Precision Agriculture and Environmental Quality: Challenges for Research and Education

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Table of Contents

INTRODUCTION

Agricultural practices and their effect on the movement of sediment and agricultural chemicals have been a source of controversy because of the inability to define precisely the impacts of various farming practices on nonpoint-source pollution. Nonpoint-source pollution links agricultural practices with offsite movement of nutrients, pesticides, and sediment. The exact relationship, however, depends upon soil, topography, meteorology, cropping practice, and landscape. What role agricultural practices have on the amount of movement of these constituents from the edge of fields has been debated for years, with little agreement about the efficacy of various practices on environmental quality. But there is agreement about the fact that agricultural practices that either reduce inputs or apply inputs at times when there is less risk of offsite movement have a positive impact on environmental quality.

Several emerging issues regarding nonpoint-source pollution should be considered in any discussion about agriculture and the environment. These include the movement of pathogens and antibiotics into nearby water bodies from agricultural fields that have had manure applied to those fields. The discussion of offsite movement is complicated, however, by one important fact: while water is the primary transport mechanism, the processes that enable the movement of nutrients, pesticides, pathogens, and sediments differ and, therefore, respond differently to management practices.

It is also important to remember that environmental quality is multi-dimensional. A number of interrelated factors are linked to offsite movement. These include soil management practices, soil type, topography, organic matter content, crop, weather events, and prior management. In many cases there is movement within a field but no loss from the field. This redistribution of sediment, nutrients, residue, or pesticides may be indicative of a suite of management practices that is less than optimal in terms of performance. Precision agriculture or site-specific agricultural practices may affect offsite movement of different components from a field. There have been few studies conducted with the specific objective of evaluating the potential role of precision agriculture on environmental quality.

A March 1999 workshop sought to address the current state of knowledge about precision agriculture relative to environmental quality and to identify what research might be undertaken in an attempt to confirm the efficacy of precision agricultural practices on environmental quality. Many challenges need to be addressed to understand the potential for changing inputs across a field in order to reduce offsite movement

SOME DEFINITIONS

A number of definitions need to be considered in this report. Precision agriculture or site-specific management refers to the differential application of inputs to cropping systems or tillage operations across a management unit (field). Input applications may vary either spatially or temporally within management units. The methods involved include application via predefined maps based on soil or crop condition or sensors that control application as machinery traverses the field. Spatial scales range from less than 1 meter to more than 10 meters, while temporal scales vary from minutes to months. Environmental quality endpoints require definition because of the need to understand how the performance of management practices is to be measured and compared among practices. Nitrate-nitrogen in drinking water has a Maximum Contaminant Limit (MCL) of 10 milligrams per liter, while atrazine has a MCL of 3 micrograms per liter. These two agricultural chemicals are present in agricultural systems, and the MCLs are used to determine if environmental quality has been compromised as a result of farming operations. Rigorous measures of environmental quality are needed to assess the impact of various management practices.

A farming system is comprised of many elements. Importantly, three classes of variation exist within a field: (1) natural, such as soil and topography; (2) random, such as rainfall; and (3) managed, the fertilizer or seed application. Offsite impacts are the result of the interactions of these three sources of variation.

Another aspect that must be defined is the interaction between natural cycles within soils and supplied inputs. An example is the interaction between mineralization of nitrogen from organic matter, a temperature-dependent process, and the application of commercial sources of nitrogen at different times of the year. Each of these supply nitrogen to the soil profile, but the nutrient's availability relative to crop uptake patterns differs between the cycles. These differences often lead to some of the environmental impacts from agricultural systems. Nitrogen available in the early growing season provides more than is needed to meet crop demand; if precipitation then exceeds crop water use, substantial nitrogen leaching can occur. These patterns must be understood to place precision farming and environmental quality in the correct perspective.

SOIL VARIATION

Soil variation is a spatial variable. Water-holding capacity or organic matter variation, along with topography, provides even a more interesting view of a field in which a producer places inputs or disturbs the soil. Other variables could be layered within this field to create a series of interacting elements. The central question is how to quantify soil variation. Wollenhaupt and colleagues (1997) provided a detailed summary of soil sampling and interpolation techniques that potentially could be used to quantify soil variation. They defined these sampling methods as judgmental sampling, simple random sampling, stratified sampling, cluster sampling, nested or multistage sampling, systematic sampling, stratified systematic unaligned sampling, and search sampling. Selection of a sampling method depends upon the goal of sampling. Collection and analysis of the samples only provides one portion of the base layer of information. Individual samples represent points; to be of value, they must be interpolated. There are as many interpolation schemes as there are sampling schemes. These schemes include central tendency, proximal, inverse distance methods, splines, and geostatistical. None of these methods or schemes are described herein, but all have been used to determine variability across a field.

Topographic variation within fields can be collected from topographic maps, but the resolution on these maps is often insufficient to provide the necessary detail about variations within fields. Topographic maps can be generated from differential or kinematic geographic positioning systems. The role of topographic variations on water use, plant growth, soil processes, yield, surface runoff, and groundwater hydrology has not been quantified for agricultural fields.

BIOLOGICAL VARIATIONS

Biological variations within fields are as great as soil variations. A number of measures of biological variation must be considered. These include soil microbial populations, weed populations, insect populations, disease occurrence, crop growth, and harvestable yield. The most commonly observed variation is through yield maps generated by producers with yield monitors. Growth and yield differences across a field can be large; the magnitude and often surprise observers. Jaynes and

Colvin (1998) determined that yield variation was due to an interaction of soil types and precipitation patterns within the growing season. In their data set, which consisted of 7 years of observation across the same field, there were large differences in yield. Several other studies of yield variation within fields have been conducted by Birrell et al. (1996), Colvin et al. (1991), Fiez et al. (1994), Karlen et al. (1990), and Stafford et al. (1996). These studies represent only a few of the emerging reports on the degree of within-field yield variation.

Insects, diseases, and weeds are variable factors within fields. But the processes leading to variation within fields are quite different. Insect patterns within fields vary as a result of migration into the field. Fleischer and colleagues (1997) examined spatial variation in insect populations and identified several interacting that lead to spatial variation on a field scale. Their conclusion: Within a field, migration, colonization, and reproduction are processes that lead to increases in population, while emigration and mortality reduce the population. But there are a number of interacting factors, for example, temperature, stage of crop development, and host plants, that will affect insect behavior and development. Comprehensive models of insect growth and populations spatially across a field have only begun to emerge. Insect patterns across a field also can have a large temporal component because these population factors are often temperature-dependent.

Spatial distribution of disease outbreaks within fields has been observed for a number of years. Observations of spatial occurrence of diseases have led to the development of integrated pest management programs for a number of crops.

Weed distributions within fields have been a topic of interest to both producers and weed scientists. Andreasen and colleagues (1991) evaluated different soil properties to show why populations of 37 different weed species varied across fields in Denmark. In the case of weeds, as contrasted to insects or diseases, the seedbank dynamics across a field become the primary factor affecting the spatial distribution of weed populations (Bigwood and Inouye, 1988). Hatfield (1998) showed how microclimatic conditions at the soil surface, as affected by crop stand and soil characteristics, could play a role in the establishment of weed populations across a field. This model describes the interactions between radiation levels at the soil surface and the energy balance in determining the likelihood of a weed seed germinating and surviving. Johnson and associates (1996) used geostatistical methods to estimate the spatial and temporal variations in weed seedling populations; they found that this methodology could be effectively used for these analyses. They found also that the location of velvetleaf (*Abutilon theophrasti*) remained constant across years but the density of weeds within an area varied among years. Earlier, Johnson and colleagues (1995) had found that populations depended upon prior management practices within a field.

Spatial variation of weeds within a field depends upon seedbank dynamics. Temporal variation patterns reflect interactions among soil, meteorological conditions, crop canopy, and growth characteristics of the specific weed (temperature and radiation requirements for germination). If these factors are layered together, a picture of the potential interactions that influence spatial and temporal weed patterns across a field begin to emerge.

SOIL PROCESS VARIATION

Nitrogen in the soil profile represents the balance that exists among a number of processes. These processes include mineralization, immobilization, denitrification, volatilization, nitrification, sorption, plant uptake, and leaching. Mulla and Schepers (1997) detailed the properties that are related to these processes; many are associated with soil water content, soil temperature, soil pH, soil texture, organic matter content, and soil drainage status. Nitrogen is one of the critical elements for plant growth. Processes that determine nitrogen availability within the soil--mineralization and nitrification--and processes that make nitrogen unavailable--denitrification, volatilization, and immobilization--vary with soil types. It is reasonable to assume that inherent changes in soil would have a direct effect on plant growth and yield. The challenge is to quantify the response to varying nitrogen levels.

Nitrogen is soluble in water, and it moves rapidly in the soil profile with water. This is particularly evident in subsurface-drained soils where nitrate-nitrogen concentrations often exceed 15 milligrams per liter. Hatfield and associates (1998) showed that nitrate loads from drained fields were linearly related to precipitation totals. This coupled with the variation in soil water use patterns across a field can give rise to variations in the amount of subsurface drainage throughout a field and within and across years. The complexity of the interactions between the physical environment and the biological response creates a situation in which it is difficult to quantify the response to different practices.

THE CHALLENGE

There is an emerging body of literature showing that precision agriculture can have a positive impact on the environment. Unfortunately, this conclusion is more a residual than a product of most studies. The proceeding discussion shows how current information can improve understanding of how precision agriculture and environmental quality are linked. The March 1999 workshop attempted to bring together scientists and practitioners to discuss this linkage and what must be understood to demonstrate the positive impacts of precision agriculture on environmental quality.

In preparation for the workshop, each participant was provided with a portion of the National Academy of Science report on *Precision Agriculture and the Environment: Research Priorities for the Nation*. This provided some common background information on the issue to help foster discussion among participants.

ENVIRONMENTAL PROBLEMS FACING AGRICULTURE

NUTRIENT MANAGEMENT

Jim Schepers provided an overview of the environmental problems facing agriculture. The concerns can be categorized as endpoints in different water bodies, for example, surface water and groundwater, by a number of different indicators, such as nutrients, pesticides, sediment, manure, feed additives, pathogens, and heavy metals. The accompanying table summarizes where the environmental risks are perceived to be the greatest for different processes.

Environmental risks from nutrients and soil organic matter

Process	N	P	K	S	OM
Leaching	+	0	-	-	-
Denitrification	+	-	-	-	-
Eutrophication	+	+	-	-	-
Precipitation	+	+	+	-	-
Runoff	+	+	-	-	+
Volatilization	+	-	-	0	-
Saltation	-	-	+	-	-

The interactions between factors and processes must be addressed in any discussion of environmental quality. Nitrate-N losses are influenced by any factor that affects the movement of water within and from the field. Because nitrate-N is soluble in water, it is readily transported with any moving water. Sources of nutrients in the upper Midwest have been cataloged by Goolsby and colleagues (2000) in their examinations of agriculture’s contribution to the hypoxic zone in the Gulf of Mexico. Hypoxia is a condition where water is depleted of its oxygen content, which results in a serious reduction of biological activity. An area—approximately 7,000 square miles—in the Gulf of Mexico where the Mississippi River empties has developed into a hypoxic zone, with very low fish and shellfish densities. The hypoxic zone is believed to be caused by an abundance of nitrogen, phosphorus, and silicate in the water.

The table of environmental risks provides a basis for examining agriculture’s impacts on environmental quality and the magnitude of those impacts. Schepers suggested that hypoxia could result from runoff, erosion, subsurface drainage, and baseflow from fields into adjacent streams. These transport processes, when coupled with nutrients, heavy metals, pesticides, antibiotics, pathogens, and sediment, give rise to differential movement of these contaminants across a watershed.

The processes outlined in the table cannot be changed, but it is possible to modify the loading of nutrients and pesticides in a field. Nutrients can be applied as inorganic sources (commercial fertilizer) or organic sources (manure or compost) to a field, and the timing of applications may be an effective method of avoiding excessive nutrients or pesticides when transport mechanisms are favorable for off-site movement.

Nutrient application requires an understanding of crop requirements for profitable yield, efficiency of crop utilization, ability of soil to supply a portion of the crop requirements, and temporal patterns of crop uptake and utilization compared to supply from the soil volume. Application of nutrients provides an opportunity for effective management of inputs while increasing production efficiency.

Two aspects of nutrient management become critical:

1. What is the soil supply of nutrients, and how can this be measured or predicted over a diverse landscape?
2. How can the plant be used as an indicator of nutrient status?

Both questions require attention to better understand nutrient management and its use in precision agriculture for environmental quality improvement purposes.

PEST MANAGEMENT

Pests associated with agricultural production include weeds, insects, and diseases. Most pesticides applied in agriculture are for weed control. The environmental problems facing agriculture from pesticide use have to do mainly with groundwater and surface water quality. Dave Mortenson explained to workshop participants, from the perspective of weed ecology within a field, that weed populations vary in response to a number of factors and that understanding the dynamics of weeds is critical to developing production systems that reduce the amount of herbicide applied to the soil or crop.

Weeds are spatially variable across fields because of organic matter, soil texture, landscape position, and the interaction of these factors with crop management, crop cultivars, tillage, planting density, cultivation, and herbicide application methods. This is a complex set of interactions that exists within all fields.

Precision agriculture provides an enabling set of technologies to help reduce potential environmental problems from pest management. These technologies include field maps of weed distribution throughout the year, detection methods for weeds within a field, application methods to apply an herbicide only on selected areas, and indications of the effects of weed populations on crop yields with data from yield monitors on combines. Each of these technologies allows for the adoption of precision agriculture to weed management. Insects and diseases can be treated similarly to weeds using the same principles.

SOIL AND WATER QUALITY

Soil and water quality are two major components of a sustainable agricultural system. Attributes of soil and water quality are inextricably linked. A good soil does not ensure good water quality, but a poor soil is likely to create conditions that contribute to poor water quality (NRC, 1993). Soil quality must be maintained to provide a supply of nutrients and water and support the developing crop. A healthy soil is thus critical to food, feed, and fiber production. Water quality problems are often considered to be pesticide- or nutrient-based; however, the largest water quality problem results from sediment due to soil erosion. Soil and water quality are linked because erosion processes remove valuable topsoil and transport it offsite, where it often becomes a water quality problem.

Soil quality can be defined as fitness for use (Larson and Pierce, 1991). Soil quality is the capacity of a soil to function in a productive and sustained manner, while maintaining or improving the resource base, environment, and plant, animal, and human health. The capability of a soil to function within ecosystem boundaries and interact with the environment, external to that system forms the basis for determining the potential impact of soil management systems on the environment (Larson and Pierce, 1991).

Soil quality measurements are needed to guide development of management practices. The land manager needs quantitative information about whether a given management practice is degrading, aggrading, or maintaining the soil’s ability to serve its intended use. Further, the manager needs to know what the status of each major attribute of the soil is so changes can be made. Measurement of soil quality should be a quantitative tool to help guide management decisions.

Because soil is such a complex material and because it varies temporally and spatially, Larson and Pierce (1991) suggested that a “minimum data set” of important parameters are needed for each soil from which measures of quality could be computed. Doran and associates (1996) suggested a similar approach. Because many soil attributes are interrelated, only a limited number of attribute measurements are needed. The measured attributes can be used to estimate other attributes by equations called pedotransfer functions. For example, if the amount and type of clay, organic matter content, and bulk density are known, the soil’s water-holding capacity can be estimated (Gupta and Larson, 1979). The measured or estimated attributes can then be used with suitable models for any intended use of the soil. Doran and colleagues (1996) pointed out that while an analytical methodology is needed for researchers' in-depth studies a more easily determined and recognizable set of indicators is needed for land managers' use.

The variability of soil nutrients within a management unit or field has long been known, as has the susceptibility to erosion. Recent yield monitoring suggests many other factors affecting soil behavior are extremely variable. Soil compaction and the resulting water drainage appear to be more common than previously thought. The discovery and quantification of these causes of variability suggest many new applications of precision agriculture and the need to develop new methods for assessing soil quality so that remedial actions can be taken in an analytical way. Larson and associates (1997) addressed the potential of precision agriculture for environmental protection, but primarily confined their discussion to nutrients, pesticides, and soil erosion.

Water quality is evaluated by the amount of harmful chemicals and sediments the water contains. Harmful chemicals are those that damage biological organisms. For many chemicals, the U.S. Environmental Protection Agency (EPA) has set maximum safe limits. During the past two decades, increasing concern has been raised about groundwater being contaminated with chemicals and surface water being contaminated with both chemicals and sediment as an impact of agricultural practices. A number of major publications have also expressed concern about available water quantities, particularly in the western United States and near major urban populations. Because agriculture is a major water user, this should alarm us. According to the U.S. Geological Survey, nitrate-N levels in groundwater were above the 10 milligrams per liter limit determined safe by EPA in at least 25 percent of sampled wells in 87 counties in the United States, mostly in the Midwest. The U.S. Department of Agriculture (USDA) estimates that nearly half the counties in the United States have groundwater supplies vulnerable to pesticide and nitrate-N contamination, potentially affecting 54 million people who rely on these sources for drinking water.

An estimated 221 million pounds of pesticides were used on cropland or pasture in the Mississippi River Basin in 1991. Five herbicides (alachlor, atrazine, metolachlor, simazine, and cyanazine) accounted for about 63 percent of herbicide use in the Mississippi Basin (Goolsby et al., l991). These herbicides are used mostly on corn, soybeans, and sorghum. Of the herbicides used on corn, atrazine exceeded allowable drinking water contaminant levels in 27 percent of samples from smaller tributaries and the lower Mississippi and Missouri Rivers. Atrazine was detected in all of 147 streams during April-June of 1989-1990 (Rabelais et al., 1992). Conservative estimates indicate that less than 1 percent of pesticides applied each year reach the Gulf of Mexico. As in the case for plant nutrients, many improved agricultural management practices are on the shelf waiting to be used, or nearly ready to be used. Since 1990, the use of herbicides and insecticides has been level, but the use of defoliants and soil fumigants has increased (USDA-ERS, 1997). Pesticide runoff potential for 13 crops is greatest in the Cornbelt, while leaching potential is greatest in the Southeast, Illinois, and Michigan (Mausbach et al., 1999). Potential for phosphorus from animal manure to meet or exceed plant uptake and removal on nonlegume-harvested cropland and hayland is scattered; significant areas exist in the Southeast and Southwest (Lander et al., 1997).

Because agriculture is believed to be the largest source of nitrogen and phosphorus in the Mississippi River, agriculture has often been pinpointed as an industry that needs to use corrective measures. The mean annual concentration of nitrate at the mouth of the Mississippi remained nearly constant through the 1950s and then doubled over the last 35 years (Rabalais et al., 1996). There is some indication that the concentrations have leveled off in recent years. Of the total nitrogen flux into the Gulf of Mexico via the Mississippi each year, 31 percent comes from the upper Mississippi, 23 percent from the lower Mississippi, 22 percent from the Ohio, 8 percent from the Central Mississippi, and 6 percent from the White/Arkansas river basins. Silicate concentrations have been reduced 50 percent over the last 35 years. Reliable data for phosphorus over this period are not available.

The data concerning plant nutrient increases in surface water over such a wide area as the Mississippi Basin is cause for concern, and elevated concentrations of nutrients occur in many other drainages across the nation. It seems prudent, therefore, that agriculture reexamine its cultural practices with regard to fertilizer and manure use and aggressively develop educational programs for use of best management practices. Many practices are available and only need implementation.

Larson and colleagues (1008) reviewed the potential environmental benefits from precision agriculture. While it seems reasonable that precise placement and amounts of chemicals, as well as other management practices according to the needs of the soil and crop, could limit movement of chemicals and sediment into surface water and groundwater, only limited direct field information is available. Larson and associates (1997) provided an example of a field containing soils with surface textures ranging from sandy loams to loams in which the average amount of nitrogen leached was 29 kilograms per hectare using precision agriculture compared to 60 kilograms per hectare using conventional rates of nitrogen application. These estimates were made using the computer-driven model of Wagenet and Hutson (1992). The difference in the amounts of nutrient leached under precision agriculture versus conventional practice varied from 99 kilograms per hectare in a loamy sand to 0 kilograms per hectare in a loam.

Soluble phosphorus concentration in runoff water is linearly related to the available phosphorus in eroded sediment. Maintaining the available phosphorus content in different areas of a field at some reasonable level, consistent with economic crop growth, would limit the concentration in surface water. Larson and associates (1997) gave examples of fields where the available phosphorus contained in surface soils varied widely. For example, in one field in Minnesota the available (extractable) phosphorus ranged from 0 to 110 parts per million (Larson et al., 1997). Phosphorus content in runoff water can also vary with the method of phosphorus management (placement, time of application), residue management, and tillage (Larson et al., 1997).

Application rate and method of management (timing, wind speed, tillage, residue management, application equipment, etc.) can also affect the amount of herbicide in surface runoff and that leaching to groundwater (Larson et al., 1997). A promising approach to addressing this problem is weed mapping followed by selective herbicide application in those areas where weed infestations are serious (Mortensen et al., 1994).

TIME AND SPACE SCALES

Precision agriculture requires an understanding of time and space scales. Time scales are critical because operations occur when they will benefit the crop most. Space scales become a fundamental principle of field management because inputs and cultural practices are varied with soil type, pest population, or crop maturity. The challenge is to determine how to use time and space scales to advantage in developing an improved understanding of agricultural management. To fully achieve the goals of precision agriculture, management must be applied in a space and time context.

Shelby Fleischer addressed the issue of time and space during the workshop using insect populations within fields as the model. Insect populations vary throughout time because of the different stages of development. Monitoring has become a critical component for quantifying insect populations within a field. Integrated Pest Management (IPM) systems for insects have used the principle of economic threshold to determine and to quantify the potential economic impact on the crop. Monitoring to determine the insect population becomes a critical component of this program. Adoption of IPM principles has led to a reduction in insecticide application. Presumably, there is reduced environmental impact as well.

Differential application of pesticides over time creates potential areas of spray versus no-spray. This, in turn, creates areas of refuge for insects and a change in the spatial variation of insects across a field or among fields. Sampling these areas over time provides a picture of insect population dynamics that will lead to better management decisions. The techniques used to understand the spatial dynamics of these populations include spatial statistics that can be layered against temporal statistics. The application of these methods to quantifying the spatial and temporal patterns across a field may help develop better management methods.

DESIGNING EXPERIMENTS IN SPACE AND TIME

The challenge of monitoring in space and time is important to document the changes that are naturally occurring within a field. To fully realize the potential impact of precision agricultural principles on environmental quality, however, will require the design and implementation of experiments in space and time.

Dan Long provided workshop participants an overview of the current statistical methods that can be used to design experiments. Some available literature for further study of this topic is listed among the references. A major challenge is to overcome the problems associated with moving from small areas with uniform soils to large fields. Precision agriculture studies will require an approach that uses geographical data statistical analysis.

The main purpose of field experiments is to compare effectiveness of different treatments. Precision and accuracy are paramount, but valid assessment of error is also important. Yield is influenced by nontreatment factors, such as pests and soil fertility. If ignored, this extraneous variation leads to erroneous comparisons. Proper field design and statistical analysis will help minimize this problem.

Classical methods for controlling extraneous variation include replication, blocking, and randomization. Replication increases the number of observations. Blocking provides local control over soil gradients, thus increasing precision. Randomization ensures the unbiasedness of treatment comparisons. An assumption that blocking will control soil gradients is unsound if fertility gradients exist within blocks. An assumption that randomization will neutralize this variability is also untenable.

In precision agriculture research, plots take up large areas when they are established across entire management units, with full-scale planting and harvesting equipment. Estimated plot effects, or plot errors, against their locations within the field will likely show substantial spatial structure or autocorrelation. Classical statistical theory that ignores this autocorrelation can lead to imprecise results and invalid assessment of error.

Classical approaches to controlling nontreatment variance include a variety of methods. Nontreatment variance can be controlled through experimental designs that employ local blocking structures within which gradients are relatively constant. The most efficient designs are impractical because of restrictions on the number of treatments and replicates. Tradition and ease of management force use of the less complicated randomized complete block design.

Spatial statistics provide an alternative to blocking designs for use over large areas. There are a number of techniques that include terms in a model to explain nontreatment trends in data. Analysis of covariance and least squares smoothing are two methods. Other techniques that indirectly model the correlated structure in error include nearest neighbor analysis and spatial autoregression. There are techniques that directly model the correlated structure in error, and some of these are the mixed models found within SAS, which is appealing because the error term is modeled directly. But success depends upon determining the correct form of the error variance-covariance matrix.

There a number of additional issues facing empirical analysis of data collected in precision agriculture studies. Because precision agriculture studies are often large, field-scale studies, there is a need to determine the most appropriate way to lay out field-scale trials. The spatially balanced, incomplete block designs ensure that treatment comparisons are made over equal distances. Comparisons over equal distances effectively neutralize plot-to-plot correlation, and the restriction on randomization increases the number of replicates. Using a series of replicated, small-plot experiments located within management zones of fields assumes an a priori knowledge of how to create management zones; it also requires use of small-plot equipment. This may negate some of the advantages of large-scale field studies. Replicated strip trials with long and narrow plots oriented lengthwise in the field allows testing application rates versus management systems. There remains the concern, however, of what constitutes the plot or experimental unit, the ease of management, and the quality of yield data.

A primary question is how to design factorial experiments for potential use in precision agriculture studies. This raises other critical questions:

1. Are experimental plots and treatments necessary?
2. Can the research questions be answered using quantitative methods in landscape ecology that can help study physical, chemical, and biological processes within management units and fields?

A number of tools exist to analyze the data, including state-space modeling, fractal analysis, cross-correlation, and spectral analysis. Classical statistics emphasizes obtaining maximal information from minimal data. The challenge of continuous-sensing technology is to summarize eloquently and to increase understanding of enormous quantities of information. A number of challenges need to be addressed to help with this problem, for example, new summary measures need to be developed (with allowance for the modifiable areal unit problem); different forms of storing, organizing, and retrieving information need to be implemented; GIS and spatial statistics need to be interfaced; and visual data-analysis techniques need development.

Many agronomists remain limited in their access to the suite of quantitative techniques that are geared toward spatial statistical analysis. To heighten awareness, information needs to be disseminated on the complications arising from applying classical statistics to spatial data, and computer software and guidelines are needed for implementing spatial statistics.

In precision agriculture we have a component of time as well as space, and the time component needs to be incorporated into spatial analyses. Time is a critical component for linking precision agriculture studies with environmental quality. Quantifying the influence of time over the spatial scale would provide additional insights into the linkages between processes and management practices.

DIMENSIONS FOR INVESTIGATION

There are three dimensions for investigation that provide insights into the complexities of interactions between precision agriculture and remote sensing. The first dimension is that of agronomic research. The primary question that arises is this: “How will precision agriculture change the loading of chemicals in space and time across scales of analyses?” Dave Mulla suggested that, at the field scale, adoption of precision agriculture practices would reduce use of crop protection chemicals and phosphorus and nitrogen fertilizer. At the river basin scale, the adoption of precision agriculture techniques on 10 to 20 percent of the land area would have significant impacts on loadings in receiving waters.

Management is another dimension for investigation, and Craig Kvein suggested that efficiency of cropping system inputs can be improved with precision agriculture. There are a number of management practices that producers use to produce a crop, for example, tillage, planting population, irrigation, weed control, insect control, and fertilizer application. These inputs are part of the management complex that farmers must consider, and improvements can be achieved in how these practices affect environmental quality.

The third dimension for investigation is the sociology of producers and the geographic context of the farm. The producer is an element in studies of precision agriculture and environmental quality research. Pete Nowak summarized that environmental problems are not distributed equally in time or space; there is infrastructure heterogeneity in terms of available technology; and there is spatial variance in agronomic behaviors (producers do not follow the same production systems to produce the same crop). These three factors add a dimension that must be understood and quantified in addressing the problem of how to link precision agriculture practices to environmental quality responses. Producers will have to become a major part of the research picture in the development of improved understanding of agricultural practices and environmental quality.

QUESTIONS

The background information discussed at the workshop provided an overview of the complexities facing agriculture in attempting to design experiments that would address the linkage between precision agriculture and environmental quality. Four questions were asked of participants at the workshop:

1. If the environmental consequences of agriculture are a national concern, would a reinvention of agricultural systems and management practices lead to enhanced environmental quality?
2. Is it possible to document the environmental impacts of adopting precision agriculture practices without public funding?
3. What is the appropriate scale at which to conduct research needed on precision agriculture practices and environmental benefits? How do we express the concerns of required experimental precision, applicability of current statistical methods, and the uncertainty of research results that are required for risk assessment of new practices?
4. The issue of precision agriculture and environmental quality involves multiple domains. Economic concerns and benefits are considered short-term and local, while environmental concerns and benefits are long-term and regional or global. How can these domains be considered simultaneously in conducting research and technology transfer?

After several breakout sessions on these questions, workshop participants defined a series of opportunities and challenges.

OPPORTUNITIES AND CHALLENGES

Precision agriculture can have a positive impact on environmental quality. The opportunity exists to show producers how changing production practices will not place crops at risk and produce positive economic and environmental benefits. Conducting these experiments will require field- or farm-scale studies and perhaps watershed-scale adoption of new management practices. Completing this type of study will require:

1. Appropriate questions that can be addressed at the field scale.
2. Methods for measuring environmental endpoints that will demonstrate the efficacy of management practices.
3. Commitment to multiple years of study to overcome meteorological variation.
4. Adequate monitoring equipment for crop production, soil properties, and environmental quality in order to understand the changes occurring due to the management practices.
5. Use of comparison fields or farms in which no changes are made to provide a validation of the improved practices.
6. Cooperation of producers to implement the practices with minor modifications across years so that variations can be isolated to the management practice and not producer influence.
7. Data base structure that includes geographic information layers and accurate global positioning system equipment to position any treatments in the same area across years.
8. Funding sources that will allow for long-term studies across large areas.
9. Interdisciplinary teams that will address the critical problems in experimental design, implementation, and evaluation of results.
10. Commitment from the scientists, producers, and educators involved to maintain interest in the project over a sufficient period of time to allow the original objectives to be achieved.

These 10 factors are critical to the development of a research effort on precision agriculture. The tools are available to address these questions. The scale of the study will require fields or subbasins of watersheds rather than experimental plots or strip trials within fields. This places an additional constraint on the design and implementation of these types of studies and will require integrating producers into the research discussion at the project development stage. One problem that has been a barrier to producer involvement has been the willingness of producers to place new management practices on fields without some assurance that profit margins will not be compromised. This aspect needs to be considered in any study design.

One important problem that will need to be addressed is how researchers begin to ask critical questions about the linkage between new management practices that are differentially applied to the landscape and environmental quality endpoints. Development of the proper question and creating an experimental design to demonstrate the effectiveness of the practice with a high degree of confidence will require a different mindset than is often seen in current agricultural research.

As research proceeds, the educational community must be involved so it understands how to communicate these impacts and changes to the wide array of audiences. There are different tools for the conduct of these studies, and educational efforts will require a different approach to training and information dissemination. The challenge is for the whole agricultural community to understand this problem and what opportunities exist to address the problem.

THE FUTURE

Opportunities will continue for precision agriculture studies. Tools will become available to apply chemicals, fertilizers, tillage, and seed differentially to a field and collect the yield or plant biomass by position across the field. Remote sensing technology will allow us to observe variation within a field throughout the growing season relative to the imposed management changes. Monitoring equipment exists for capturing the surface water and groundwater samples needed to quantify the environmental impact through surface runoff or leaching. The technology exists to capture the volatilization of nitrogen or pesticides from the field into the atmosphere from modified practices.

The future direction of agriculture will depend upon the research community’s ability to conduct this type of study, with confidence from the environmental and producer communities that changes will benefit the environment and increase the efficiency of agricultural production.

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Biographies for Program Presenters and Panelists

WORKSHOP CHAIR
Jerry L. Hatfield, National Soil Tilth Laboratory,
USDA Agricultural Research Service
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JERRY HATFIELD is Director of the National Soil Tilth Laboratory in Ames, Iowa, a post he has held since 1989. Previously, he was Research Leader at the Plant Stress and Water Conservation Unit in Lubbock, Texas and Biometeorologist at the University of California, Davis. During a 1982 sabbatical from UCD, Dr. Hatfield was Research Scientist at the U.S. Water Conservation Laboratory in Phoenix, Arizona and the Evapotranspiration Laboratory in Manhattan, Kansas.

Dr. Hatfield is responsible for the scientific program development and implementation of the National Soil Tilth Laboratory. Priorities include investigating the impact of farming systems on water use and environmental quality; evaluating the impact of livestock systems on water and air quality; and developing tools for the evaluation of livestock and cropping practices on environmental quality. He is chair of the Steering Committee of the multi-agency Agricultural Systems for Environmental Quality program for USDA and Principal Investigator of the Iowa Management Systems Evaluation Areas project on water quality.

Dr. Hatfield holds three degrees in agronomy: a B.S. from Kansas State University; a M.S. from the University of Kentucky; and a Ph.D. from Iowa State University. He is a fellow of the American Society of Agronomy, the Soil Science Society of America, and the Crop Science Society of America. He is a member of the Editorial Board of Advances in Soil Science and Editor-in-Chief for the American Society of Agronomy. He is author or co-author of more than 250 refereed publications and editor of seven monographs.

James S. Schepers
USDA Agricultural Research Service
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JIM SCHEPERS is a soil scientist with the USDA-Agricultural Research Service in Lincoln, Nebraska where he is also an adjunct professor in the Agronomy Department at the University of Nebraska. He received his B.S. and M.S. degrees in Soil Science from the University of Nebraska in 1968 and 1970 and received his Ph.D. in Soil Physical Chemistry from the University of Illinois in 1973.

Dr. Schepers is the Research Leader of the ARS Soil and Water Conservation Research Unit in Lincoln. His research activities include developing management practices and cropping systems to more efficiently use fertilizers, water, and animal wastes so as to protect surface and groundwater quality. Particular interests include using various types of remote sensing to evaluate soil properties and monitor crop growth to enhance precision agriculture practices. Experiences include grid soil sampling, variable rate nutrient application, fertigation, chlorophyll meters, tissue testing, yield monitors, global information systems, and remote sensing.

David A. Mortensen
Department of Agronomy
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DAVE MORTENSEN is Associate Professor of Agronomy at the University of Nebraska-Lincoln. Dr. Mortensen is a well-known weed ecologist and dedicated teacher whose principal research interests include plant ecology, site-specific crop management, integrated weed management, and the development of agronomic decision support software. He recently served on the National Research Council panel entitled *Precision Agriculture in the 21st Century: Geospatial and Information Technologies in Crop Management*. He received the 1994 Distinguished Young Scientist Award by the North Central Weed Science Society and in 1996 served as chair of the weed science panel for the National Research Initiative competitive grants program. He received his Ph.D. from North Carolina State University and his M.S. degree from Duke University.

William E. Larson
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BILL LARSON is Professor Emeritus at the University of Minnesota. His professional efforts have been principally in research, advising of graduate students, and in administration at his various academic assignments. His research interests have centered on applied soil physics, soil mechanics, tillage, erosion control, soil management, and waste utilization on land. He has published over 250 research articles including about 35 chapters for books.

Dr. Larson received his B.S. and M.S. degrees from the University of Nebraska, majoring in soil science. He received his Ph.D. from Iowa State University in 1949 with a major in soil science and a minor in chemistry. Following a brief period as an Assistant Professor at Iowa State University, he joined the USDA Agricultural Research Service at Montana State University. In 1954, he returned to Iowa State University with the ARS. In 1965-66, he spent a year with CSIRO in Adelaide, Australia on a Fulbright Scholarship. In 1967, he transferred to the University of Minnesota, still with the ARS. In 1982, he became Head of the Soil Science Department (now the Soil, Water, and Climate Department) at the University of Minnesota. He retired from that position in 1989, but remains professionally active with writing, lecturing, and consulting. He retains an office at the University of Minnesota.

Dr. Larson was President of the Soil Science Society of America in 1980 and President of the American Society of Agronomy in 1985. He is a Fellow of the Soil Science Society of America, the American Society of Agronomy, the Soil and Water Conservation Society, and the American Association for the Advancement of Science. He received an Honorary Doctor of Science degree from the University of Nebraska in 1985 and has received numerous other awards from scientific societies, universities, and others. He has testified before congressional and legislative committees and served on numerous national science-related committees. He has traveled and lectured in 26 countries.

Shelby J. Fleischer, Department of Entomology
Pennsylvania State University
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SHELBY FLEISCHER is Associate Professor of Entomology at Pennsylvania State University. He served as Research Scientist on the Gypsy Moth Project in the Department of Entomology, VPI & SU in Blacksburg, Virginia from 1987 to 1991 before going to PSU. Dr. Fleischer earned his Ph.D. in Entomology in 1987 from Auburn University in Alabama. He has authored 38 manuscripts since 1995.

Dr. Fleischer is interested in the structure and dynamics of insect populations. Past work focused on developing sampling plans for IPM in alfalfa fields, a 12-million acre areawide project in Appalachian hardwood forests, and leafy greens in the Caribbean. These plans have been widely adopted. More recently, he has emphasized studying spatial structure, and targeting controls with respect to maps of insect density in a manner that is analogous to precision agriculture, which he calls Precision IPM. Students are currently mapping insect densities in alfalfa, potatoes, tomatoes, grape vineyards and within protected structures; data themes are being correlated with maps of plant factors, sex ratio, etc.; and sampling utilizing global positioning systems (GPS) is being developed. Geostatistical measures of describing spatial structure are being defined with respect to changes in insect density, population phenology, and management strategy. Using insect maps to target pesticides achieved a 40% reduction in pesticides, and reductions in phenotypic expression of insecticide resistance due to the creation of within-field temporally dynamic refuges. A categorical approach to pest mapping, where the map expresses the probability of exceeding threshold, is being developed as a tool for Precision IPM.

Concurrently, Dr. Fleischer's Extension assignment is in vegetables and mushrooms. Applied research develops new options based on an understanding of biological and ecological processes. Priority is placed on economically feasible technologies that improve farmworker and environmental safety. The Extension education program works closely with county-based staff at sites accessible to clientele, with presentations at about 20 sites per year, reaching close to 2,000 growers. Environmental issues, such as the Food Quality Protection Act of 1996, are influencing both the Extension and Research programs.

Daniel S. Long
Northern Agricultural Research Center,
Montana State University, Havre, Montana

DAN LONG is Assistant Professor in Crop/Range Science in the Department of Research Centers at Montana State University, a post he has held since 1994. He is stationed at the Northern Agricultural Research Center in Havre where his research focuses on developing site-specific crop and range management practices in the Northern Great Plains and transferring this information to the private and public sectors. He helps provide scientific leadership in designing and conducting field research of spatially variable crop and range landscapes using geographic information systems, Global Positioning System, remote sensing, soil survey, and spatial statistics. Currently, he participates in a variety of team-oriented field research programs including: identifying potential nitrogen deficiencies and prescribing fertilizer inputs using information from on-the-go sensing of wheat yield and protein content; determination of profitability of variable-rate fertilizer and pesticide applications; aerial mapping for site-specific management of wild oats; remote sensing to regionally assess quality of wheat and range forage; comparison of pest management interactions in wheat-cover crop and wheat-fallow cropping systems; and establishment of a GPS-based livestock tracking system.

Dr. Long holds a B.S. degree in Soils from Washington State University and an M.S. degree in Soils from Montana State University. He earned his Ph.D. in Agronomy with emphasis in land resource inventory and analysis from Cornell University in 1993. Between 1992 and 1993, he was with the Department of Soil Science, University of Minnesota, assisting Dr. P. C. Robert in his research program in site-specific management. He served in the U.S. Coast Guard from 1971 to 1977.

Dave Mulla
Department of Soil, Water, and Climate,
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DAVE MULLA is a Professor at the University of Minnesota where he serves as the W. E. Larson Chair for Soil & Water Resources in the Department of Soil, Water, and Climate. Previously he served on the faculty at Washington State University in Soil Physics in the Department of Crop and Soil Sciences from 1983 to 1995. In 1991, Dr. Mulla's research accomplishments in spatial variability and site-specific crop management were recognized when he received the Junior Faculty Research Award in WSU's College of Agriculture and Home Economics.

He received a B.S. with emphasis in geophysics from the University of California at Riverside in 1979. He obtained the M.S. and Ph.D. degrees in Agronomy from Purdue University with emphasis in soil chemistry (1981) and soil physics (1983), respectively.

Dr. Mulla and his coauthors have produced over 70 publications, including 49 refereed journal publications and chapters in books, 15 technical papers and reports, 7 extension publications, and numerous published abstracts. His research has been funded by State and Federal agencies or agribusiness at over $3,400,000. He has directed 3 post-doctoral research associates, 9 M.S. and 9 Ph.D. graduate student theses, and been a member of the thesis advisory committee for over 13 M.S. and 22 Ph.D. students.

Dr. Mulla is a recognized researcher and scholar in Soil Science. His scientific peers recently elected him Fellow and Division Chair for Soil Physics (S-1) in the Soil Science Society of America (SSSA). He served two terms as Associate Editor for SSSA Journal (Division S-1), and is currently Technical Editor for SSSAJ. In 1994, he was selected as Panel Manager for the $3.8 million USDA-CSRS National Research Initiative Competitive Research Grants Program in Water Resources Assessment and Protection.

Peter Nowak
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PETE NOWAK is a Professor at the University of Wisconsin. At the College of Agriculture and Life Sciences in Madison, he holds an appointment as a research professor in the Department of Rural Sociology, a Soil and Water Conservation Specialist in UW Extension's Environmental Resources Center, and is a Co-Director of the College's Nutrient and Pets Management Program. He served as both an assistant and associate professor at Iowa State University before joining the faculty at the University of Wisconsin in 1985.

Dr. Nowak's work has focused on the adoption of new agriculture technologies with a special emphasis on those practices with natural resource implications. He also served on the Board of Directors of the Soil and Water Conservation Society, the Editorial Board of the Journal of Soil and Water Conservation, Editorial Board of the Journal of Precision Agriculture and serves on the Board of the Foundation for Environmental Agricultural Education. He received his Ph.D. from the University of Minnesota's College of Agriculture in 1977.

Craig K. Kvien
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CRAIG KVIEN is Professor of Crop Physiology in the Department of Crop & Soil Sciences at the University of Georgia. Dr. Kvien chairs the 8-member executive committee which governs the National Environmentally Sound Production Agriculture Laboratory (NESPAL). This research facility is dedicated to the development of environmentally and economically sound agricultural production systems. To meet its broad-based research goals, NESPAL integrates a wide range of research disciplines into a cohesive research unit dedicated to the development of environmentally and economically sound production agriculture systems. Scientists working with NESPAL have expertise in the disciplines of animal science, chemistry, crop science, ecology, economics, engineering, entomology, food processing, horticulture, information and technology transfer, microbiology, plant pathology, precision farming, rural sociology, soil science, statistics, systems analysis, toxicology, and weed science.

One of NESPAL's research programs focuses on helping build the human and technical resources required to enable southeastern agriculture to benefit from precision farming technologies. This program involves members of many departments of the University of Georgia, the USDA, NASA, Georgia farm operations, major food companies, and many agricultural equipment and service companies.

Francis J. Pierce
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FRAN PIERCE serves as Professor of Soil Science in the Department of Crop and Soil Sciences at Michigan State University (MSU). He obtained in MS and Ph.D. degrees in Soil Science from the University of Minnesota. Dr. Pierce's responsibilities at MSU include teaching a course in Soil Management and Environmental Impacts to 45 students annually and conducting research in soil management. Since arriving at MSU in 1984, his research has focused on soil management, with a special emphasis on conservation tillage systems and their impact on crop production and soil and water quality. In the 1990s, he has worked to develop the concept of soil quality and methods to assess changes in soil quality in relation to land use.

Dr. Pierce is also working to develop site-specific or precision management systems for agriculture based on the principle of managing the spatial and temporal variability in soils and crops. He has recently co-authored an overview of precision agriculture for Advances in Agronomy entitled "Aspects of Precision Agriculture" with Peter Nowak. He currently serves on the design team and as chair of the cropland working group as part of the national effort facilitated by the H. John Heinz III Center for Science, Economics, and the Environment in Washington, DC, to develop a report on the state of the nation's ecosystems.

Marc Vanacht, President
Metz Vanacht Consulting
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MARC VANACHT is recognized for his insights in strategic applications of information technology in agriculture, such as precision farming, and in the Internet, intranets, strategic databases, and customer service.

He works with and consults commercial companies involved in agriculture, both in the U.S. and abroad. He has given briefings to consulting, aerospace, consumer goods, financial, information services, and computer companies about recent structural and information technology trends in the agricultural market.

Mr. Vanacht was a member of the “Task Force on Future Directions in Field Office Business Process Automation” (1997), and the “Blue Ribbon Panel on Data Collection and Analysis” (1995), and also of the Natural Resources Conservation Service (NRCS), an agency of the USDA.

Mr. Vanacht has Bachelor’s degrees in Philosophy and Economics, and Master’s degrees in Law and Business Administration. He is fluent in five languages.