The Role of Precision Agriculture in Cropping Systems

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SUMMARY. Precision agriculture is a new and developing discipline that incorporates advanced technologies to enhance the efficiency of farm inputs in a profitable and environmentally sensible manner. Yield monitoring and variable rate application are the most widely used precision technologies. Versatile guidance systems utilizing the global positioning system (GPS) and management zone approaches are also being developed to further increase productivity by reducing error, cost, and time. These technologies provide tools to quantify and manage variability existing in fields across an array of cropping systems. A review of precision farming technologies that are currently being used in the United States and around the world is presented in this article.

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INTRODUCTION

As we venture into a new century of advanced information technology, agriculture has taken on a whole new approach filled with an array of exciting, sophisticated and useful concepts. Centuries ago the horse and plow were the only implements in farming, today agricultural implements are controlled via computers and located via satellites. Known as precision agriculture, or site-specific farming, we are using spatial information technology (Thrikawala et al., 1999) such as the global positioning system (GPS), and geographic information systems (GIS) to make precise management decisions in different cropping systems throughout the world. A cropping system can be defined as a multi-crop rotation in a particular area undergoing crop production. The majority of current research in precision agriculture is focused on one crop of interest, but as conclusions are made about particular crops this new discipline of site-specific farming will undergo research throughout a multitude of cropping rotations.

Precision agriculture is defined as the art and science of utilizing advanced technologies for enhancing crop production while minimizing potential environmental pollution (Khosla, 2001). This technology recognizes the inherent spatial variability that is associated with most fields under crop production (Thrikawala et al., 1999). Once the in-field variability (both, spatial and temporal) is recognized, located, quantified, and recorded, it can then be managed by applying farm inputs in specific amounts and at specific locations (Khosla, 2001).

Application of farm inputs on specific locations is achieved by farming equipment that utilizes GPS receivers. The GPS receivers secure satellite signals from a trilateration of at least four (of the 24) US military satellites orbiting 20,200 kilometers above the earth. In addition, there is a differential GPS (DGPS) receiver, which is capable of receiving another signal (i.e., "differential signal") from an earth-based network of stations such as US Coast Guard beacons or transmitters. Differential transmitters are at known stationary locations, thus the DGPS receiver is able to correct systematic errors (i.e., satellite clock errors, orbital errors, ionospheric and atmospheric errors, multi-path errors, receiver errors, induced errors or selective availability) associated with GPS signals. This allows the precision farming equipment to be accurate within 1 m on the ground, making this technology very site-specific. In addition to standard DGPS, the introduction of real-time-kinematic (RTK) DGPS can accomplish dynamic accuracy within 20 cm and static accuracy within 1 cm of the actual location. However, RTK differential systems are costly and require the user to construct a private base station and radio link, making standard DGPS the most practical system for precision farming at this time (Strombaugh and Shearer, 2000).

Precision farming yields a threefold advantage. First, it provides the farmer useful information, that can influence their use of seed, fertilizer, chemicals, irrigation, and other farm inputs. Second, economics are optimized by enhanced efficiency of farm inputs. Finally, by varying the amount of farm inputs (fertilizers, pesticides, and irrigation) used for crop production, and applying those inputs exactly where they are needed, the environment is sustained (Strombaugh and Shearer, 2000; Fleming, Westfall, and Bausch, 2001; Fleming et al., 2000).

Precision farming technologies today are being studied and adopted for varied cropping systems. Besides the traditional crops, i.e., corn (*Zea mays* L.), soybean (*Glycine max* L.), wheat (*Triticum aestivum* L.), and barley (*Hordeum vulgare* L.), precision farming practices are now being implemented in potato (*Solanum tuberosum* L.), onion (*Allium cepa*), tomato (*Lycopersicon lycopersicum*), sugar beet (*Beta vulgaris* L.), forages, citrus, grape (*Vitis* spp.), and sugarcane (*Saccharum* spp.) (Heacox, 1998). Practices of yield monitoring, variable-rate fertilizer and chemical application, variable-rate seeding, and parallel swath navigation, are being studied and used throughout a variety of crop production systems. Furthermore, different ways of determining quantity and location of crop inputs are being proposed and studied. Site-specific grid sampling is now being compared to the production level management zone approach to identify the most profitable method of determining crop-input application.

Yield monitoring, variable-rate application, parallel swath navigation, and crop-input determinations are the most important aspects of precision agriculture. The objective of this article is to review these aspects and present the current role of precision farming in cropping systems research.

YIELD MONITORING

Yield monitoring and mapping are key elements of site-specific farming and they were the most widely used components of precision farming initially (Heacox, 1998). Yield monitoring offers the most intensive measure of spatial yield variability that exists in farm fields allowing producers to assess how management skills and environmental factors effect crop production (Stombaugh and Shearer, 2000). This assessment provides direct and valuable feedback to the farmer enabling them to make better management decisions (Pelletier and

Upadhyaya, 1999). Such feedback includes but is not limited to: instantaneous yield and moisture documentation, creation of yield and moisture maps, digitally flagged pest documentation and organization of data by year, farm, field, load, and crop. Yield monitoring over time creates a unique GIS database that assists farmers to easily identify yield variability within a field, to make better variable-rate decisions, and create a history of spatial field data (Doerge, 1999a). Yield monitoring has become a common practice in traditional grain crops and corn-soybean rotation systems. This technology is being researched and commercialized for other crops such as potato, onion, sugar beet, tomato, hay, citrus, grape, and sugarcane.

Impact plates, optical volumetric measurements, radiometric techniques, and continuous weighing methods are some of the common practices used for grain yield monitoring. However, for bulkier products such as potatoes, onions, and tomatoes, there are fewer options: (1) bulk weighing/drop bucket; (2) total weight; or (3) the use of belt weighing methods related to the ones invented by Campbell, Rawlins, and Han (1994) and Hofman et al. (1995) for potatoes, sugar beets, and tomatoes. Pelletier and Upadhyaya (1999) have developed and researched a continuous weigh-type monitor consisting of a three-idle weigh-bridge, an angle transducer, a belt speed sensor, and a DGPS receiver that successfully measures and maps tomato yield. This device, installed on a harvester, is used to measure yield variability and produce yield maps.

Over the past few years, installation of yield monitors on commercial potato harvesters are increasing in North America and Europe. The idea is to assess the spatial variability in potato yields and relate this variability to yield limiting factors in the soil and landscape (DeHaan et al., 1999). Reports have indicated that after successful calibration of potato yield monitor; measured yields have been within 5% accuracy (DeHaan et al., 1999; Rawlins et al., 1994; Godwin and Wheeler, 1997). DeHaan et al. (1999) reported that analysis of yield monitoring data has quantified differences and shown yield benefits associated with no-tillage or conservation tillage as compared to conventional tillage. This technology has also proven to be valuable in determining the relationship between potato yield and the level of soil degradation.

Impact-plates, volumetric, and radiation-based sensing devices have been commonly used and found to be suitable for combine harvesters (Stombaugh and Shearer, 2000). Unfortunately, this technology is not reliable in monitoring forage crops due to challenges of texture and moisture variability in forages. Forage crops falsify impact measurement, vary in density, and require an intense radiation source for monitoring (Wild and Auernhammer, 1999). Wild, Auernhammer, and Rottmeirer (1994) reported a round bale yield monitoring system that uses load cells on the tongue and strain gauges on the axles of the baler to measure the total weight of the baler and bale. This method of weighing bales in the round baler has proved to be an acceptable method of yield determination and errors less than 1% were established. Although these weights of round bales provide yield-monitoring data, yield maps are limited to the size of the area from where the bale was produced (Wild and Auernhammer, 1999).

Extensive yield monitoring research is being conducted in the area of fruit production. Schueller et al. (1999) developed a simple system to produce reliable, low-cost yield maps for hand-harvested citrus. Using a commercial GPS receiver, individual harvest container locations were recorded to measure yield variations within a citrus block. In oranges (*Citrus sinensis* L. Osbeck) and various other citrus fruits, management practices are usually carried out on blocks that range from 2 to 100 ha. Traditionally, citrus management practices have been implemented uniformly within each block. However, soil and topographical differences, differences in pest infestations (nematodes), and variations in tree ages have all contributed to spatial variations within a block. The method used by Schueller et al. (1999) was to map the location of each harvest container as it was collected. This was achieved by the use of the Crop Harvest Tracking System (CHTS) developed by GeoFocus.[1] The CHTS uses a GPS receiver to record the container location each time the collection button is pushed on the container collector. The method proved to be efficient, reliable, and relatively inexpensive in mapping yield variation within citrus blocks. Initial yield maps have shown spatial yield variability to have a possible correlation to tree canopy size (Whitney et al., 1999). A regression model was produced plotting yield per hectare versus percent canopy ground cover. The results displayed an association between yield and tree canopy size with an r-value of 0.45 and a p-value of 0.0001. This association can visually be observed by dividing the aerial photograph of the citrus field into yield zones (Whitney et al., 1999). As citrus harvest becomes mechanized, individual tree yields will be mapped, and this will further enhance management decisions in citrus production (Schueller et al., 1999).

Researchers at Washington State University have developed a yield monitoring system in conjunction with HarvestMaster to examine how mechanical pruning and thinning influence yield and quality of juice grapes. The HarvestMaster-500[1] yield monitoring system was mounted on a mechanized grape harvester consisting of a conditioning and control unit, belt speed sensors, load cell sensors, an inclinometer, a DGPS receiver, and a hand-held computer. After the analysis of grape yield maps, it was concluded that variations across the vineyard were due to type of pruning technique and field variability (Wample, Mills, and Davenport, 1999).

Currently, there are no yield monitors commercially available for sugarcane (Cox, Harris, and Cox, 1999), but sugarcane yield monitoring is undergoing

1. Mention of a trade name neither constitutes endorsement of the equipment or products mentioned nor criticism of similar ones not mentioned by the authors or Colorado State University.

extensive research (Whitney et al., 1999). The University of Southern Queensland and DAVCO Farming in Australia have been exploring techniques of mass sensing, volume measurement, and measurement by power consumption. After rigorous field trials, they have selected and patented a direct mass measurement technique. Using GPS and ArcView, yield maps were produced. These yield maps displayed a significant amount of yield variability from 70 to 190 Mg ha^{-1}. This technique is still being assessed and analyzed (Cox, Harris, and Cox 1999).

Several examples of the use of yield monitoring were provided above in a vast array of row, vegetable, fruit, and specialty crops. Table 1 presents a variety of crops and their corresponding sensor types that are being used for yield monitoring purposes in North America and elsewhere. New ideas using yield monitors are being proposed and researched throughout all cropping systems. Commercial advancement of yield monitor research will definitely be significant in the years to come.

Errors in Yield Monitoring

Yield monitoring sensors measure grain mass or volume of a crop per unit area, while a combine is harvesting through a crop field. Measurement of such yield parameters is subject to many sources of error. Lag time, overlapping of data points, moisture content error, and velocity changes are common sources of error associated with yield monitoring, the first two are the most significant errors (Pierce et al., 1997). Most grain flow sensors are mounted on a harvester in a position to sense clean grain flow. This causes a distinct difference in harvester's location from the point of crop harvest and the location where the

TABLE 1. Crop type, sensor type, sensor location on harvester, state of development, and geographical location of various types of yield monitors.

Crop	Sensor Type	Sensor Location	State of Development	Geographical Location
Corn	IP, R, OV	Clean grain auger	C	Worldwide
Soybeans	IP, R, OV	Clean grain auger	C	Worldwide
Potatoes	LC	Under conveyor	C	N. America and Europe
Onions	LC	Under conveyor	C	N. America
Tomatoes	LC	Under belt	Exp	CA
Forages (hay)	LC, SG	Tongue and axle	Exp	Germany
Oranges	LC	Under truck bed	Exp	Florida
Grapes	LC	Under conveyor	Exp	WA, CA
Sugarcane	DMS	Crop intake area	Exp (pat.)	Australia

IP: Impact plate, R: Radiometric techniques, OV: Optical volumetric measurement, LC: Load cell, SG: Strain gauge, DMS: Direct mass sensor, C: Commercial, Exp: Experimental, Pat: Patented.

grain flow is measured (National Research Council, 1997). Lag time is the difference in time from the point of harvest to grain arrival at the sensor. Lag time causes significant errors that, at this point, cannot be completely removed from yield data (Pierce et al., 1997).

Overlapping of data is another significant source of data error that can occur in many ways. Movement of a yield monitor equipped harvester over already harvested areas, wheel-slippage while harvesting crops on rolling topography, and incorrect harvest widths are some common causes associated with overlapping of yield data points. All of these occurrences can either affect the data by over or under estimating yield (Pierce et al., 1997). Although yield monitoring is one of the most widely practiced components of precision agriculture, yield values should be used as a reference as there is much needed improvement in yield monitor accuracy (National Research Council, 1997).

VARIABLE RATE TECHNOLOGY (VRT)

Technology to vary the rate of farm inputs such as fertilizers, pesticides, and seeds is available and is being used with various cropping systems in North America and other parts of the world (Peterson and Wollenhaupt, 1996). Variable rate drills and planters, fertilizer spreaders, and sprayers are commercially available for VRT. Variable rate precision irrigation systems are also being currently studied and developed (D. Heermann, personal communications). Farm machinery equipped with VRT controllers typically have a DGPS receiver to identify the precise location of spatial variability in the field and automatically control the rate of application based on pre-derived input application maps. Integrated control systems have been developed that work across farm equipment so that they can be shared between combines, tractors, and variable-rate equipment. This allows a farmer to obtain a single, cost efficient system that can be implemented in many field operations (Dampney and Moore, 1999). However, because of the cost associated with this technology, the majority of farmers still rely on custom application when using VRT. There are various applications of VRT technology in site-specific cropping systems management. Some of the widely adopted applications of VRT are discussed below.

Site-Specific Nutrient Management

The most widely used form of VRT is variable-rate fertilizer application (Cambouris, Walin, and Simard, 1999). This practice has been used for the past several years and is being researched in a variety of cropping systems. It is well documented that spatial variability in soil properties across landscapes affects crop yield (Ortega, Westfall, and Peterson, 1997). Uniform application of fertilizers, therefore, can result in under-fertilization of certain parts of a field and over-fertilization in other areas (Frasier, Whittlesey, and English, 1999; Khosla, Alley, and Griffith, 1999). Under-fertilization may result in a yield loss and over-fertilization can be harmful to the environment (Cambouris, Walin, and Simard, 1999; Hammond, 1993). With the invention of VRT, it has become possible to manage soil nutrient variations throughout a field with prescription fertilizer applications.

Although variable-rate fertilization in corn and soybean is not a new concept, there is still a significant amount of on-going VRT research in this type of cropping system. Iowa State University's Departments of Agronomy and Statistics have been comparing uniform and variable-rate phosphorous (P) application in on-farm strip trials. Using differential GPS, yield monitors, and grid soil sampling, four strip-trials were conducted at four different farmer's fields. The P treatments consisted of a non-fertilized control, a uniform P rate, and a variable rate P determined by soil P tests that were done prior to planting. The grain yields were taken and recorded every second with combines equipped with yield monitors and DGPS receivers. It was concluded that yield corresponding to P fertilization methods varied among the trials (Mallarino et al., 1999). Variable-rate P reduced the amount of total P fertilizer applied on three out of four farm fields. However, a grain yield increase was observed only in one trial. These results indicate that variable-rate P fertilization in corn and soybean is a more economically efficient and environmentally prudent way of fertilizer distribution (Mallarino et al., 1999).

With the economic and environmental benefits of variable-rate fertilization, the adaptation to other, more non-traditional cropping systems is also undergoing extensive research. Vegetable crops, such as potatoes, demand high amounts of fertilizer and possess a great economic value. Significant correlations between yield and soil physical properties such as slope, cation exchange capacity, and water holding capacity have been measured (DeHaan et al., 1999). It has also been demonstrated that the spatial variability of P and potassium (K) contents in the soil affects yield and tuber quality (Cambouris, Walin, and Simard, 1999; Kunkel et al., 1991).

A study at the Soils and Crops Research Centre of Quebec, Canada investigated the efficiency of variable-rate application of P and K in potatoes. The experiment consisted of three P and K treatments: conventional, variable rate, and a control. A uniform rate was applied for conventional treatment, variable rates of P and K were applied in the VRT treatment by krigging soil test values to produce an application map, and no fertilizer was applied in the control. The first year results indicated that the VRT treatment produced similar yields as the conventional method. However, since lower amounts of fertilizer were applied to the VRT treatment, it reduced the input cost and enhanced the input use efficiency. In addition, the VRT treatment increased tuber quality as compared to that of the conventional method. This shows that there is an agronomic and economic payoff if the cost of the variable-rate application does not exceed the fertilizer savings (Cambouris, Walin, and Simard, 1999).

Besides vegetable and conventional crops, variable-rate fertilization is being explored in other crops. A case study involving sugarcane was conducted in Australia, where yield mapping and DGPS soil sampling were used as data-layers to determine a variable rate of fertilizer to be applied (Cox, Harris, and Cox, 1999). Soil properties coupled with previous year's yield maps to generate variable rate gypsum application maps on high sodic soils were used. An economic analysis of the study showed a \$563 ha^{-1} benefit over five years when comparing VRT with standard uniform input application. Due to sugarcane's value and high input costs, the National Center of Engineering in Agriculture, Australia has proposed that this crop is a good candidate for precision farming practices.

Site-Specific Weed Management

For decades farmers have uniformly broadcast or band applied herbicide to decrease yield loss due to weed competition, reduce weed seed contamination in harvested grain, and improve crop harvestability (Johnson, Cardina, and Mortensen, 1997). In a century of increased concern over environmental issues and the need for higher input efficiency, uniform application of chemical herbicides may be replaced with a site-specific form of herbicide application. Pressure to reduce food, soil, and water contamination and increased herbicide costs have prompted the need for precision technologies to target herbicide application more accurately. Thus, providing a higher degree of optimization in herbicide use (Stafford and Miller, 1996).

It is documented that a degree of spatial variation exists in weed distributions (Johnson, Cardina, and Mortensen, 1997; Cardina, Sparrow, and McCoy, 1996; Johnson, Mortensen, and Gotway, 1996; Mortensen, Johnson, and Young, 1993; Dessaint, Chadoeuf, and Barralis, 1991). The spatial variability across an agricultural field in terms of weed density and species is due to factors such as seed dispersal mechanisms, physical and chemical soil properties, and past management practices (Johnson, Cardina, and Mortensen, 1997; Stafford and Miller, 1996). Therefore, these spatially distributed weed populations provide the use of new technologies that detect, describe, and manage these weed populations (Johnson, Cardina, and Mortensen, 1997).

Over-application of herbicides can result in environmental contamination, increased herbicide cost, and injured crop. Likewise, under-application can cause poor weed control resulting in yield losses (Johnson, Cardina, and Mortensen, 1997; Wilson et al., 1993). Three approaches have been proposed to manage spatial aggregation of weed populations to prevent the under- or over-application of herbicides (Johnson, Cardina, and Mortensen, 1997). The first approach involves the collection of spatially referenced weed populations carried out prior to the herbicide application. Digital application maps are generated corresponding to the aggregated weed populations to serve as a basis for the variable-rate herbicide spraying. Map-based variable herbicide application has resulted in herbicide reductions ranging from 7 to 69% (Stafford and Miller, 1996). The second approach instantaneously senses the presence of weeds and applies herbicides accordingly. The quantity of reflected light of a particular wavelength is measured using real-time weed detection sensors mounted on spraying equipment. These sensors use "optical contrast indices" to distinguish targeted weeds from the crop (Johnson, Cardina, and Mortensen, 1997). The information generated by the sensors is passed to a control system that turns the sprayer on or off accordingly. Guyer et al. (1986) suggested that the use of sensor based spot spraying would substantially reduce herbicide application in the US corn and soybean crops. Shearer and Jones (1991) reported herbicide reductions of 15% after sensors were used to control and activate spray nozzles. Christensen, Heisel, and Walter (1996) evaluated and reported variable herbicide application in cereal crops as a response to weed distributions. The study showed a 47% decrease in herbicide cost. The third approach manages spatially aggregated weed populations by varying herbicide rate according to soil physical and chemical properties. Soil properties are known to influence herbicide-plant interactions (Johnson, Cardina, and Mortensen, 1997; Sonon and Schwab, 1995). Herbicide rates could be varied according to variable soil properties such as organic matter, soil structure, and pH. Implementation of this concept would require algorithms combined with soil property maps to produce herbicide rates and variable application maps (Johnson, Cardina, and Mortensen, 1997). Other methods are being studied to vary herbicide based on in-field management zones that are delineated using stable physical and chemical soil properties (P. Westra, personal communications).

Site-Specific Planting

Another site-specific application is seed placement and planting rate. Site-specific planting involves the proper placement and population of seeds to achieve maximum yield and quality. There are known correlations among spatial variations in yield, crop quality, soil attributes, seed spacing, and plant population. Monitoring these variations provide an opportunity to plant various crops on a spatially selective basis (Rupp and Thornton, 1992; Hess et al., 1999; Cambouris, Walin, and Simard, 1999; Fleming et al., 2000).

A team of agronomists and engineers from the University of Idaho and the Idaho National Engineering and Environmental Laboratory has been researching and monitoring the seed placement of potatoes for the past several years. The primary objective of this study was to measure real-time seed placement and develop an analysis system to assist the growers in potato seed placement based on in-field spatial variability. It is essential to have a good stand of properly distributed plants to achieve high yield and quality in potato production. Improper seed distribution and skips cause varied plant growth and increased competition between individual plants (Hess et al., 1999; Holland, 1991; Rupp and Thornton, 1992). By obtaining seed spacing accuracy of 75% or higher, farmers can expect a 5 to 10% yield increase and a 20% improvement in crop quality. These improvements were obtained with essentially no cost increases (Hess et al., 1999; Harris, 1997; Holland, 1991, 1994). The monitoring system used in this study effectively proved that there are significant spatial deviations from the primary placement target when planting a potato crop. Spatial variations in soil types and soil conditions affected the performance of the planter's drive wheel.

Universities, extension centers, and engineering firms are not the only agencies that are conducting variable-rate planting research. Progressive farmers from the Great Plains to the midwestern corn-belt are also conducting on-farm, production level research. Nebraska growers have been utilizing automatic population rate controllers to vary corn populations between irrigated circles and non-irrigated corners. This is achieved by collecting position and guidance data on center pivots by means of GPS receivers. The data is stored on a data card and is put into a yield monitor mounted in the planter tractor. Electro-hydraulic population controllers are used to switch between seeding rates (Stombaugh and Shearer, 2000). The position information stored on the data card is sent to the population controller and seeding rate is controlled automatically. Irrigated circles are planted at a rate of about 67,950 seeds ha^{-1}, as the planter crosses into non-irrigated corners the rate is reduced to 44,475 seeds ha^{-1} (Wilcox, 2000b, 2001a). Growers in Iowa and Kansas are also studying variable-rate planting and making population changes based on observations. These changes in plant populations are based on "yield zones" which are derived by changes in soil tests, soil type, and past knowledge of the field (Fleming, Westfall, and Bausch, 2001).

Parallel Swath Navigation

A parallel swath bar, or light bar, is a guidance system that utilizes location information from GPS. This technology allows the user to map the field perimeter and have the guidance system automatically lay a set of parallel swaths between the boundaries. User inputs such as spacing between parallel lines and number of lines are usually required (Tyler, Roberts, and Nielsen, 1997). After these calibrations are made, if the operator deviates from parallel tracks, the swath bar will visually and/or audibly respond so a correction can be made (Wilcox, 2000b, 2001b). This guidance system allows a trained operator to drive straight while spraying pesticides, applying fertilizers, working at night, and almost any other instance where there is a need to drive in a parallel track (Wilcox, 2000b). With proper training on this guidance system such technological advances greatly increase the efficiency of farming operations.

The swath bars are excellent for guiding spraying in cornstalks or drilled beans (*Phaseolus* sp.) where foam makers are hard to follow (Holmberg, 2001). Newer systems are now displaying cursors, representing vehicle position, and fill color on the on-board computer screen for the area of the field that has been traveled over so an operator can be confident that all parts of the field were covered (Tyler, Roberts, and Nielsen, 1997). A convenient benefit of a parallel swath bar is that it can be easily moved between various pieces of equipment (Wilcox, 2001b). Grain producers ranging from the Midwest to the Pacific Northwest are implementing this versatile navigation system in large fields under crop production to optimize planting, tillage, and harvest patterns (Tyler, Roberts, and Nielsen, 1997). The precision of these swath bars relative to foam markers, tillage swaths, harvest patterns, and other guidance systems is only as accurate as the GPS receiver used. Preliminary results from an ongoing study at Ohio State University indicated that 95% of the time the accuracy of all GPS guidance system used in the study on a straight line was better than 0.51 m (R. Ehsani, personal communications). Although not commercially required, GPS receivers having sub-meter accuracy are recommended for optimum accuracy and efficiency of guidance systems.

GRID SAMPLING AND MANAGEMENT ZONES

Before crop inputs can be varied on a spatially selective basis, determination of application rates and location must be assessed. Therefore, different approaches of determining how much, when, and where crop inputs are to be distributed in the field are being proposed and researched. Developing accurate variable-rate application maps is a key element to implementing precision farming technology (Fleming and Westfall, 2001). Grid soil sampling was the very first approach used by researchers to make prescription application maps (Figure 1a). Since the early 1990s application maps have been developed for the use of variable-rate fertilizer application based on results from sparsely spaced grid soil sampling (Doerge, 1999b). Due to the spacing between sampling points, estimates of the soil test values in between the sample points must be interpolated. Kriging and Inverse Distance Weighing (IDW) are the most suited methods for interpolation (Doerge, 1999b). Figure 1b shows an interpolated soil tests results map using IDW interpolation technique. Grid soil sampling when performed at a scale that produces a spatially dependent data yields a more precise spatial information compared to whole field composite sampling. In addition, it detects spatial features previously unaware and ignored about a field (Doerge, 1999b; Ferguson et al., 1999). However, the accuracy of interpolation technique depends on unique spatial properties of each data set and may produce different predicted surface maps depending on the interpolation technique used. Furthermore, the scale at which grid sampling is performed plays a significant role in capturing the spatial variability and can lead to incorrect interpretation of existing variability in the field. Several different scales of grid soil sampling and their comparison have been discussed in the literature (Anderson-Cook et al., 1999; Wollenhaupt and Wolkowski, 1994; Bullock et al., 1994). Regardless of the technique used, grid soil sampling on small grids (i.e., 0.4 ha or less) is time consuming and cost intensive (Gotway, Ferguson, and Hergert, 1996). Furthermore, grid soil sampling for nitrogen fertilizer recommendations needs to be conducted each year and for every field that will undergo variable N fertilizer application (Khosla, 2001).

The goal of crop input determination is to collect the information needed to make accurate application maps at the lowest possible cost. The profitability

FIGURE 1. a, b, c, d. An example of grid soil sampling, IDW interpolation of soil test results, bare soil imagery, and management zone delineation on an experimental field.

a. Non-aligned grid soil sampling.

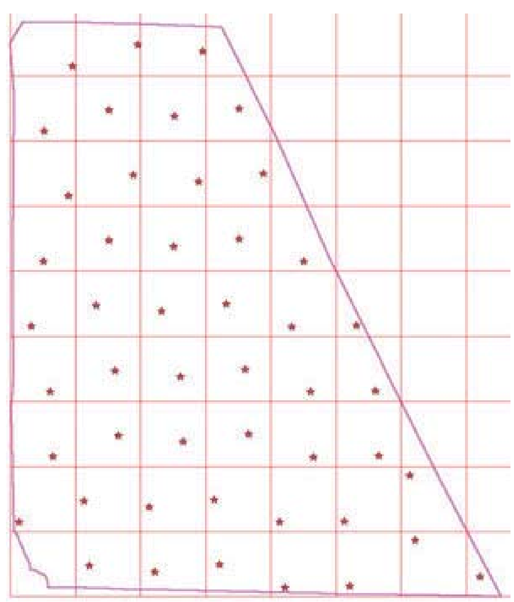
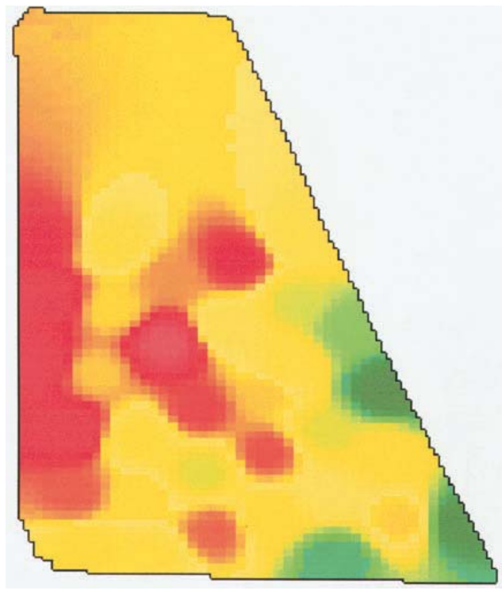


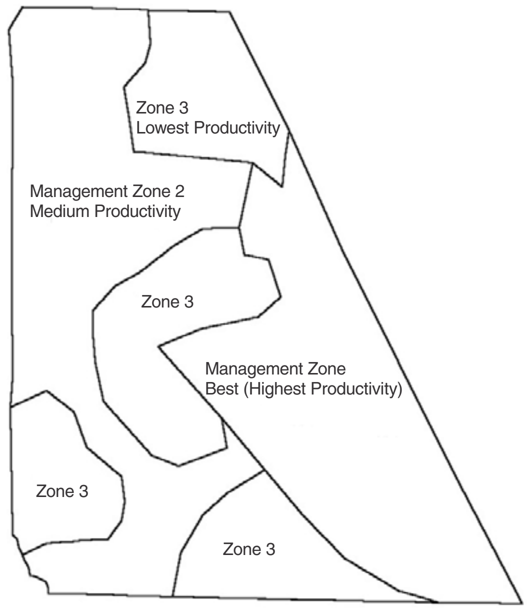
FIGURE 1 (continued)

b. Interpolated soil test results using IDW interpolation technique.



c. Bare soil imagery of an experimental field.

d. Management zones delineation based on bare soil imagery.



potential for site-specific fertilizer management is significantly enhanced if the initial means of forming application maps are inexpensive (Peterson and Wollenhaupt, 1996). There has been an increasing need for a method of managing crop input variability that is less time, labor, and cost intensive, as well as one that remains stable for several years. Ongoing research trials conducted by scientists from Colorado State University, USDA-ARS, and various other agencies in different parts of the country have established a more economically feasible system that divides farm fields into different regions referred to as production level management zones (Khosla, 2001; Fleming et al., 2000; Fleming, Westfall, and Bausch, 2001).

Production level management zones are defined as homogenous sub-regions of a field that have similar yield limiting factors (Doerge, 1999b; Khosla and Shaver, 2001). The current technique of delineating management zones in western US includes three GIS data layers, i.e., bare soil imagery, topography, and farmer's experience. Figure 1c presents an example of bare-soil imagery used for delineating management zones on an experimental field. This type of management zone delineation, however, is limited to conventional tillage.

Using this system of delineating management zones, a field can be divided into three different zones: high, medium, and low, based on the productivity potential of these areas. These management zones provide the grower with an opportunity to optimize their fertilizer applications. Areas of the field that have a high yield potential would receive a high fertilizer rate, medium productivity areas would receive a medium rate, and low productivity areas would receive the lowest rate. Figure 1d presents an example of delineated management zone on an experimental field. Varying the rate in this manner reduces the overall amount of fertilizer applied while maintaining or increasing the grain yields (Khosla and Shaver, 2001). Managing in-field spatial variability by management zones reduces the amount of crop input application, maximizes input efficiency, maintains or increases grain yields, reduces environmental impact, and enhances farm profitability (Khosla, 2001).

CONCLUSION

Precision farming technologies are being researched and implemented in a multitude of cropping systems. It is evident from the review of the literature presented herein that precision agriculture is successful in its role of enhancing crop production while minimizing environmental impact. Utilizing the GPS, precision agriculture recognizes and quantifies the inherent spatial variability in fields and manages this variability by applying inputs at specific amounts, when and where they are needed.

There are various elements of precision farming that play their own important role in cropping systems. Yield monitoring is being used to measure the yield variability of corn, soybean, potato, tomato, onion, sugar beet, hay, orange, grape, sugarcane and has become the most widely used component of precision farming. Besides yield variability, crop variety comparisons, yield damage reports, and field efficiency are being assessed with the use of yield monitoring systems.

Likewise, technologies to vary the rate of farm inputs such as seed, fertilizers, chemicals, and irrigation are being researched and are becoming available to a variety of cropping systems throughout the world. Varying the rate of fertilizers to correlate with the spatial variability of essential nutrients has become one of the most common practices of precision agriculture. Scientists and farmers alike have been monitoring placement and seeding rates. By conducting research in site-specific planting, input costs may be decreased and yields and quality may be increased.

Parallel swath navigation provides a guidance system that utilizes GPS to navigate equipment and reduce over application and skips. This new technology allows the day and/or night operation of applying fertilizers and chemicals without worry of costly skips or overlaps. It also provides better yield monitor accuracy in drilled soybean harvest.

Developing accurate application maps is a key element when implementing precision farming technologies. Several approaches are undergoing evaluation to determine which is the most efficient and profitable method of determining crop input application. Grid soil sampling is now being compared to the various management zone approaches. Although grid soil sampling has offered advantages in the past, it has proved to be time, labor, and cost intensive. Research in applying inputs to meet the production potential of individual management zones has indicated increase in input use efficiency, enhanced farm profitability, and reduced environmental impact.

Most importantly, throughout all types of cropping systems, the producers need to recognize, research, and implement these precision technologies and management practices at an on-farm production level. The future of farming needs profitability with minimal environmental impact. Precision agriculture technologies can help achieve these goals.

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