Resources & Environment


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# Precision Agriculture: Information Technology for Improved Resource Use

*A farmer walks through his soybean field in central Illinois, heading for a spot pinpointed by a remote sensing image the farmer downloaded in that morning's e-mail. Pest infestation in this small spot, indicated by a change in the "vegetative index," would not ordinarily be detected this quickly. Untreated, it could spread rapidly and destroy his entire crop. The farmer opens his palmtop computer, brings up information on the pest, completes an economic threshold analysis, and determines what control measures he will use. He records the exact location of the infestation using the integral global positioning system (GPS) receiver and alerts his pest control advisor and custom pesticide applicator via cellular phone link.*

*Meanwhile, a wheat farmer in Nebraska is recording yields as her combine passes through the field, pinpointing the location of each yield amount with the GPS receiver linked to the yield monitor. This and previous years' yield maps entered into a geographic information system (GIS) help her plan the fertilizer regime for this field to optimize economic yield and reduce nitrogen leaching to the groundwater.*

These vignettes are not science fiction. Precision agriculture (PA), a new suite of information technologies, has the potential to improve resource use, increase profits, and reduce environmental impacts of agricultural production. While its promises are attractive, the performance of PA systems remains largely unproven. The National Research Council (NRC) recently convened an expert committee to assess precision agriculture and explore its implications for 21st-century farming, particularly for the public role in its adoption and development. This article highlights the committee's findings.

### *What Is Precision Agriculture?*

As with any fledgling technology, precision agriculture has various definitions. The NRC committee defines it as "...a management strategy that uses information technologies to bring data from multiple sources to bear on decisions associated with crop production." Fundamentally, precision agriculture acknowledges that conditions for agricultural production—as determined by soil resources, weather, and prior management—vary across space and over time. Given this inherent variability, management decisions should be specific to time and place rather than rigidly scheduled and uniform.

Precision agriculture provides tools for tailoring production inputs to specific plots within a field, thus potentially reducing input costs, increasing yields, and reducing environmental impacts by better matching inputs applied to crop needs. Information technologies used in precision agriculture cover three aspects of production: data collection or information input, analysis or processing of the precision information, and recommendations or application of the information.

*Data collection* occurs both before and during crop production, and is enhanced by collecting precise location coordinates using the GPS. Data collection technologies operating in advance of crop production include grid soil sampling, yield monitoring, remote sensing, and crop scouting.

Other data collection takes place during production through "local" sensing instruments mounted directly on farm machinery. For example, soil probes mounted on the front of fertilizer spreaders can continuously monitor electrical conductivity, soil moisture, and other variables to predict soil nutrient concentrations and to instantaneously adjust fertilizer application at the rear of the spreader. Optical scanners detect soil organic matter, or "recognize" weeds, to instantaneously

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The National Academy of Sciences is a private, nonprofit society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Under its charter granted by Congress in 1863, the Academy has a mandate to advise the Federal government on scientific and technical matters.

## Glossary of Precision Agriculture

***Artificial intelligence (AI) systems***. Predict outcomes or recommend actions based on computer-based learning that incorporates experience through developing heuristic rules, rather than through encoding theoretical relationships between variables from disciplinary science.

***Crop scouting***. Periodic ground-level inspection of the crop for weed, insect, disease, and moisture stress problems. Scouting often involves use of pheromone or other insect traps to estimate pest levels as part of integrated pest management (IPM) approaches.

***Expert systems***. Often considered a branch of AI, expert system models are differentiated from other AI approaches because the rules governing decisions are input by human experts, rather than deduced experientially by the system. In PA, expert systems would include rules for when to spray for specific pests, when to till, etc., modified by the past, current, and expected conditions represented by soil, weather, pest level, and other data input from the GIS.

***Geographic information systems (GIS)***. Computerized map and database program that contains spatial (map) and attribute (characteristic) data linked by a common geographic identifier. GIS software provides for overlays and geographic analyses of multiple mapped layers, representing the spatial patterns of soils, crop yields, input applications, drainage patterns, and other variables of interest in a PA system.

***Global positioning system (GPS)***. Determining precise location (latitude and longitude) based on radio signals from 4 or more of the 24 satellites in the GPS launched and maintained by the U.S. Department of Defense (DOD). GPS location is generally accurate to within 100 meters, with 95 percent probability, because DOD purposefully degrades the signal timing to frustrate enemy use of more precise locational information, a process called “selective availability.” Selective availability is scheduled to be lifted within the next decade.

***Grid soil sampling***. Collection of soil samples based on a systematic grid laid out across a farmed field. Soil samples are analyzed in a laboratory to determine soil characteristics such as texture, organic matter, pH, and concentrations of nitrogen, phosphorous, potassium, or other nutrients.

***Local sensing***. A generic term for sensors mounted on farm machinery or equipment to detect soil conditions, nutrient concentrations, weed density and location, soil moisture, livestock identity, and other conditions for real-time input to variable-rate applications.

***Process models***. Detailed simulations of crop, livestock, or tree growth based on agronomic, physiologic, or hydrogeologic theory and implemented at short (daily, hourly) time steps.

***Remote sensing***. Data on light reflectance—collected by instruments carried in airplanes or orbiting satellites—that can be used to estimate the spatial pattern and vigor of vegetation at small areas within the field. Satellite remote sensing, such as the LANDSAT thematic mapper and SPOT satellites, can collect data with a spatial resolution of 10-30 meters, while airborne sensors and the next generation of satellites can achieve spatial resolutions of 1-5 meters.

***Yield monitoring***. Automated measurement of the amount of production taken at intervals as the combine or harvester passes over a field. To date, reliable yield monitors have been developed for corn, soybeans, and wheat, and are being developed for potatoes and sugarbeets. Data from the yield monitor must be integrated with data on vehicle speed, head position, and crop moisture level derived from separate sensors. These data are combined in onboard computers to produce an estimate of harvested yield for each area of the field that can be incorporated into a GIS database for the field.

alter the amount or application of herbicides applied.

Precise data are useless unless they can be *analyzed or processed* to enable management adjustments. Geographic information systems (GIS) are the principal technology used to integrate spatial data coming from various sources in a computer. This is primarily an intermediate step, because data collected at different times on the basis of different sampling regimes and different scales must be combined for use with subsequent decision technologies, such as process models, artificial intelligence systems, and expert systems. Computer process models use frequent time-steps to simulate the processes of crop growth, or the generation and movement of nutrients and pesticides through the environment. Artificial intelligence systems use heuristic or empirical decision rules, rather than the theoretically based relationships in most process models, to recommend appropriate management choices. Expert systems incorporate the “rules of thumb” used by human experts that match the conditions reflected in the input data in order to reach recommendations.

This is not “push button” farming. The alternatives and recommendations of these decision technologies are subject to the expert judgment of agronomists, crop consultants, and the producer. Precision agriculture applications may depend on these immediate technologies, or may simply pass “raw” data directly from the GIS to the human decisionmakers.

The point of collecting and processing precise data is to manage each part of the field appropriately. Ideally, recommendations and applications of production inputs for each plant could be adjusted to optimize output according to the producer’s agronomic, economic, and environmental goals. In practice, technology limits how small an area can be addressed and how finely inputs can be calibrated. Variable-rate technology (VRT) application generally describes precise control of inputs, which can include fertilizer and micronutrient application, liming, seed variety and rate, pesticides, irrigation water, and drainage.

Communications links cut across all three stages of the precision farming process, contributing to data collection, analysis, and application. Fiber optic and satellite communication links, local area networks (LAN's), and the like link producers, cooperatives, Extension experts, processors, input dealers, consultants, and others involved in the production process. These communications links enable a nearly continuous electronic "conversation" or virtual community that puts many heads to work on interpreting precision information for better production decisionmaking.

### Not Yet Widely Adopted

Precision agriculture has not been widely adopted to date. Because it is a suite of technologies that can be adopted piecemeal and combined in various ways, estimating the current level of adoption is difficult. Only a small percentage of farmers actively seek out new technologies and apply them.

Adoption of precision agriculture for subfield management is a refinement of good whole-field management practices. USDA's Cropping Practices Survey data for 1994 show that only a third of acres planted to major field crops (corn, wheat, soybeans, cotton, and potatoes) was soil-tested for nutrients. Pest scouting was done on slightly more than half of planted acres. Given the relatively low adoption of whole-field practices, the rapid adoption of subfield management technologies is not likely.

Precision agriculture is driven by computers, but a USDA survey shows that only 31 percent of the 2 million U.S. farmers and ranchers had computers in 1997, and only 13 percent had Internet access. A 1996 Purdue University survey of 1,500 ag chemical dealers found that only about a quarter of dealers had 10 percent or more of their customers using field mapping or other PA practices. A quarter of dealers surveyed expected that over 30 percent of their customers would be using field mapping, yield monitors, and other precision ag techniques within 2 years.

Combine-mounted crop yield monitors are one of the most popular ways for producers to get into precision agriculture, with industry sources reporting about 17,000 in use in North America in 1997, up from 50 in 1992. Commercially available yield monitors are currently available only for corn, soybeans, and wheat, and are being developed for bulky crops like potatoes, sugarbeets, and peanuts.

Co-ops and other input dealers are key drivers in precision agriculture adoption. The Purdue University survey also found that by 1998, 30 percent of the respondents expected to offer grid soil sampling with GPS, 35 percent expected to offer field mapping, and 29 percent expected to offer controller-driven variable-rate application. There are important regional and size differences in expected dealer adoption of PA services: 45 percent of Midwest dealers and 54 percent of co-ops and large independent dealers expected to offer field mapping by 1998 versus 17 percent in other regions and 34 percent of small independent dealers.

There has been some concern that there is a scale bias to precision agriculture, with larger farms more able to adopt and reaping more potential gains. PA technologies can give operators of large farms the same explicit detailed knowledge of their land that operators of small farms have had implicitly. However, the size of the investment required for precision agriculture (about $7,000 for a yield monitor and GPS receiver, plus $3-$7 per acre for grid soil testing) is not prohibitive for smaller operations.

The most expensive component of precision agriculture, variable-rate fertilizer application, is offered on a custom basis by fertilizer dealers, with the cost often embedded in fertilizer material prices. Although many larger farms have been PA innovators, the advantage may be one of technological sophistication rather than deep capital resources.

**The Suite of Precision Agriculture Technologies**

| Production aspect | Technology | |
|---|---|---|
| **Data collection/input** | Global positioning system (GPS) | |
| | *In advance of production:* Grid soil sampling, yield monitoring, remote sensing, crop scouting | *During production*: Local sensing of: nutrients, pH, weeds |
| **Analysis/processing** | Geographic information systems (GIS), process models, artificial intelligence systems, expert systems, human decisionmakers | |
| **Recommendation/ application** | *Variable-rate application:* Fertilizer, micronutrients, lime, herbicides, insecticides, seeds, seed variety, drip irrigation | *Selective harvest:* Harvest timing |

### Implications for Profits & for the Environment

At this stage in the emergence of precision agriculture, neither the economic nor environmental advantages of subfield management have been definitively demonstrated. Any assessment of precision agriculture has several serious conceptual problems to overcome. Information technologies often contribute in indirect ways to the farmer's better understanding of his cropping system and changes to it. Some of those changes, such as reductions in total use of chemical fertilizers, are easily observed. Other changes are more subtle but will be expressed in higher productivity and lower runoff that, given the year-to-year variation in results due to a multitude of factors, may be impossible to isolate.

Because precision agriculture is a suite of technological tools that can be adopted piecemeal or in varying combinations, there are unlikely to be uniform answers regarding performance for all the possible permutations. Precision agriculture adjusts management decisions to suit variations in resource conditions. Because these conditions vary so widely from farm to farm and region to region, generalizations about performance across all situations are unlikely to be true.

Current costs for precision agriculture are estimated at $9-$23 per acre; future costs are likely to drop. Much less is known about the labor and time needed to integrate the systems and keep them running, or what true custom rates would be if “unbundled” from services provided by farm chemical and input dealers. Most of the costs likely to be borne by the farmer are to acquire information about the soils, yields, and pest problems occurring over the field. Chemical dealers are making major investments in PA equipment, particularly VRT applicators, because they can purchase larger, more economical equipment and can spread the costs over many farmers’ fields, reducing the cost per acre.

Most of the scant literature on the profitability of precision agriculture focuses on variable-rate fertilizer application. A review of 15 studies showed that precision methods were not profitable in 5 studies, profitable in 5, and showed mixed results in 3 (2 studies were inconclusive).

The studies showed little uniformity in the period over which investments are amortized, the discount rate, which PA components farmers invest in and which are acquired through consultants or dealers at custom rates, the grid size for soil sampling, and the nutrients that are managed on a precision basis. The duration of studies varied as well, with empirical studies at most 3 years, and simulation studies varying from 1 to 24 years. There is likely as much temporal variation in PA profitability as there is across resource situations, so the longer the study, the more reliable the results.

Cost reduction is only part of the promise of precision agriculture. Analysis by USDA’s Economic Research Service shows that a 10-percent reduction in nutrient and pesticide applications for major field crops would reduce costs only $2.14 to $23.97 per acre, while a 10-percent increase in yields would produce gains of $11 to $162 per acre. Thus, any increases in crop yields from precision management are likely to be as much or more of a basis for adoption than are cost reductions.

Much of the enthusiasm off the farm for precision agriculture can be attributed to the eminent good sense of matching input applications to plant needs. Precision agriculture is simply a more disaggregated version of the kinds of best management practices (BMP’s) already recommended at the field level. But there is much more to learn about the impact of PA on water and air quality relative to conventional techniques.

Plot studies in Minnesota and Missouri showed reductions in nitrogen applied and in unrecovered nitrogen in the soil with variable-rate application, at little or no loss in crop yield. A study in Nebraska demonstrated reductions in pesticide applications from early detection, and reductions in herbicides from selective application to weeds.

Synergy between variable-rate application and biotechnology offers another way that precision can improve agriculture’s environmental performance. Seed systems enhanced with natural insecticidal properties of *Bacillus thuringiensis* (Bt) can confer economic and environmental benefits when employed on a whole-field basis, but are likely to be more effective when applied on a precision basis.

For example, if there are yield penalties associated with some of these varieties, they may be planted only in areas of high weed infestation or where onboard sensors indicate higher organic matter (that could be associated with greater need for pre-emergence herbicide application). Precision application of Bt-enhanced seed could slow the development of resistance compared with whole-field application.

## *Public Roles in Precision Agriculture*

One of the more important charges to the National Research Council committee studying precision agriculture was to assess appropriate public roles in the development of the technology. Each of the recommendations made by the committee implicitly envisions a role for public agencies.

Precision agriculture is based on satellite imagery, the GPS satellite network, and the Internet, all developed with massive public investments for defense and space objectives. Despite this initial large, but inadvertent, public role in technological infrastructure investments, the committee was generally convinced that private interests were well able and motivated to further the development and dissemination of precision agriculture. The committee regarded public roles in measurement technology, new approaches to research, unbiased evaluation, and training and education as filling critical ancillary or facilitative roles in an otherwise robust private development of the technologies.

Publicly funded research into the science underlying potential improvements in measurement methods is key, both in developing new sensors and manipulating and analyzing spatially referenced data. The committee also called for new approaches to basic agronomic research. PA methods for the first time open up the possibility of accounting for interactions between factors affecting crop growth in a way that cuts across scientific disciplines, using data generated by precision farmers themselves. The ever-finer spatial scales enabled by the technology make earlier generalizations from limited plot studies obsolete.

An area of concern for the committee is an objective evaluation of the pros and cons of PA technologies. Farmers are caught in a barrage of competing claims and hyperbole generated by developers and boosters of precision agriculture. Unbiased evaluations of the economic and environmental performance of precision cropping systems are needed to help farmers decide whether and when to adopt these new methods. The committee concluded that public leadership in collaborations among agencies, professional organizations, technology providers, and producers would provide the fullest and fairest basis for comparing methods.

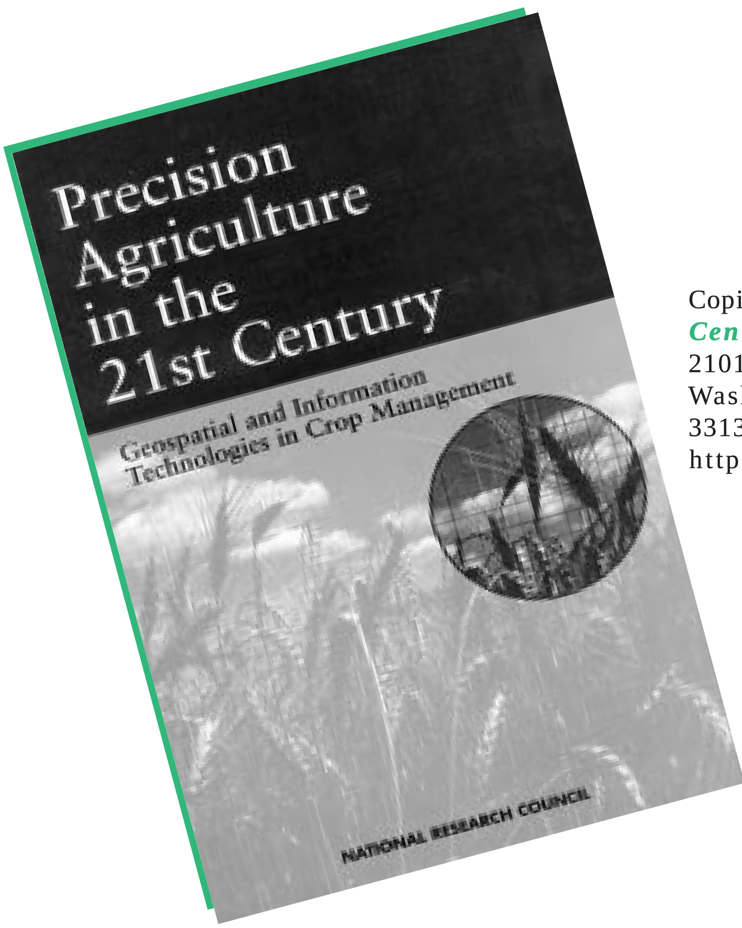
The committee’s other recommendations concern the movement, ownership, aggregation, and provision of data. In general, the capacity to move large quantities of digital data has been developed in proportion to population, with the highest “band width” for electronic data in urban areas.

Widespread adoption of precision agriculture will be accompanied by a many-fold expansion in the volume of electronic data moving among producers, suppliers, consultants, and customers in rural areas. Ensuring that adequate connectivity exists in rural areas is at least partly a public role.

The large volume of data generated by grid soil testing, satellite images, crop yield monitoring, and other precision technologies has to be shared among producers (who may or may not collect the data), consultants and input suppliers, Extension agents, university and USDA researchers, and commodity buyers. All of these may exercise some control or ownership over the data.

Issues of ownership and privacy are compounded as the data are combined with that from other entities, transformed, aggregated, interpreted, and analyzed. These kinds of intellectual property issues, while new to farming, are not unique. A public role is to search out existing law on such issues, reinterpret it for PA needs, and ensure that all parties agree to and exercise appropriate protections for data ownership and privacy.

*Ralph Heimlich (202) 694-5477*
*heimlich@econ.ag.gov* AO

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