the ability to perform statistical and economic analysis.

Non-GIS Users

Over a third of the respondent researchers do not use a GIS in their work. A summary of the statistics from these respondents is also listed in Table 2. These researchers spend, on average, only half the time that the GIS-using researchers spend on precision-farming work. The majority of these respondents use some form of computer-generated maps to view or analyze their spatially referenced data. The two most often used pieces of software for this purpose are SAS (used by 56 percent of researchers) and Sigma-plot (33 percent) (Table 1). A variety of other software is also used, including Systat, various spreadsheets, Agrilogic, GS+, neural-net software, and custom software. All respondents use MS-DOS as an operating system although in two cases other systems are used as well (OS/2 and VMS).

The work of this group of researchers is concentrated in yield mapping and soil parameter mapping (Table 2). There is less tendency to perform correlations between mapped parameters. This is partly due to the more specialized nature of the work of certain of these respondents who were looking at relationships within map layers rather than between layers. In general, however, this group of researchers is less advanced in precision-farming research relative to their GIS-using counterparts. If they do expand their research in the area, it would be expected that they will need to use a GIS. Virtually all of the respondents indicated that they would need to use a GIS in the future.

About 70 percent of the non-GIS software used scored a three or above in terms of suitability to researchers aims (Table 3). This contrasts with the higher suitability ranking of GIS by GIS users. This was not expected given that the non-GIS software has generally been in use for a much greater period of time with a much less specialized market and much more development. This probably bears witness to the great potential for GIS in this field. There were not great differences in the perceptions of potential obsolescence of software used between the GIS and non-GIS groups.

Only one researcher used real time manipulation of data, although a similar proportion to that of the GIS-user group thought that it was necessary for precision farming. Almost all of the researchers who do not use GIS have considered using it at one time or another. The most common reasons for not using GIS are high start-up costs and the steep learning curve.

Conclusions

Precision farming, with its potential to simultaneously increase crop yields and reduce environmental pollution, is rapidly expanding in both research and production agriculture. As this expansion occurs, GIS will become more integrated as a data management and analysis tool for agricultural applications. Placing the GIS at the center of the process provides the advantage of a single database and data management system. To succeed, a precision-farming GIS application must include precise geographic positioning for all data layers and ground control for all image sources and on-the-go coordinate measurements. A logical approach is to target ground control points in a field and use them as references for all data collected. DGPS provides the needed accuracies and the capabilities for both static and dynamic measurement of coordinates associated with precision-farming variables. Integrating the DGPS-collected information with GIS allows the necessary manipulation and analysis to support generation of farm-management decisions and digital maps which can be used to drive VRT sprayers and other equipment.

From the questionnaire survey, one may conclude that GIS are currently an integral and indispensable part of precision farming. GIS are widely used through much of the U.S.A. for precision-farming research. Almost all respondents either use a GIS or believe that they will in the future. It is

TABLE 4. SOFTWARE OBSOLESCENCE IN THE NEAR FUTURE

	GIS-Users	Non-GIS Users
No	16	23
Already	29	31
Within one year	10	8
Within two years	10	8
After two years	16	15
Unable to say	19	15

also readily apparent that significant development must occur and experience must accrue before precision-farming research and data management using GIS are successful applications. Suggestions for improvement in GIS were not lacking in responses. Better user interfaces, more statistical and economic functions, less complexity, incorporation of models, better database resources, real-time linkage with positioning systems, and faster operation speeds are seen as priority improvements in GIS. The ability for a GIS to incorporate economic data is considered essential, while advanced statistical functions and real-time data manipulation abilities are considered highly desirable. It is probably fair to say that, as a result of problems associated with GIS, few researchers have fully utilized the potential. A more complete utilization of GIS appears to be essential for a successful precision-farming operation and is likely to occur as a result of the use of GPS to link the GIS data layers.

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