United States Department of Agriculture

NRCS

Natural Resources Conservation Service

East National Technology Support Center

Soil Quality National Technology Development Team

June 2007

Agronomy Technical Note No. 1

Precision Agriculture: NRCS Support for Emerging Technologies

Issued June 2007

Agronomy Technical Note No. 1 was prepared by Philip R. McLoud and Ron Gronwald, Technology Transfer and Assistance Team, and Holli Kuykendall, Soil Quality National Technology Development Team, East National Technology Support Center, Natural Resources Conservation Service, Greensboro, North Carolina.

For further information, contact the East National Technology Support Center at (336) 370–3331.

Precision Agriculture: NRCS Support for Emerging Technologies

Introduction to "as needed" farming

There are many definitions of precision agriculture, and the definition is often influenced by the commercial equipment or technology currently in vogue. For the purposes of this technical note, precision agriculture is defined as: **a management system that is information and technology based, is site specific and uses one or more of the following sources of data: soils, crops, nutrients, pests, moisture, or yield, for optimum profitability, sustainability, and protection of the environment** (adapted from Precision Ag. 2003). This definition fits very well with Hugh Hammond Bennett's admonition to "… use every acre within its capability and treat it according to its needs."

There are many potential impacts from precision agriculture. Some of the primary impacts are cost reduction and more efficient use of production inputs, use of information technology to increase the size and scope of farming operations without increasing labor requirements, improved site selection and control of production processes that help in the production of higher value or specialty products, improved recordkeeping and production tracking for food safety, and environmental benefits (Lowenberg-DeBoer and Boehlje 1996). From the farmer's perspective, precision agriculture is primarily driven by economic return but, in many cases, site-specific management provides a positive environmental impact. Soil and water quality benefits can result from reduced or targeted application of inputs such as nutrients, pesticides, and irrigation water. When used to precisely control where equipment travels in a field, precision agriculture can also reduce soil compaction and erosion (Bongiovanni and Lowenberg-DeBoer 2004).

At a basic level, precision agriculture can include simple practices such as field scouting and the spot application of pesticides. However, precision agriculture usually brings to mind complex, intensely managed production systems using global positioning system (GPS) technology to spatially reference soil, water, yield, and other data for the variable rate application of agricultural inputs within a field. Research is ongoing to develop or improve yield monitoring methods and equipment, determine economic and environmental impacts of variable rate application of agricultural inputs, and use remotely sensed data to make management recommendations.

Many farmers think that precision agriculture will allow them to achieve uniform production over their farm. In reality, the goal of precision agriculture should be to optimize inputs for agricultural production according to the capability of the land. Precision agriculture methods help farmers recognize areas that have productivity and environmental problems and to select the best solution for each one. At the extreme, precision agriculture may help a producer identify land that should be taken out of the current production system because of economic and environmental considerations.

Curiosity, economic, and production considerations might be the first things to entice a farmer to investigate precision agriculture methods. However, NRCS assistance in developing a plan to use precision agriculture to address a resource concern could be the incentive a farmer needs to invest in the information management and equipment required for precision agriculture. This technical note identifies some of the positive environmental impacts from precision agriculture and how NRCS can help farmers achieve them.

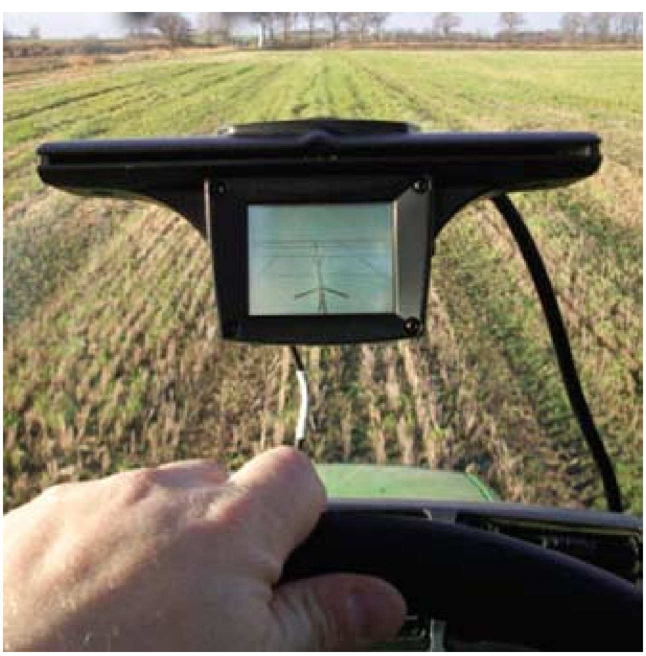
Equipment, methods, and technology supporting precision agriculture

Auto-steer—a GPS guidance system that steers agricultural equipment with centimeter accuracy. This level of accuracy requires real time kinematic (RTK) correction of GPS signals. Auto-steer is an add-on component for equipment. It includes both the GPS system to receive and process the signals, software and hardware to allow the input of control maps and the mechanical equipment to actually steer the tractor. Some new tractors are available "auto-steer ready."

Light bar guidance systems—a GPS guidance system mounted in the cab of agricultural equipment that provides direction to the driver by means of a horizontal display of lights (fig. 1). A series of lights enables the operator to align the tractor with the next set of rows requiring treatment to prevent overapplication of nutrients or pesticides. Newer models can provide some auto-steer functions. Light bars are less accurate than RTK auto-steer systems and are generally used for spreading or spraying applications. Light bar technology is relatively inexpensive and can quickly have an environmental payoff.

Differential GPS—a generic term for the process to improve the positional accuracy of satellite broadcast GPS signals. Differential GPS (DGPS) requires that a GPS receiver be set up on a precisely known location. This GPS receiver is the base or reference station. The base station receiver calculates its position based on satellite signals and compares this location to the known location. The difference is applied to the GPS data recorded by the second GPS receiver, which is known as the roving receiver. The corrected information can be applied to data from the roving receiver in real time in the field using radio signals or through post processing after data capture using special processing software. The positional error of these systems is generally 1 to 3 meters. The U.S. Coast Guard system and Wide Area Augmentation System (WAAS) are examples of widely available DGPS signals. In some areas of the country, DGPS signals are available commercially.

Figure 1 Light bar guidance system



Commercial differential GPS—commercially available DGPS signals. These signals are available from several companies that provide a wide-area DGPS service using satellite broadcast techniques. Data from many widely spaced reference stations are used to achieve sub-meter positioning. The signal is proprietary and users are charged a fee.

Nationwide differential GPS—a system operated by the U.S. Coast Guard using 37 ground stations that provide GPS signal corrections to provide better position accuracy. Nationwide differential GPS (NDGPS) service is provided for the coastal continental United States, the Great Lakes, Puerto Rico, portions of Alaska and Hawaii, and a greater part of the Mississippi River Basin. NDGPS provides accurate dynamic navigation information with 1-meter accuracy (accuracy deteriorates as the distance to the ground station increases). There is no charge for this service.

Wide area augmentation system—a system of satellites and ground stations that provide GPS signal corrections to provide better position accuracy. A WAAS-capable receiver can give a position accuracy of better than 3 meters 95 percent of the time. WAAS is operated by the Federal Aviation Administration. This signal is available without charge.

Real time kinematic—a process to produce very accurate locations from GPS signals. RTK is currently the most accurate and most expensive commercially available GPS system. RTK systems use a single base station receiver and one or more mobile units. The base station can be a temporary base station set up by farmers for their own use or permanent station set up to broadcast a signal for general-purpose use. In some parts of the country, there are commercially available RTK signals. The base station re-broadcasts the phase of the carrier that it measured, and the mobile units compare their own phase measurements with the ones received from the base station. This allows the units to calculate their relative position to millimeters, although their absolute position is accurate only to the same accuracy as the position of the base station. The typical nominal accuracy for these dual-frequency systems is 1 centimeter (3/8 inch) ± 2 parts-per-million (ppm, refers to the variance or level of uncertainty of the measurement) horizontally and 2 centimeters (3/4 inch) ± 2 ppm vertically.

Grid sampling—the collection of samples from small, uniform-sized cells based on a systematic grid laid out across a field. Grid location in the field is used to develop a field map for the attribute measured. Samples can be taken from within cells or, more commonly, in the immediate vicinity of the grid point. Grid sampling is a popular sampling strategy for precision agriculture because it is relatively easy to implement, and there is potential to discern patterns in a field about which little else is known or for which no spatial information exists (Pocknee et al. 1996). However, grid sampling can be expensive and time consuming, while not providing the best information about a field. Grid sampling should be the start for the development of more sophisticated strategies such as directed sampling.

Directed sampling—a strategy for dividing a field into units based on prior knowledge of spatial patterns within the field and then sampling each of the units individually with an intensity appropriate for its variability. Information sources include soil type, management history, yield, and past grid sampling maps, as well as aerial crop and soil color images. Sampling different soil types separately is supported by several university soil testing laboratories. GPS, geographic information systems, and variable rate technology are removing some of the barriers to collecting and practically applying the information gained from this sampling method (Pocknee et al. 1996).

Management zones—specific areas within a field that respond to management practices in a similar way. Management zones are developed based on data collected from a field. The type of data collected and the establishment of the zones is dependent on the management objectives.

Remote sensing—data from light reflectance collected by instruments in airplanes or orbiting satellites. The data can estimate vegetation characteristics on small areas within a field. High-resolution (1–5 meters) satellite images are currently available to producers from private vendors.

Variable rate application—computer-controlled equipment that continually readjusts the application. Sampling data provides the prescription for the particular fertilizers or pesticides to be applied to each area. A GPS receiver in the spreader truck enables the computer to recognize where it is in the field. Computer-controlled nozzles vary the types and amounts of inputs according to the variable rate application plan.

Yield monitoring systems—area-specific yields in the field are measured using combine-mounted sensors or volume meters. A GPS receiver mounted on the combine supplies the spatial coordinates so that estimates of yields can be assigned to small areas of a field to create a yield map. Yield monitors are available for grain, forage, and cotton crops.

The building blocks of a precision agriculture system

The starting point for developing a precision agriculture plan may be different depending upon the results a farmer is trying to achieve. However, in general, to be successful with precision agriculture from both an economic perspective and environmental perspective, a farmer should have the following basic components:

- background data
- a recordkeeping system
- analysis and decision making process
- specialized implementation equipment
- evaluation and revision

Background data is spatial information about crop production fields that is used to make decisions. Sources of background data include grid soil samples, detailed soil mapping, aerial photography, topographic maps, yield maps, soil texture maps, environmentally sensitive areas, and others. Background data needs to be georeferenced or tied to an identified location in the field. For precision agriculture, the locations are usually identified with GPS. Some of this data, such as aerial photography and topographic maps are available already georeferenced. Other data will need to be georeferenced as it is collected.

A recordkeeping system is very important for successful implementation of precision agriculture. Precision agriculture can produce large amounts of data. If the farmer does not have a way to organize and process the data, it will become overwhelming and meaningless. Commercial software packages can help with this task by producing maps that allow the farmer to see differences within fields. In many cases, farmers use consultants to assist them with recordkeeping. With proper organization, records become background data the farmer needs to make decisions.

An analysis and decisionmaking process is a crucial step in developing a precision agriculture plan. Data is meaningless unless it is properly analyzed and the results applied to solve a problem or meet farm goals. Because of the complexity of the information and time requirements, a qualified crop consultant may be needed to analyze the data and make recommendations to achieve the desired outcome.

Specialized implementation equipment may be needed to precisely apply variable rates of crop inputs and measure yields to understand crop response. GPS guidance systems, variable rate application equipment, and yield monitors are examples of the type of equipment that might be needed. Specialized equipment, such as electrical conductivity and moisture measuring devices, may also be needed for data collection to help develop the precision agriculture plan.

Evaluation and revision of the precision agriculture plan is needed after each cropping season. As more data is gathered for each crop and year of production, more can be learned about the field. More information allows further refinement of the precision agriculture plan.

The benefits of precision agriculture

The primary benefits from precision agriculture, both economic and environmental, result from reduced or targeted placement of crop inputs such as nutrients, pesticides and water. There are many other benefits.

Precise nutrient applications can provide significant economic and environmental benefits. The goal is to apply only the nutrients that the plants need and can use. In addition, there may be a need to control application in environmentally sensitive areas. Application rates will vary within the field based on existing fertility levels, soil types, and environmental sensitivity. Some soils in a field simply do not have the yield potential to justify maximum rates of nutrient application. Other areas may require reduced rates because of environmental sensitivity.

One of the objections many farmers have to variable application of nutrients is that it may require three trips over a field to precisely apply N, P, and K. The number of trips can be reduced by applying a blend of N and either P or K that best matches the required ratio of these nutrients and then making another pass to spot apply the third nutrient to areas that are deficient in it. Lime, on the other hand, can be applied in one trip. By knowing georeferenced lime requirements, a farmer may quickly recoup equipment and planning costs in lime savings.

Variable rate application requires equipment that can control application according to its location in the field. WAAS or other sub 3 meter accuracy GPS systems (as opposed to RTK) are usually sufficiently accurate to control application equipment.

The information necessary to determine appropriate nutrient application rates can include the following items. Not all of this information is needed, but more information can provide more detailed application maps.

- Grid soil sampling—over time, as more information is learned about a field, grid sampling can evolve into sampling of similar zones to reduce the number of samples taken.
- Yield monitoring—knowing how much different areas of a field actually yield provides perhaps the most important clue about potential and appropriate application rates.
- Detailed soils information—knowing the properties of the soils in a field provides important information about yield potential and environmental sensitivity. County soils maps, while helpful, generally do not provide the necessary level of detail. Electrical conductivity mapping provides information about soil texture that is useful in understanding its production potential.
- Remote sensing—new technologies will use aerial photography to identify in-season nutrient deficiencies and other problems causing crop stress and reduced yield. This is an evolving science. Generally, field scouting is still necessary to positively identify the cause of poor growth patterns identified remotely.
- Environmentally sensitive areas—georeferenced the location of waterways, streams, ditches, wetlands, high leach potential soils, and tile inlets can help protect these areas from over application of nutrients.

Precise pesticide applications can provide both environmental and economic benefits. One of the quickest and least expensive environmental payoffs for pesticide applications is the use of light bar guidance systems. Light bar guidance systems are relatively inexpensive, compared to other guidance systems, and they provide an easy way to guide equipment across a field to prevent overlapping when spraying pesticides. More sophisticated variable rate application plans can be developed for pesticides, similar to those used for nutrients, but additional planning information and equipment will be needed for implementation. As with nutrients, sub three-meter accuracy is usually sufficient for the variable rate application of pesticides.

The information necessary for the variable rate application of pesticides can include the following items. As with nutrients, not all of this information is needed, but more helps.

- Scouting—georeferencing areas that show insect or weed problems.

- Remote sensing—new technology promises to identify in-season insect damage from aerial photography.
- Yield monitoring—when other causes have been ruled out, pests may be the cause of low yields.
- Environmentally sensitive areas—georeferencing the location of waterways, streams, ditches, wetlands, high leach potential soils, and tile inlets can help protect these areas from over application of pesticides.
- Detailed soils information—knowing the properties of the soils in a field will provide important information about yield potential and environmental sensitivity. County soils maps, while helpful, generally do not provide the necessary level of detail. Electrical conductivity mapping provides information about soil texture that is useful in understanding the potential for a soil.

Variable rate irrigation is an emerging technology that is being used in conjunction with center pivot irrigation systems. Center pivot irrigation systems typically apply a relatively uniform amount of water. The variable nature of fields may result in different amounts of water being needed in different areas. The variability in a field is caused by any combination of factors such as variable soil types, topography, or multiple crops.

In addition to variability, center pivot irrigation is complicated by irregularly shaped fields, overlapping center pivot systems, and the presence of farm lanes and farm ditches. A possible solution lies in matching field variability with an equally variable irrigation application. The technology to do this is known as variable rate irrigation.

Research projects dealing with spatially variable irrigation water application have been ongoing for a number of years (Evans and Harting 1999; Heerman, Hoeting, and Duke 1999; Perry, Pocknee, and Hansen 2003; Sadler et al. 2000). The rate of application is controlled by varying the amount of time a sprinkler or a bank of sprinklers is “on.” This is accomplished using air solenoids and water control valves that are connected to an air compressor using air lines. The rate of application is also controlled by varying the speed at which the center pivot moves.

Systems have been installed in the southeastern part of the country that are providing water savings. However, some farmers have questions about the long-term reliability of systems and the economic return on investment. As the technology continues to mature, the reliability should increase. The economic return will be dictated by the expense and regulation of water and the value of crops grown.

To retrofit an existing center pivot system can be expensive. In 2007, the average was about $15,000, but it is highly variable depending on the length of the system and the degree of spatial resolution desired. Based on a study made of three VRI systems installed on commercial farms in South Georgia, it was found that 5.7 million gallons of water were saved on 279 acres in 2002.

A 2-year study conducted in Idaho compared water use and crop production in a potato field with a variable rate center pivot irrigation system. The field was divided into zones, and one set of zones was provided with variable rate irrigation based on the available soil moisture in each zone. The other set was given a uniform irrigation based on the average available moisture in those zones. The study found no significant water savings using variable rate technology and the slight improvement in yield was unlikely to justify the cost of the variable rate components (King, Stark, and Wall 2006).

Variable rate irrigation systems require a custom design and specialized equipment, as well as extensive planning of water application zones. Water application zones may be based on soil properties, soil moisture monitors, yield maps, topography, and producer knowledge of the field. Design of these systems should be done by irrigation professionals with experience in variable rate irrigation.

Other uses for precision agriculture may or may not be related to the variable rate application of inputs. One of the most important uses is the control of traffic on fields to limit compaction to defined wheel tracks. With GPS auto-steer for all equipment used in the field, the same wheel tracks are used year after year. Over time, this will result in less compaction and improved soil quality in the areas outside the wheel tracks where crops are planted.

Auto-steer tractors can also be used to precisely follow a contour line or other established alignment. This can help with the establishment and maintenance of any field practices that must be on or near the contour or must be parallel to some existing alignment, such as a fence or wind break. Some examples where auto steer is useful are:

- marking off contour strips once the alignment is identified

- plowing in parallel terraces once the key terrace is identified
- maintaining parallel terrace systems
- planting vegetative barriers along a contour or other previously identified alignment
- planting in relationship to subsurface drip irrigation lines
- avoiding buried irrigation lines or other buried infrastructure with tillage equipment

Auto-steer equipment was used to plant rye wind strips along a contour to protect watermelon seedlings from damage caused by wind (fig. 2). The practice controls erosion, protects water quality, and improves the quality of the crop.

With the increased interest in using biomass for energy production, precision agriculture may allow for variable rate harvest of biomass based on the ability of the soil to withstand the loss of residue for erosion protection and sustainable soil quality. This is an emerging technology, and the factors necessary for decision-making, as well as equipment for variable harvest, are still being developed. A method to use RUSLE2 to estimate the quantity of residue available for harvest at sustainable soil loss levels is described in Soil Quality—Agronomy Technical Note No. 19, Crop Residue Removal for Biomass Energy Production: Effects on Soils and Recommendations.

Variable rate technology can also be used to adjust seeding rate. Seeding rate may need to be higher or lower depending on the soil's ability to support the target plant population, potentially increasing ground cover and erosion protection.

Table 1 presents costs associated with implementing a precision agriculture system.

Figure 2 Rye wind strips planted on the contour

Table 1 Costs to implement precision agriculture

	Costs	Benefits
Background data	Time is required to collect data or pay a consultant for the service. Soil sampling generally costs $3–7/a, but can be considerably more for more intensive collection. Other services from a crop consultant are generally based on an hourly charge.	Data may identify problems and opportunities the farmer was unaware of. This can be particularly true of low-yielding areas or environmentally sensitive areas where overapplication of crop inputs may cause problems.
Recordkeeping	Software can range from very little for shareware or public domain packages to several thousand dollars for commercial mapping or geographic information system programs.	Organized data allows the farmer to make logical decisions.
Analysis and decisionmaking	Crop consultants generally charge $40–80/hr.	Analysis allows the farmer to make the right economic and environmental decisions.
Equipment	Auto-steer: $30,000–40,000 Light bar guidance: $3,000–5,000 Yield monitors: $4,000–7,000 Variable rate spray/fertilizer controller: $2,000–3,000	Crop inputs can be reduced and the environment protected.

Environmental concerns: NRCS' role in precision agriculture

To date, the main driving force behind precision agriculture has been the economic return to the farmer. Many people recognize that precision agriculture, in some instances, may also have a positive environmental impact. The most appropriate role for NRCS in precision agriculture seems to be to encourage techniques that address an environmental issue. In some localities, NRCS is currently rewarding farmers with payments through conservation programs to implement aspects of precision agriculture. However, to achieve a positive impact on the environment, the use of precision agriculture needs to be part of a system that is developed specifically to address a resource concern. To be effective, the entire system needs to be implemented, not just a few random precision agriculture techniques.

Following are a series of steps that can be used in developing a precision agriculture system that addresses an environmental issue. The important concept to consider is the development of a strategy that uses precision agriculture techniques to address an environmental problem with a system of actions that NRCS can encourage through technical assistance and conservation programs.

Steps for the environmental focus of precision agriculture

1. Identify a resource concern for which precision agriculture techniques can have a positive impact.
   - Identify the precision agriculture techniques that can be used to address the resource concern.
   - Determine which techniques have the most positive effect on the resource concern and can be used by farmers.

2. Identify background data that is needed to address the resource concern.
   - Consider the difficulty of collecting the data and whether the farmer can collect the data independently or if a consultant is needed.
   - Determine if specialized equipment is needed and available to collect the data.
   - Consider the use and value of data, records, or other information the farmer collects for other purposes.

3. Determine if the farmer has an appropriate method to keep track of geospatial data.
   - The farmer needs to develop or acquire a recordkeeping system or hire a consultant to organize data so that it can be analyzed.

4. Develop a plan for how precision agriculture will be used to address the resource concern.
   - Analysis of the background data is required.
   - A consultant might be needed to analyze the data and develop a farm-specific plan to address the resource concern using precision agriculture.

5. Determine the type and availability of specialized equipment required to implement the plan.
   - This might include an auto-steer tractor, a light bar guidance system, variable rate application equipment, a yield monitor, or other equipment.

6. Evaluate and revise the plan after each cropping season.
   - The results of this evaluation feed back into steps 3 and 4 to allow the farmer to fine tune the precision agriculture plan for the next cropping season.

NRCS may provide payments through conservation programs to offset the cost of some or all of these steps to implement a precision agriculture system to solve a resource concern.

Precision agriculture for the environment

The following is an example of how a resource concern can be addressed by encouraging the use of precision agriculture methods.

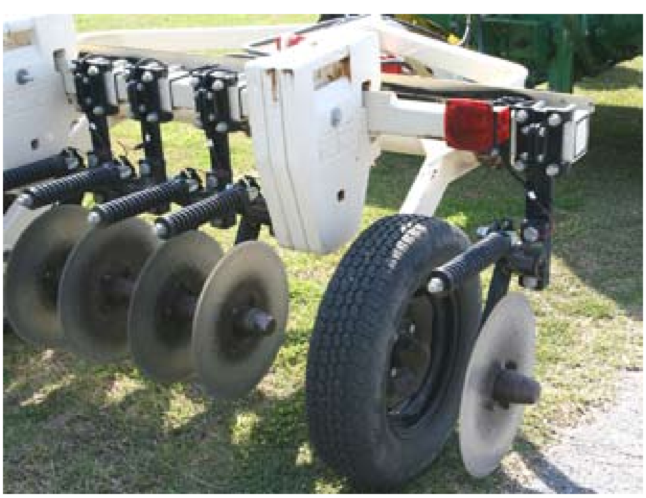
Pest management prescription

Resource concern—Root knot nematodes cause millions of dollars of losses annually to cotton and peanut growers. Nematicide treatment to control root knot nematodes can be expensive and controversial because of health concerns for farm laborers exposed to the chemicals (Vick, Caulkins, and Zapp 2000), and the potential for nematicides to negatively effect ground water quality and nontargeted soil biology (National Registration Authority for Agricultural and Veterinary Chemicals 2001). Producers typically treat their entire cotton and peanut acreage with nematicide when the level of infestation and economic damage to the crop is perceived to justify the expense of application. However, root knot nematode populations are not evenly distributed, but instead have higher populations in sandy, coarse textured areas of fields. Cotton yield losses to root knot nematodes usually range from 10 to 25 percent, but may exceed 50 percent in sandy fields exposed to drought conditions (Gazaway 1996). To reduce economic and environmental risks associated with nematicide application, precision agriculture can be used to limit treatment to areas of the field that have high infestations of nematodes.

Background data—Geospatially referenced electrical conductivity measurements can be used to delineate sandy areas of a field since the primary electric conductivity response is due to soil texture variances (National Environmentally Sound Production Agriculture Laboratory 2007). Electrical conductivity is measured on-the-go using commercially available equipment (fig. 3). Geospatially referenced yield data can identify areas in the field with low yield. Field scouting may be needed to confirm low yields are the result of nematodes.

Recordkeeping—A system will be needed to store electrical conductivity data, yield and scouting results, and produce maps from the data.

Figure 3 Georeferenced electrical conductivity equipment is used to develop soil texture maps



Data analysis and decisionmaking—The data must be reviewed and a plan developed for where nematicide will be applied. This should result in a spatially referenced pesticide application map to be used with precision agriculture equipment to control "on/off" nematicide application to treat targeted areas, while leaving nontarget areas untreated.

Implementation—A GPS guidance system will be needed for the pesticide application equipment. A sub 3 meter accuracy system, such as a light bar should be adequate for this task. Variable rate spray equipment controlled by GPS will be needed to control pesticide application. Yield monitoring equipment may be needed to develop background data and evaluate the precision agriculture plan.

Evaluation—Yield data and field scouting should be used each year to develop spraying plans for the next season.

Summary

Economic return on investment is paramount to a producer's voluntary investment in precision agriculture equipment. Without doubt, the question is asked, "Will precision agriculture equipment pay for itself with increased yield and more efficient application of required agricultural inputs?" Interviews with several large producers in southwest Georgia engaged in precision agriculture confirm that production enhancement is their primary motivation.

While some producers recognize resource protection as a secondary benefit, it is seldom the primary motivator for precision agriculture. There are many resource concerns that can be addressed with precision agriculture. They include nutrient and pesticide application effects on surface or ground water quality; pesticide effects on nontarget species, nutrient cycling, and pesticide resistance; overapplication of agricultural chemicals due to operator error or inaccurate row marking equipment; heavy equipment and traffic effects on compaction, infiltration, and runoff; and under or overapplication of irrigation water based on the general needs of a field rather than zone specific requirements. NRCS can help producers recognize the potential for precision agriculture to address these problems and how it might be used to accomplish this. In cases where the use of precision agriculture can provide an important means to address a resource concern, NRCS assistance might provide the impetus to encourage producers to make the investment in precision agriculture.

References

Bongiovanni, R., and J. Lowenberg-DeBoer. 2004. Precision agriculture and sustainability. Precision Agriculture 5:359–87.

Evans, G.W., and G.B. Harting. 1999. Precision irrigation with center pivot systems on potatoes. *In* Proceedings of the ASCE 1999 International Water Resources Engineering Conference. Seattle, WA.

Gazaway, W. 1996. Nematodes in Cotton in Alabama. Alabama Cooperative Extension System. ACES. *http://www.aces.edu/pubs/docs/A/ANR-0967/*. Accessed May 31, 2007.

Heerman, D.F., J. Hoeting, and H.R. Duke. 1999. Interdisciplinary irrigated precision farming research. *In* Proceedings of the Second European Conference on Precision Agriculture. J.V. Stafford, ed. Sheffield Academic Press Sheffield. United Kingdom.

King, B.A., J.C. Stark, and R.W. Wall. 2006. Comparison of site-specific and conventional uniform irrigation management for potatoes. Journal of Applied Engineering in Agriculture 22:667–88.

Lowenberg-DeBoer, J., and M. Boehlje. 1996. Revolution, evolution or dead-end: economic perspectives on precision agriculture. *In* Proceedings of the Third International Conference on Precision Agriculture. P.C. Robert, R.H. Rust, and W.E. Larson, eds. American Society of Agronomy, Crops Science Society of America, Soil Science Society of America. Madison, WI.

National Environmentally Sound Production Agriculture Laboratory: Precision Agriculture. Using soil electrical conductivity to identify nematode-prone areas in a field. *http://nespal.cpes.peachnet.edu/precisionag/nematode.asp*. Accessed May 31, 2007.

National Registration Authority for Agricultural and Veterinary Chemicals. 2001. Evaluation of the new active 1,3–DICHLOROPROPENE in the products Telone Soil Fumigant and Telone C–35 Soil Fumigant. Australian Pesticides and Veterinary Medicines Authority. *http://www.apvma.gov.au/publications/prsdic.pdf*. Accessed May 31, 2007.

Perry, C., S. Pocknee, and O. Hansen. 2003. A variable rate pivot irrigation control system. *In* Proceedings of the Fourth European Conference on Precision Agriculture. J. Stafford, and A. Werner, eds. European Commission on Preservation and Access.

Pocknee, S., B. Boydell, H. Green, D. Waters, and C. Kvien. 1996. Directed soil sampling. *In* Proceedings of the Third International Conference on Precision Agriculture. P.C. Robert, R.H. Rust, and W.E. Larson, eds. American Society of Agronomy, Crops Science Society of America, Soil Science Society of America. Madison, WI.

Precision Agriculture. 2003. *http://www.precisionag.org/html/introduction.html*. Accessed May 31, 2007.

Sadler, E.J., R.G. Evans, G.W. Buchleiter, B.A. King, and C.R. Camp. 2000. Design considerations for site specific irrigation. *In* Proceedings of the Fourth Decennial National Irrigation Symposium. R.G Evans, B.L. Benham, and T.P. Trooien, eds. American Society of Agricultural Engineers. St. Joseph, Ml.

Vick, K., P. Caulkins, and B. Zapp. 2000. USDA/EPA MeBr Working Group Report on Efficacy and Regulatory Issues of Telone. USDA Agricultural Research Service. *http://www.ars.usda.gov/is/np/mba/jul00/telone.htm*. Accessed May 31, 2007.