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On the Doorstep of the Information Age

Recent Adoption of Precision Agriculture

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Abstract

The adoption of precision agriculture, which encompasses a suite of farm-level information technologies, can improve the efficiency of input use and reduce environmental harm from the overapplication of inputs such as fertilizers and pesticides. Still, the adoption of precision agricultural technologies and practices has been less rapid than envisioned a decade ago. Using Agricultural Resource Management Survey (ARMS) data collected over the past 10 years, this report examines trends in the adoption of four key information technologies—yield monitors, variable-rate application technologies, guidance systems, and GPS maps—in the production of major field crops. While yield monitoring is now used on over 40 percent of U.S. grain crop acres, very few producers have adopted GPS maps or variable-rate input application technologies.

Keywords: Information technology, precision agriculture, variable-rate technology, yield monitors, Global Positioning System (GPS) mapping, auto-steering, conservation technology

Acknowledgments

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Contents

Summary

What Is the Issue?

Efficient input use in agriculture is increasingly a priority of producers, the public, and policymakers. One way to increase efficiency in agriculture is through the adoption of precision technologies, which use information gathered during field operations, from planting to harvest, to calibrate the application of inputs and economize on fuel use. While it holds promise for improving the efficiency of input use, adoption of precision agriculture—encompassing a suite of farm-level information technologies to better target the application of inputs and practices—has not been as rapid as previously envisioned. This report examines the prevalence and effectiveness of these technologies based on survey response data collected over the last 10 years.

What Did the Study Find?

Adoption of the main precision information technologies—yield monitors, variable-rate applicators, and GPS maps—has been mixed among U.S. farmers. Recent data from the Agricultural Resource Management Survey (ARMS) show that use of yield monitors, often a first step in utilization of precision technology for grain crop producers, has grown most rapidly, being used on 40-45 percent of corn and soybean acres in 2005-06. However, farmers have mostly chosen not to complement this yield information with the use of detailed Global Positioning System (GPS) maps or variable-rate input applicators that capitalize on the detailed yield information. Some of the factors that could be contributing to this adoption lag include farm operator education, technical sophistication, and farm management acumen. The report is not testing the impacts of precision agriculture on other farm practices like conservation tillage, but some associations between the various factors are noted. Among the report's findings:

- Corn and soybean yields were significantly higher for yield monitor adopters than for non-adopters nationally. This yield differential for corn grew from 2001 to 2005. Yield monitors are being adopted more quickly by farmers who practice conservation tillage.

- Corn and soybean farmers using yield monitors had lower per-acre fuel expenses. Average per-acre fertilizer expenses were slightly higher for corn farmers that adopted yield monitors, but were lower for soybean farmers.

- In the Corn Belt, GPS maps and variable-rate technologies were used on 24 and 16 percent respectively of corn in 2005, and 17 and 12 percent of soybean acres in 2006, but nationally the adoption rates for variable-rate technologies were only 12 percent for corn and 8 percent for soybeans.

- Average fuel expenses were lower, per acre, for farmers using variable-rate technologies for corn and soybean fertilizer application, as were soybean fuel expenses for guidance systems adopters.

- Adopters of GPS mapping and variable-rate fertilizer equipment had higher yields for both corn and soybeans.

- Adoption of guidance systems, which notify farm equipment operators as to their exact field position, is showing a strong upward trend, with 35 percent of wheat producers using it by 2009.

How Was the Study Conducted?

The Agricultural Resource Management Survey (ARMS) provides data on technology choices, input costs, and yields for a nationally representative sample of U.S. farms growing selected commodities. Phase II of the ARMS is conducted on a rotating set of commodities, and this study relies primarily on the 2001 and 2005 surveys of corn, 2002 and 2006 surveys of soybeans, and 2004 and 2009 surveys of winter wheat, with secondary emphasis on other crops and years. Descriptive statistics are presented at the national level and by production region as defined by USDA's National Agricultural Statistics Service. Simple statistical difference-of-means tests are conducted to examine differences in input costs and yields between precision technology adopters and non-adopters.

Introduction

Farmers and agricultural managers regularly adopt new technologies like hybrid seeds, as they become available. Nonetheless, they have been slower to adopt new information technologies, like those that contribute to precision farming, even though their availability has increased over the last several decades (Whipker and Akridge, 2006-09 annual service dealers' survey). Precision agriculture—a suite of information technologies used as management tools in agricultural production—has recently become more accessible to farmers, and the use of some of these technologies has become more prevalent, but far from universal. In 1997, the National Research Council discussed the potential impact of widespread adoption of information technologies on farm structure, rural employment, and environmental quality. However, 8 years later, survey data showed that the most widespread information technology, yield monitoring, was being used on less than half of corn, soybean, and winter wheat acres nationally, with complementary technologies much less prevalent.

Fertilizer application rates were once predicated on applying enough nutrients to match the highest requirements of a crop in any part of a specific field. This kind of uniform nutrient management, an "optimal risk aversion strategy," has become less common with the advent of precision agricultural technologies (Whelan and McBratney, 2000) and less affordable with higher fertilizer prices. The prices of all three main agricultural nutrients—nitrogen, phosphate, and potash (or potassium)—have risen dramatically in the last decade (Huang, 2009). Despite the price increases, fertilizer demand increased over this period as farmers aimed to exploit the full potential of high-yielding seed varieties during a period of relatively high crop prices. In 2006, $119.2 billion was spent on agricultural fertilizer worldwide, with 62 percent of this on nitrogen, 22 percent on phosphate, and 11 percent on potassium. With variable-rate technology (VRT), applicators can apply seeds, fertilizer, and pesticides to suit different sections of a field depending on soil conditions, nutrient needs, and the severity of pest problems, thereby economizing on inputs without sacrificing yield.

In addition to higher costs, there are other pitfalls to overuse of fertilizer. Excessive or poorly timed fertilizer application can contribute to nutrient runoff from farms into wells, waterways, wetlands, and estuaries (Carpenter et al., 1998). And when rainfall increases, typically in the spring, nutrient delivery to the Gulf of Mexico can enlarge the size of the hypoxic "dead zone" at the mouth of the Mississippi River. In 2009, the delivery of nutrients to the Gulf was 11 percent above the 1979-2009 average and among the highest on record (U.S. Department of the Interior, 2009). A large share of this pollution may come from agricultural runoff (Goolsby et al., 2001; Goolsby et al., 1999). Nitrogen, when overapplied and not incorporated into the soil, can oxidize (into N_2O) and vaporize into greenhouse gas (GHG). The Intergovernmental Panel on Climate Change (2007) included reduced N_2O emissions through improved agricultural fertilizer application techniques as a key GHG mitigation practice.

This report documents the level of adoption of various precision agriculture practices over the last 10 years in the United States. This approach enables us to determine where the adoption of these practices and technologies has stalled and offer a few observations on the patchy adoption across different growing regions and on various crops. The concluding section discusses factors related to pollution and yields that could increase the adoption of precision agriculture in the future.

Data

The Agricultural Resource Management Survey (ARMS) has been conducted every year since 1996 by the Economic Research Service (ERS) and USDA's National Agricultural Statistics Service (NASS) (see http://www.ers.usda.gov/Briefing/ARMS/). The ARMS collects crucial data on resources required for agricultural production—including seeds, fertilizer, pesticides, machinery, labor, and the use of information technologies, along with yields obtained (Phase II questions)—and expenditures on inputs, as well as farm household characteristics, such as farm capitalization levels, leveraging, and sources of off-farm income (Phase III questions). While the number of crops surveyed for specific production practices (Phase II questions) varies each year, individual crops are surveyed only every fourth or fifth year, due to respondent burden and budget constraints. Corn was most recently surveyed in 2001 and 2005 (the 2010 corn survey results were not yet available when this report was prepared), soybeans in 2002 and 2006, and winter wheat in 2004 and 2009. The number of States covered by the surveys depends on the crop, though all major producing States and 90 percent of crop acreage are represented. In this report, we compare the mean values of different groups of farms and technologies and use difference-of-means statistical tests for all cost estimates, as well as yields, to determine if the differences observed are statistically significant at a 90-percent or higher level of confidence. Individual observations with higher-than-normal variability are denoted in the tables and charts with a # symbol, indicating that their coefficient of variation is greater than 0.25.

Increasing Adoption of Yield Monitoring Technology

Yield monitoring is the most popular component of precision agriculture, with soybean producers reporting its use on 45 percent of acreage in 2006, corn producers on 42 percent of acres in 2005, and winter wheat growers on 35 percent of acreage in 2009 (fig. 1). In the Corn Belt[1], yield monitor use grew from 28 percent of corn acreage in 2001 to 44 percent in 2005, while the Lake States and Northern Plains[2] had similarly high corn acreage under yield monitoring by 2005 (table 1). Soybean producers in these regions increased their use of yield monitors from 30 percent of acreage or less in 2002 to almost 50 percent by 2006.

Recently, yield monitors have allowed farmers to use Global Positioning System (GPS) maps to pinpoint yield variation within their fields (Gebbers and Adamchuck, 2010). Yield monitoring is sometimes used without the

[1]Corn Belt States are Illinois, Indiana, Iowa, Missouri, and Ohio.

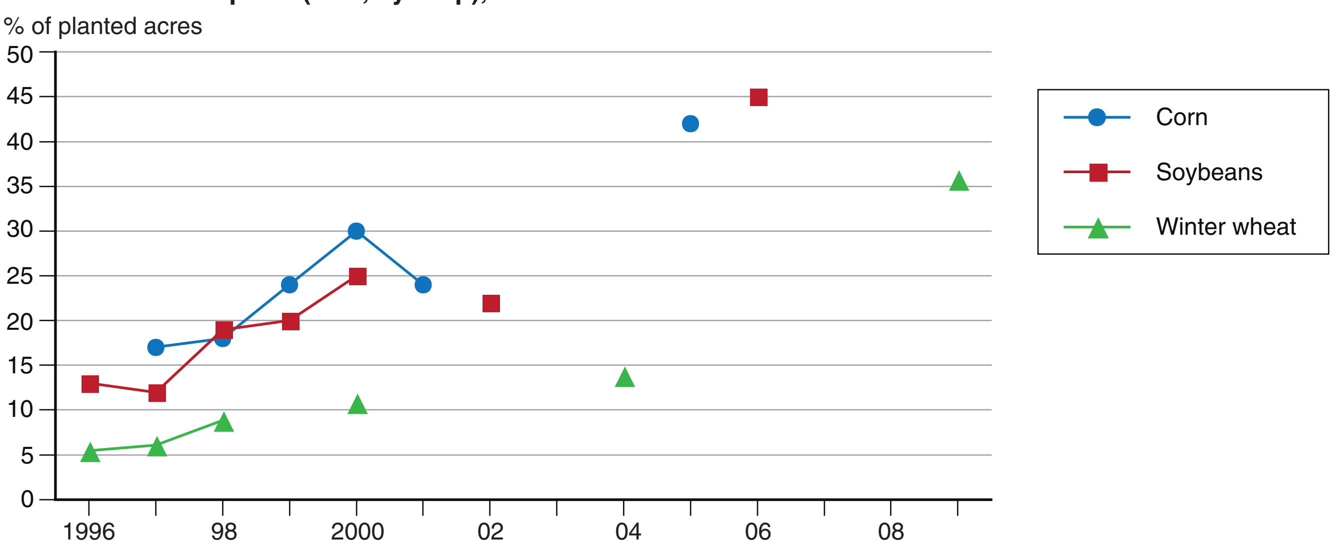
[2]The Lake States are Michigan, Minnesota, and Wisconsin; the Northern Plains include Kansas, Nebraska, North Dakota, and South Dakota.

Table 1
Yield monitor adoption for corn and soybeans by region, 1996-2006

	1996	1997	1998	1999	2000	2001	2002	2005	2006
	Percent of planted acres								
Corn									
Corn Belt		21	18	28	34	28		44	
Lake States		10	19	18	29	17		39	
Northern Plains		15	24	19	28	27		43	
Soybeans									
Corn Belt	13	15	21	23	28		24		49
Lake States	16#	11	16	15	30		29		48
Northern Plains		9#	17	21	22		17		48

Source: Agricultural Resource Management Survey, USDA, ERS/NASS.
# indicates coefficient of variation greater than 0.25.

Figure 1
Yield monitor adoption (U.S., by crop), 1996-2009



Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

Geographic Information System (GIS)[3] capability to store plot-level information. This strategy enables the producer to roughly monitor crop moisture (Griffin and Lowenberg-DeBoer, 2005), much as crop-moisture indicators on combines have been used for decades to minimize the cost of drying harvested grain. Although weather generally determines moisture levels over a wide area, precision technology utilizing GIS could allow farmers to see if plot-level yields would benefit from a change in management practices within a single field.

[3]Geographic Information System (GIS) refers here to enhanced field mapping with GPS that allows the overlaying of multiple layers of data for all subsections of a field in a database. In this way, multiple characteristics of one location can be determined and the data used for multiple purposes.

Variable-Rate Technology (VRT) Adoption Mixed

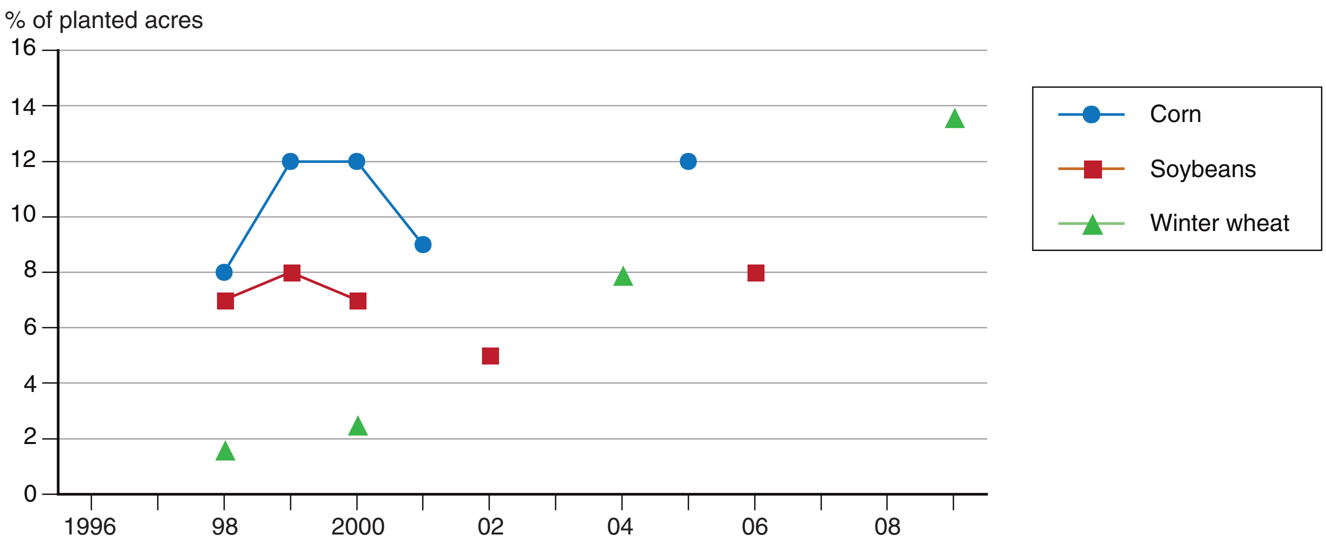
Variable-rate technology allows producers to make use of factors that influence yields by adapting their practices "on the fly." (The sequential adoption of precision agriculture technologies is discussed in the box, "Three-Step Approach to…"). VRTs are seeders, sprayers, and other fertilizer and pesticide application equipment that can be continually adjusted during field operations to optimize the application of inputs depending on field conditions. VRT use for corn nationwide (12 percent in 2005) has been consistently above VRT use for soybeans (8 percent in 2006), although adoption rates are low and fairly flat for both crops. VRT use for winter wheat was at 14 percent in 2009 and is steadily increasing (fig. 2).

Guidance systems for field equipment make use of GPS readings to alert equipment operators as to their field position coordinates. GPS can improve the accuracy of variable-rate applicators and help operators reduce the incidence of overlapping or missed sections in their field operations. Guidance systems have recently been adopted on between 15 and 35 percent of nationally planted acres for corn, soybeans, and winter wheat (fig. 3). GPS adoption was highest for corn in the Corn Belt in 2005 (table 2), which is also true for VRT (table 3).[4] GPS use for soybeans is highest in the Corn Belt and Lake States, at 17 and 12 percent, respectively, in 2006, but adoption rates for both GPS and VRT among soybean growers have been erratic at best. Guidance systems are being used more heavily than VRT across regions (table 3).

Variable-rate technology has been commercially available for more than a decade, but commercial crop use—at 8 to 14 percent over 2005-09—is far below that projected by farm dealerships (Whipker and Akridge, 2006). The uncertain profitability of variable-rate technology has discouraged its adoption among some farmers. For example, the GPS mapping of crop yield response to managed inputs, field topography/soil characteristics, and

[4]Extension agents report that some producers have manually applied fertilizer using VRT sprayers without GPS, relying on personal knowledge of field conditions to estimate appropriate application rates. Some producers characterized GPS maps as "too troublesome," but continued to use the VRT sprayers that they had already paid for.

Figure 2
Variable rate technology adoption (U.S., by crop), 1998-2009

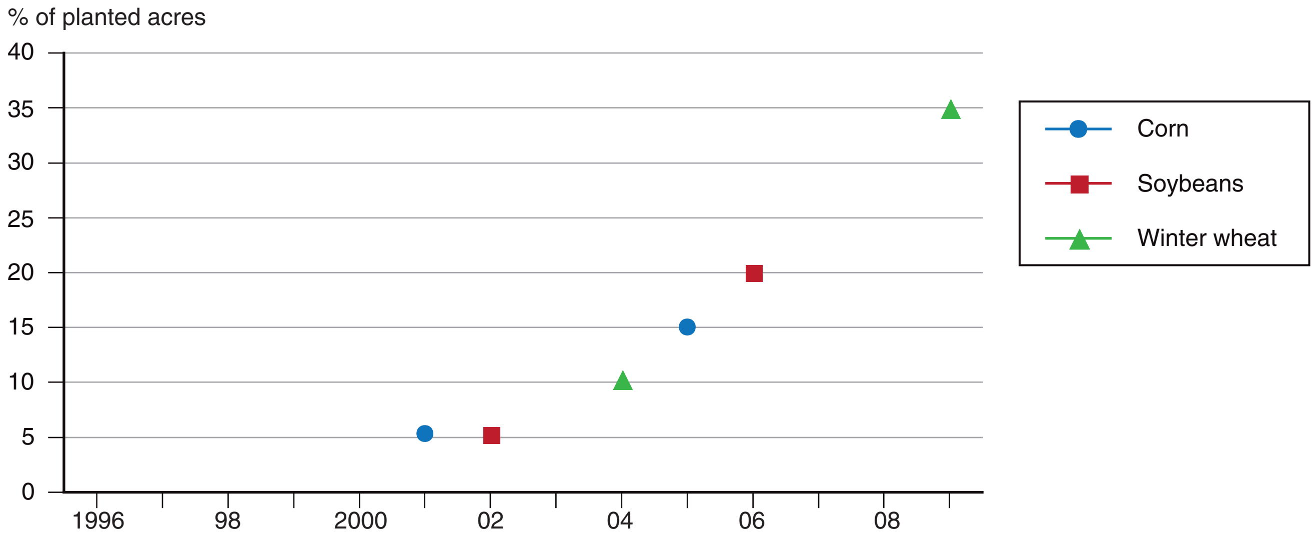


Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

weather is regarded by many as too difficult, and thus profitability is difficult to gauge under a wide range of circumstances (Bullock et al., 2002). Bullock et al. (2009) hypothesize that information and VRT are economic complements—more of either increases the marginal productivity of the other, shifting out its demand curve.

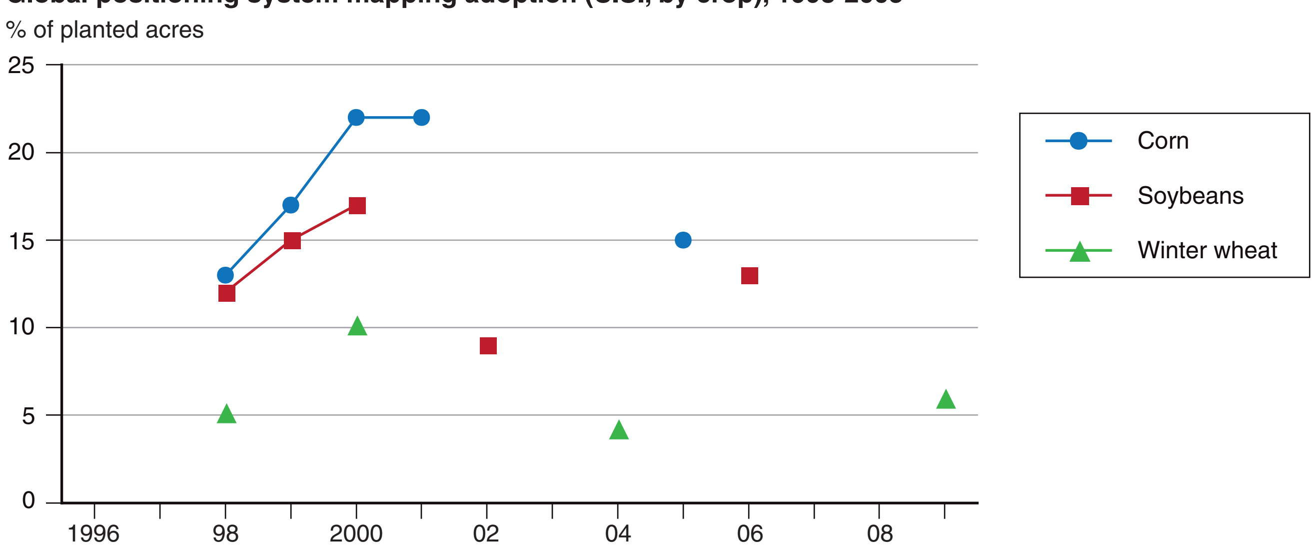
The ARMS also collects data on the adoption of soil mapping for precision agriculture applications. The use of these GPS maps increased in the late 1990s for both corn and soybeans, before declining to about 15 percent in 2005/6 (fig. 4). Extension agents in the Corn Belt indicated that they were not surprised by this dropoff as some farmers had characterized the maps as troublesome (personal communications, 2009, Iowa State University, Keokuk

Figure 3
Guidance system adoption (U.S., by crop), 1996-2009



Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

Figure 4
Global positioning system mapping adoption (U.S., by crop), 1998-2005



Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

Table 2

Global Positioning System (GPS) adoption for corn and soybeans by region, 1996-2002

	1996	1997	1998	1999	2000	2001	2002
	--------------------Percent of planted acres--------------------						
Corn							
Corn Belt	19	23	32	31		24	
Lake States	8	7	15	16		7#	
Northern Plains	9#	9#	10	12		5#	
Soybeans							
Corn Belt	16	21	24		10		17
Lake States	11#	6#	15		11#		12
Northern Plains	9#	9#	6		6#		9

# indicates coefficient of variation greater than 0.25 .
Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

Table 3

Variable-rate technology (VRT) and guidance system adoption for corn and soybeans by region, 1998-2006

	1998	1999	2000	2001	2002	2005	2006
	--------------------Percent of planted acres--------------------						
VRT							
Corn							
Corn Belt	19	23	32	31		24	
Lake States	8	7	15	16		7#	
Northern Plains	9#	9#	10	12		5#	
Soybeans							
Corn Belt	16	21	24		10		17
Lake States	11#	6#	15		11#		12
Northern Plains	9#	9#	6		6#		9
Guidance system							
Corn							
Corn Belt				6.9		13.2	
Lake States				3.9#		9.3	
Northern Plains				3.1#		23.3	
Soybeans							
Corn Belt					3.6		18.4
Lake States					4.1#		16.6
Northern Plains					9.8		30

# indicates coefficient of variation greater than 0.25.
Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

County Extension, Sigourney, Iowa; and University of Illinois Extension, Crop Sciences Research and Education Center, Urbana, Illinois).

There is a logical sequence, starting with yield monitoring, for the adoption of precision agriculture technologies (see box, "Three-Step Approach to Adoption of Precision Agriculture Practices"). To test for this sequential adoption, both corn and soybean farmers in ARMS were split according

Three-Step Approach to Adoption of Precision Agriculture Practices

Step One—Yield Monitors: Collecting Yield Information

Data on crop yields can come from yield monitors, which have recently started to become standard equipment on some models of farm machinery, especially combines. On later models of farm tractors and combines, yield monitors can usually be retrofitted at reasonable cost. While farmers perform their harvesting routines, the monitor collects data on bushels per acre or other yield measures and stores the information electronically by location on a digital storage disk, often using pre-installed Geographic Information System (GIS) computer software. GIS software, like the most widely used ArcInfo, allows different kinds of information on yield response to be stored and retrieved easily on plots throughout a farmer's field. GIS software tools like ESRI (Environmental Systems Research International) are available on the ArcInfo platform through commercial vendors. Another package is MapInfo, which recently became part of Pitney Bowes Business Insight Software products.

Step Two—Soil Maps: Collecting Information on Field Characteristics

Another step in the use of information for site-specific farming is creating a soil map of each farmed field. Some soils data are available from the USDA Natural Resources Conservation Service's National Cartography and Geospatial Center, which has archived a Soil Survey Geographic database (soildatamart.nrcs.usda.gov/). The soils data display the location of features too small to delineate on geological survey maps, though still significant enough to influence input use and management. The soil map units are linked to attributes in the National Soil Information System database, which gives the proportionate extent of the component soils and their properties. This information is in the form of soil boundaries and could be augmented with pay-for-services onsite sampling, testing, and detailed study of specific sites for intensive cropping uses. Additional information may also be obtained through field tests on soil organic matter and closely related pH levels, factors that influence nutrient availability. Bullock and Bullock (2000) found that measures of topology, in addition to soil characteristics, were significant in explaining yields. Specific elevation features they used were the compound topographic index (CTI), specific catchment area (SCA), and stream power index (SPI). These variables capture the fact that on long stretches of gently sloping land, the transition from one soil type to another is likely to occur gradually over many feet. Where land shifts abruptly from steep to level and vice versa, the transition zone might be quite narrow. Both soil and topography are likely to influence how moisture and nutrients move through the soil. This in turn is likely to influence optimal nutrient application rates that might vary from site-to-site within any individual field. For instance, farmers often ponder after a wet spring how much nitrogen has been lost from different sections of their fields.

USDA created a Geospatial Data Gateway (datagateway.nrcs.usda.gov/, accessed 3/31/2011) to house soils and topography data. The site is especially useful if downloading large sets of data from the Web is not feasible for the user. A CD or DVD containing only the user's required data can be ordered from the website for a nominal fee. Soil survey data, spatial and tabular, are available along with elevation data at 10- and 30-meter resolutions. The site also provides access to 8- and 12-digit watershed boundary data, land use/land cover and cropland data layers, general soil maps (from STATSGO), and temperature and precipitation averages.

The Agricultural Resource Management Survey (ARMS) collects data on the adoption of soil mapping for precision agriculture applications. The development and use since 1996 of Global Positioning System (GPS) maps for monitoring site-by-site soil properties within a farmer's fields are shown in figure A. The use of these maps increased in the late 1990s for both corn and soybeans, then declined to about 15 percent in 2004/5. Extension agents in the Corn Belt indicated that they were not surprised by this dropoff as some farmers had characterized the maps as troublesome (personal communications, 2009, Iowa State University, Keokuk County Extension, Sigourney, to whether they had used yield monitoring or not. Both corn and soybean producers who had not adopted yield monitoring also had much lower rates of GPS mapping, particularly since 2002 when their adoption percentages were under 5 percent (fig. 5), whereas producers with yield monitors used GPS mapping on over 25 percent of acres. The same is true of VRT adoption percentages when survey respondents are split into GPS users and non-users (fig. 6). VRT and guidance system (GSYS) adoption for both corn and

Iowa; and University of Illinois Extension, Crop Sciences Research and Education Center, Urbana, Illinois).

There is some evidence that this situation might be changing. GPS capability has begun to be offered as standard equipment on some farm machinery. Deere & Co. offers the GreenStar™ Lightbar GPS device, which aids in determining row width and location. Wider availability of GPS could combine with more detailed mapping to increase the value of GPS to producers. Higher resolution topological maps of individual farms are not common at present, but some of these maps have been created using Real Time Kinematic (RTK) satellite systems. Four-wheeled trailers can be mounted with an RTK-GPS device and drawn through a field during any other whole-field farming operation. RTK is a processor that makes GPS signal corrections that are transmitted to a satellite and subsequently stored in real time. The readings that are recorded are based on carrier-phase measurements from the GPS where a single reference station provides real-time topology corrections, providing accuracy up to 1 centimeter of field elevations. While not simple to create, digital terrain maps do not change much over time, and their use has been shown to improve crop yields on a few test farms in Illinois (Bullock et al., 2009). Three non-satellite-based soil sensing systems are available commercially. These are electrical or electromagnetic sensors of soil conductivity, optical spectra sensors of visible or near-infrared light (both useful for determining nitrogen deficiency), and electrochemical sensors of hydrogen, potassium, and nitrate levels.

Step Three—Variable-Rate Technology (VRT): Putting Yield and Soil Information Together

Investments in field equipment and machinery that enable continuous changes in seeding, fertilizer, and pesticide application rates can be profitable when combined with adequate information on soils and yield history. The farmer or custom services operator aspires to a profit-maximizing level of inputs on each section of a field, given the physical characteristics apparent from a GPS map or other management strategy. Custom service operators in particular have recently made greater use of GPS guidance systems; 56 percent used a GPS guidance system with auto control/auto steer for at least some of their work in 2009, up from 28 percent in 2008 (Whipker and Akridge, 2009).

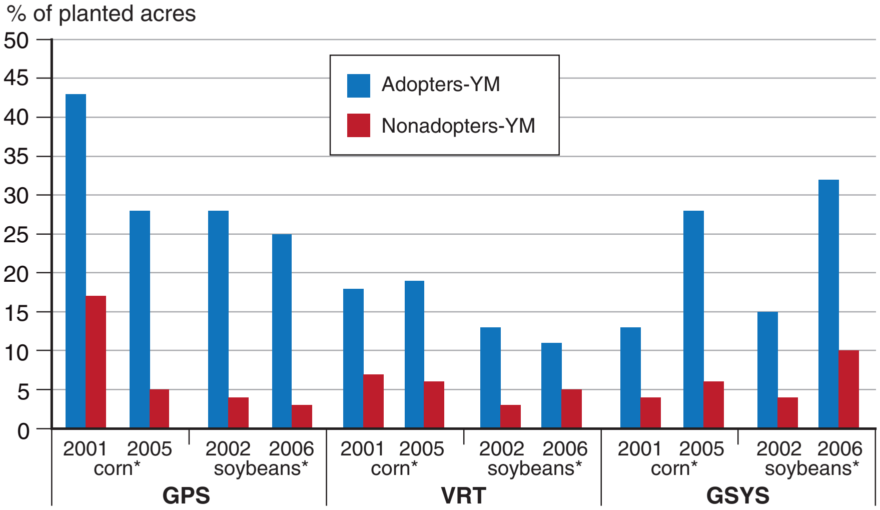
This three-step information technology adoption process presumes that yield monitoring is largely adopted by corn and soybean producers prior to their embrace of complementary technologies like GPS soil mapping and variable-rate input application. Yield monitors (step 1) are available as standard equipment on some tractors and combines and can be used with little computer programming if the data are not stored and combined with other information. Once a GPS soil properties map is created (step 2), the infrastructure is in place with which to store and retrieve detailed information on specific sites in a farmer's field. The use of VRT (step 3) physically capitalizes on the antecedent technologies. There is, however, no reason why this logical sequence has to apply, and it is possible that VRT and GPS mapping could be adopted independently of yield monitoring.[1]

Bullock et al. (1998) posit a direct link between profitability and how widely precision agriculture's information tools are implemented. If VRT and information on field characteristics are complements, VRT might only become profitable when enough information is available in an individual producer's precision agricultural system to make it that way. VRT may not be profitable in situations where all the farmer gets out of a capital investment in the information technology are recommendations to apply more fertilizer than normal to one area and less to another area in their field. The question becomes not so much whether the information technologies are profitable in general, but rather if they are profitable when used intensively. In many cases, limited adoption of precision information technologies is unprofitable because of their substantial startup costs.

[1]A GPS map could be created based on satellite data for topography and water movement or catchment areas on a parcel of land, with that information used to support VRT applications. It might also be possible to perform soil tests on subplots in a field and create a GPS map with this information, but these tests are usually expensive and time consuming as samples must be sent to a lab.

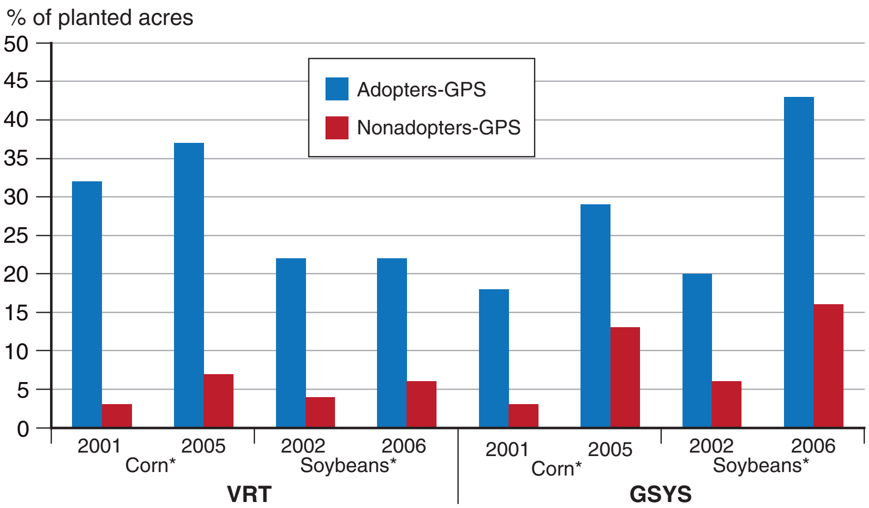
soybean producers nationally were higher for those that used GPS mapping. These adoption gaps indicate that precision information technologies are adopted sequentially, with yield monitoring the basis of GPS and VRT use. Basic soil testing may serve as an entry point for some farmers, who adopt GPS maps in order to store information on soil characteristics. The recent surge in GSYS adoption might also have been a first step into information technology adoption for some corn and soybean producers.

Figure 5
Comparison of GPS/VRT/GSYS use among yield monitor adopters and nonadopters



*indicates statistically significant difference of ratios, at 10% levels.
GPS = Global Positioning System. VRT= variable-rate technology. GSYS refers to guidance system.
Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

Figure 6
Comparison of VRT and GSYS use among GPS adopters and nonadopters

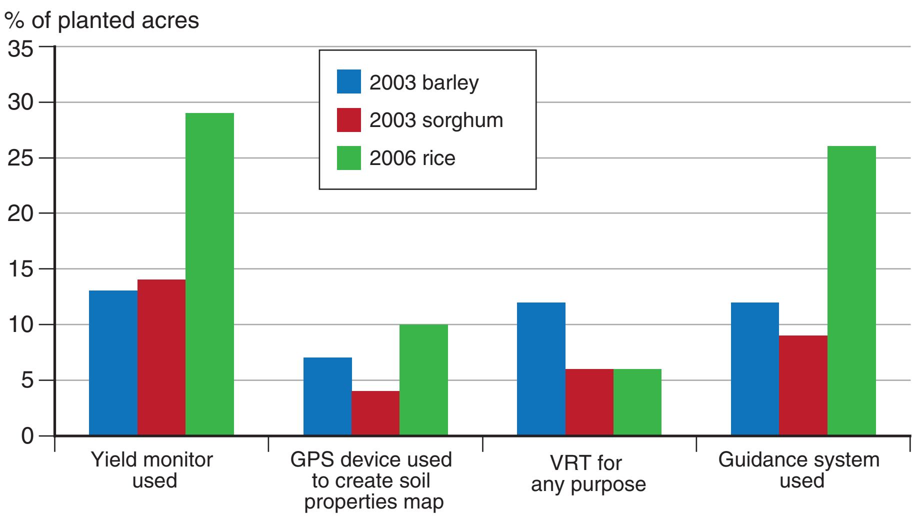


*indicates statistically significant difference of ratios, at 10% levels.
GSYS refers to guidance system. VRT= variable-rate technology. GPS = Global Positioning System.
Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

Producers of Minor Crops Not Neglecting Precision Agriculture

Despite the more apparent fit of precision agriculture to large-scale crop production, information technologies have been applied to a wide range of agricultural businesses, including orchards, pasture, turf management, and livestock production (Gebbers and Adamchuk, 2010). Among minor crops, yield monitoring is more prevalent than GPS or variable-rate technology for barley, sorghum, and rice (fig. 7). Earlier data for other minor crops (AREI, 2006, table 4.7.3) show that sugarbeets (2000) had 29 percent GPS adoption and 15 percent VRT adoption. Potatoes (1999) had 10 percent yield monitoring, 19 percent GPS, and 18 percent VRT. Sunflowers (1999) had 17 percent yield monitoring, 4 percent GPS, and 3 percent VRT. Sugarbeets and potatoes are high input-cost and high-value crops (Patterson, 2009), so VRT is likely profitable for them under a wider range of circumstances than for some field crops and sunflowers.

Figure 7
Precision agriculture use on minor crops (U.S. by crop)



GPS = Global Positioning System. VRT= variable-rate technology.
Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

Tillage Systems and Precision Agriculture Adoption

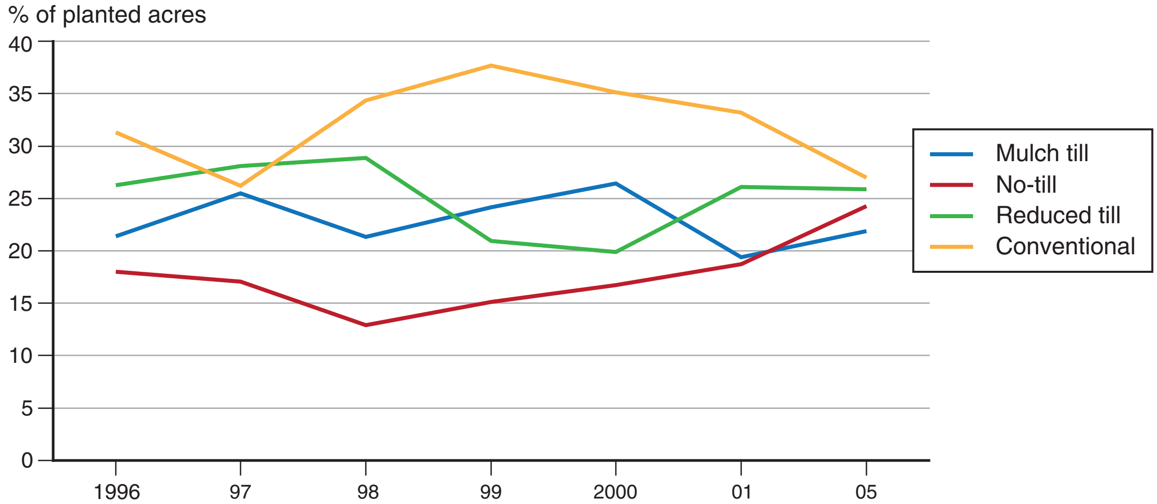
The adoption of information technologies is likely to be influenced by a number of regional factors (see box, "Why We Might Expect Regional Differences in the Adoption of Precision Technologies"). Factors that influence the adoption of reduced tillage systems are probably similar to those influencing the adoption of precision agriculture technologies; both sets of technologies have similar positive impacts on production and the environment while reducing costs. This section considers whether specific tillage practices and information technologies are being used together in certain circumstances.

No-till and mulch till are conservation tillage practices that leave at least 30 percent of the soil covered by crop residues after planting, while reduced-till leaves 15-30 percent and conventional tillage leaves less than 15 percent of the soil covered (Horowitz et al., 2010). Reducing soil erosion and mitigating the impact of higher energy prices are both motivations for reducing tillage. Switching from conventional or chisel plowing to no-till planting reduces soil erosion and requires less fuel (Zinser et al., 1985). Reduced tillage can protect soil from erosion because, in contrast to chisel plowing, it leaves crop residues relatively undisturbed on the soil surface. Lower machinery-related costs related to the number of trips required through a field with reduced tillage are offset by higher pesticide costs and potentially higher fertilizer costs. No-till also produced slightly lower corn and soybean yields in some field tests, and thus slightly lower returns to land and farm management (Klemme, 1985, tables 1 and 2).

Studies on tillage intensity note that, as with information technologies, managerial skills, size of operation, years of additional schooling, and use of extension services increased the adoption of conservation tillage systems (Rahm and Huffman, 1984). Prokopy et al. (2008), in reviewing 25 years of studies on the adoption of farm-level best management practices, identify the most influential farm characteristics as levels of farm capital and income, access to information, and utilization of social networks.

The use of no-till in U.S. corn production has been increasing since 1998, and conventional tillage has declined since 1999 (fig. 8). Herbicide-tolerant (HT) crops became more popular over this period, as these crops allow the application of glyphosate directly over post-emergent plants to control a larger weed problem often associated with no-till. To explore the relationship between tillage systems and the use of information technologies, we use the ARMS data on joint adoption of information technologies and tillage practices in U.S. corn and soybean production. Yield monitor use is highest on no-till soybean acres (50 percent in 2006, table 4). Use of GPS soil maps on both conventional and no-till acres for corn and no-till soybeans dropped between ARMS surveys (2000-01 to 2002-05) (table 4). The national averages for VRT adoption by corn and soybean producers stalled at 6-9 percent of no-till corn and soybean acres between 2002 and 2005 (table 4). We suspect that those farmers tending toward early adoption of technology had already adopted VRT by 2005. Conventional and no-till corn producers changed their VRT acres very little between 2000 and 2005.

Figure 8
Tillage systems (U.S. corn), 1996-2005



Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

Table 4
Precision agriculture adoption by tillage system

	1996	1997	1998	1999	2000	2001	2002	2005	2006
	Percent of planted acres								
Yield monitors									
Conventional corn		11	13	20	22	16		33	
No-till corn		21	23	27	26	27		43	
Conventional soy	10#	5	7#	14	17		18		21
No-till soy	18	13	22	21	26		26		50
GPS									
Conventional corn			11	13	17	19		14	
No-till corn			11	17	19	24		11	
Conventional soy			8#	16	10		10		
No-till soy			12	12	23		9		
VRT									
Conventional corn			8	8	11	9		10	
No-till corn			7#	13#	10	10		9	
Conventional soy				8#	3#		3#		
No-till soy			6	8	9		6		

# indicates coefficient of variation greater than 0.25.
Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

Why We Might Expect Regional Differences in the Adoption of Precision Technologies

Adoption rates for yield monitors and variable-rate technology differ across regions. This finding is consistent with earlier research on adoption rates for hybrid corn technology, which despite nearly universal use now, varied by State in its adoption timetable. Hybrid corn was adopted first in Iowa in 1933 and more slowly in Alabama starting in about 1943. The curves used by Griliches (1957) have become the standard technology diffusion and adoption curves for both agricultural and non-agricultural technologies (fig. A). The curves are flatter early in the adoption dissemination period and have a steep middle section when technology adoption is quickest.

Skinner and Staiger (2005) extend Griliches' study to modern technologies including computers in the 1990s and beta-blockers for heart attacks and provide data on the adoption of both of these advances up to 2000. They find that while profitability influences early adopters, a different set of factors explains why some regions are slow to adopt even "highly effective technologies." The factors that slow adoption in some regions are related to social capital and the strength of information networks.

Figure A
Copy of figure from Griliches (1957)

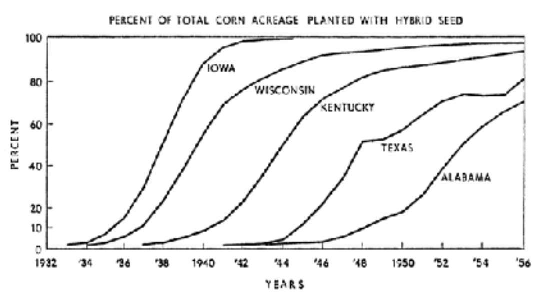


FIGURE 1.—Percentage of Total Corn Acreage Planted with Hybrid Seed.
Source: U.S.D.A., *Agricultural Statistics*, various years.

For farm information technologies, Fernandez-Cornejo et al. (2001) find that farm operators who study beyond high school have a 15-percent greater likelihood of adopting precision technologies. Griffin et al. (2004) consider the adoption of precision agriculture to be "human capital intensive" (p. 11). These observations could be related to an element of technology adoption that has been noted in other agricultural settings: learning-by-doing. This insight offered by Arrow (1962) and applied by Luh and Stefanou (1993) to agricultural productivity, explains technology adoption as a process that takes time for new users to master. Farm operators with more education likely learn more quickly, and education levels likely vary across the United States.

Other information technologies are subject to both education and regional adoption factors. Stenberg et al. (2009) find that college education and age of farm operator are significant in explaining adoption of Internet-based technology on farms. They also find that broadband adoption on farms is most dense in the Corn Belt and portions of the other Lake States and Northern Plains, where the use of yield monitors for corn and soybean production is highest.

Paxton et al. (2010) arrived at similar findings for the adoption of precision agricultural practices in cotton production. Younger, better educated cotton producers and those that that used computers for management decisions were significantly correlated with the number of precision technologies adopted. Table A combines reported use of yield monitoring, VRT, GPS, and auto-guidance from the ARMS survey and shows how regional adoption varies for these precision agriculture practices in cotton production. Use of these technologies is higher than the national average in the Delta States, but is lower in the Southern Plains, Southeast, and Appalachia.

Table A

Precision technology adoption for cotton (by region)

	2003	2007
National	19.5	27.6
Southern Plains	17.7	23.7
Delta	28	46.3
Southeast	12.4	19
Appalachia	16.8	20.5

Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

Just et al. (1980), in considering whether farm size matters in technology adoption, find that uncertainty and fixed investment/information costs place a lower limit on farm sizes that may be able to adopt. As these fixed costs increase, the size of the farm that will adopt increases (Fernandez-Cornejo et al., 2007). And as uncertainty increases, farm size, learning, and fixed costs play a larger role in rates of technology adoption (Feder and Mara, 1981); the more uncertain the technology, the more likely that only larger farms able to spread the fixed cost will adopt.

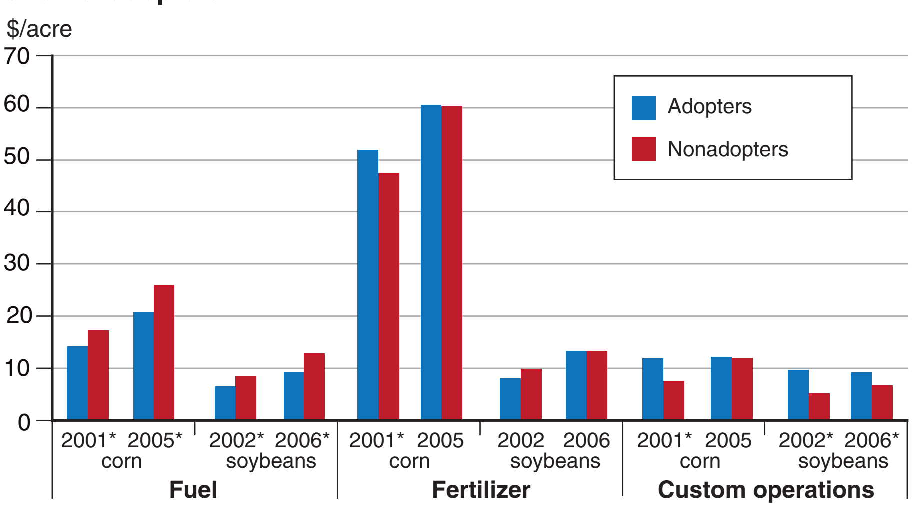
Aversion to risk has been shown to have a large negative impact on the adoption of information technologies, contributing more than all other factors combined (Fernandez-Cornejo, Daberkow and McBride, 2001, Table 2). El-Osta and Mishra (2001) found similar positive empirical results for farm size, which varies across the country, and level of education on the adoption of precision technologies, but did not find a profitability benefit of VRT in their data that pre-dates the latest ARMS results presented here. Land tenure and borrowing capacity also vary by crop and region and have been linked to adoption of other farm technologies through fixed, initial investment costs (El-Osta and Morehart, 1999).

Precision Agriculture and Input Expenditures

Fuel and fertilizer expenses might be expected to decline with adoption of precision technologies. GPS mapping and guidance systems can reduce the need for overspraying by precisely defining the borders of previously sprayed areas. Yield monitoring can help farmers identify areas in their fields where changes in practices might be beneficial, while variable-rate technology can put that knowledge to practical effect. ARMS data show that fuel expenses incurred, per acre, by both corn and soybean farmers were lower for those who used a yield monitor (fig. 9). Custom service expenses were higher per acre for 2001 corn and 2002 and 2006 soybeans, indicating that some additional custom operations were likely used when yield monitors were adopted (fig. 9). Average fuel expenses were lower per acre for farmers using VRT for corn and soybean fertilizer application (fig. 10). Adopters of guidance systems had significantly lower fuel expenses per acre for 2006 soybeans (not shown).

To understand the avenues by which VRT and GPS mapping might be adopted by producers, we investigate how often they might be obtaining these services from outside providers. Guidance system adopters might also be influenced by the availability of support services by service providers. It is possible that the reason that there are no significant differences between fertilizer expenses incurred by corn producers using VRT (fig. 10) and guidance systems (not shown, magnitudes are similar) is that fertilizer application itself is reduced, with the cost savings paying for custom application.

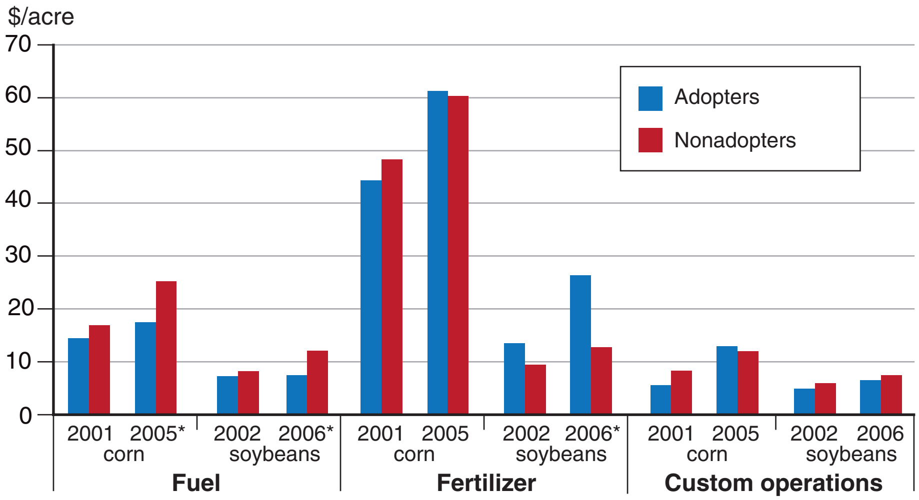
Figure 9
Comparison of expenses among yield monitor adopters and nonadopters



*indicates statistically significant difference of ratios, at 10% levels.
Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

The 2009 Precision Agricultural Services Dealership Survey (Whipker and Akridge, 2009) covers 241 cooperatives, local independent seed and chemical suppliers, and regional or national input companies in the Corn Belt. Dealerships were asked about the types of precision services that they offer and their profitability. Input dealers were also asked in 2009 about foreseeable changes over the next 2 to 3 years in the input retailer-manufacturing business. The most common service offered by these input dealerships since 1999 has been soil sampling reported in GPS format (52 percent of all surveyed). Field mapping with GPS was second most common (44 percent), while 39 percent of dealerships offered yield monitor data analysis, a new high for the survey and consistent with ARMS results showing a recent jump in yield monitor use. Custom VRT application of fertilizer, lime, and pesticides, as well as variable-rate seeding with GPS, was provided by one-third of dealerships in 1999 and 2000 (Whipker and Akridge, 2009). By 2009, that percentage had increased to 56 percent, with survey respondents indicating that they expected that portion of their business to continue to grow to over 60 percent by 2011. The ARMS results understate the use of VRT because some of these services are obtained from custom dealers.

Figure 10
Comparison of expenses among VRT-fertilizer adopters and nonadopters



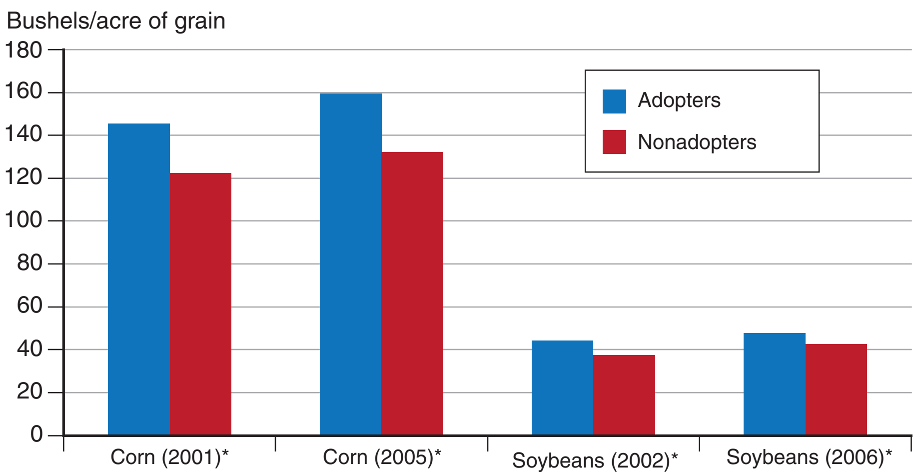
*indicates statistically significant difference of ratios, at 10% levels.
VRT= variable-rate technology.
Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

Precision Agriculture Adopters and Crop Yields

Many factors influence crop yields. Environmental and management factors may favor the adoption of precision agriculture, which may affect crop yields. Heisey (2009) points out that research investment has been a major factor raising corn yields, and Monsanto is close to having a drought-tolerant variety of corn available for field testing (Lybbert and Bell, 2010). Monsanto indicates that rather than offsetting the need for precision agriculture, their new seed technologies complement it (Monsanto, 2011).

ARMS Phase II and III data show clear relationships between information technology adoption and corn/soybean yields. Corn and soybean yields in 2001/2 and 2005/6 are significantly higher for yield monitor adopters than for nonadopters (fig. 11). Many factors could be contributing to this gap, including some of the same factors contributing to the very adoption of yield monitors themselves, like farm operator education, technical sophistication, and farm management acumen. The yield difference increased for corn from a little over 20 bushels/acre (10-percent differential) in 2001 to almost 30 bushels/acre (23 percent) in 2005. Adopters of GPS mapping also had significantly higher yields for both corn and soybeans in 2001/2 and 2005/6, with the differential ranging from 14 to 18 percent (fig. 12). The yields obtained by adopters of variable-rate fertilizer equipment (fig. 13) are also significantly higher for both corn (2001 and 2005) and soybeans (2002 and 2006). Guidance system (GSYS) adopters had significantly higher yields for corn and soybeans in 2001/02.

Figure 11
Comparison of yields among yield monitor adopters and nonadopters

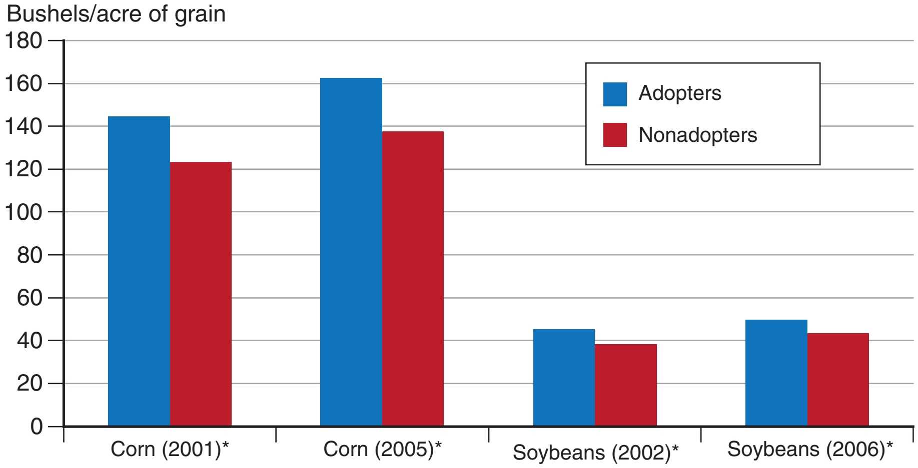


*indicates statistically significant difference of ratios, at 10% levels.
Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

A recent survey of 234 studies of precision agriculture found that 210 addressed profitability (Griffin and Lowenberg-DeBoer, 2005). In the 26 corn or soybean studies that investigate VRT use and profitability, all find that growers increased profit.[5] These results seem to support Bullock et al.'s (2009) contention (restated slightly) that low adoption rates for VRT are not necessarily caused by VRT's inherent nonprofitability, but by a lack of information concerning the profitable incorporation of VRT data into farming practices.

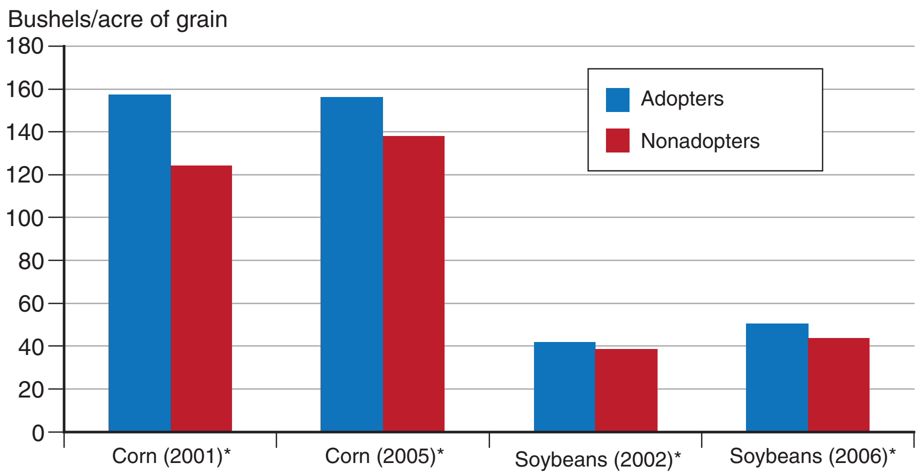
[5]Of the 234 surveyed studies, 37 percent discuss corn in combination with any precision agriculture practice, and 73 percent of these report increased profit (Griffin and Lowenberg-DeBoer, 2005, table 6). Two percent of the studies discuss soybeans only, and all report higher profits. Corn and soybeans are discussed together in 9 percent of the studies, with 76 percent of these finding higher profits with VRT.

Figure 12
Comparison of yields among Global Positioning System mapping adopters and nonadopters



*indicates statistically significant difference of ratios, at 10% levels.
Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

Figure 13
Comparison of yields among VRT-fertilizer adopters and nonadopters



*indicates statistically significant difference of ratios, at 10% levels.
VRT= variable-rate technology.
Source: Agricultural Resource Management Survey, USDA, ERS/NASS.

Factors Likely Affecting the Adoption of Precision Agriculture

Precision agriculture remains in the early stages of adoption, and the suite of information technologies are not expected to be adopted at the same time across the country (see box "Why We Might Expect Regional Differences in the Adoption of Precision Technologies," p. 14). For all the crops considered, yield monitors have had the most widespread adoption, probably because they are available as standard equipment on some new farm machinery or can be installed with the fewest technical difficulties. The creation of GPS maps and use of VRT equipment both require an extra level of expertise with data and information management, entail greater additional cost, and pose the most potential problems in successful implementation. Both technologies need more information and data than yield monitors, requiring many times the storage capacity and programming skill to use. And VRT requires a substantial investment in the equipment to apply fertilizer and pesticides or to seed at variable rates.

Changes in the popularity and cost of other farming practices may have affected the rate at which information technologies are adopted. Since 1998, no-till has gained in popularity for corn production while conventional tillage has declined (fig. 8); when mulch-till, reduced tillage, and no-till are considered altogether, total acres planted to alternative tillage far exceeded the acres planted conventionally in 2005. Yield monitors have been adopted more quickly by corn and soybean farmers using conservation tillage practices like no-till (table 4).

The potential for these information technologies has also been linked to a host of emerging environmental and farm management questions (Hatfield, 2000; Frisvold, 2000; NRC, 1997). Precision agriculture may have a positive impact on environmental quality through more efficient use of inputs. Farm management might also be enhanced by more complete information on field conditions.

Conclusions

The recent rapid adoption of yield monitoring technology is likely due to its increased retail availability, reduced cost, and increasing ease of use. Yield monitoring appears to be an entry to precision agriculture technology, with very few nonadopters of yield monitors creating global positioning system (GPS) maps or using variable-rate input application technologies (VRT) that rely on GPS maps. Coincident with yield monitor adoption is the growing popularity of conservation tillage systems. This report does not attempt to determine whether these practices are linked, but yield monitors are most popular among corn and soybean farmers practicing conservation tillage. Average fuel expenses, per acre, for both corn and soybean farmers are lower for farmers who use yield monitors. VRT for fertilizer application is associated with lower fuel expenses for both corn (2005 ARMS) and soybeans (2006). Average fertilizer expense—which includes expenses for custom application—is higher for soybeans if applied by variable-rate technology.

ARMS data indicate that adopters of yield monitors had higher corn and soybean yields than non-adopters in 2001/2 and again in 2005/6. Even though the adoption of GPS mapping is less prevalent than yield monitors, both corn and soybean farmers achieved higher yields nationwide when GPS was used. Likewise, when variable-rate technology was used to apply fertilizer, higher yields were obtained for both crops.

The future viability of precision agriculture will likely depend on (1) whether the technologies become less expensive and/or easier to install/maintain; (2) whether conservation tillage becomes even more widespread; and (3) the relative prices of fuel, fertilizer, and custom applications. The reduced use of fuel and more economical application of fertilizer under precision agriculture indicate its potential utility in reducing air and water pollution. The value of the data obtained from these information technologies increases as farm costs increase, as maps grow more detailed, and as yield responses become more certain.

References

Arrow, K.J. 1962. "The Economic Implications of Learning by Doing," *Review of Economic Studies* XXIX:154-74.

Bullock, D.S., and D.G. Bullock. 2000. "From Agronomic Research to Farm Management Guidelines: A Primer on the Economics of Information and Precision Agriculture," *Precision Agriculture* 2:71–101.

Bullock, D.G., D.S. Bullock, E.D. Nafziger, T.A. Doerge, P.R. Carter, T.A. Peterson, and S.R. Paszkiewicz. 1998. "Does Variable Rate Seeding of Corn Pay?" *Agronomy Journal* 90: 830-836.

Bullock, D.S., J. Lowenberg-DeBoer, and S. Swinton. 2002. "Adding Value to Spatially Managed Inputs by Understanding Site-specific Yield Response," *Agricultural Economics* 27:233–45.

Bullock, D.S., M.L. Ruffo, D.G. Bullock, and G.A. Bollero. 2009. "The Value of Variable Rate Technology: An Information-Theoretic Approach," *American Journal of Agricultural Economics* 91(1):209-223.

Carpenter, S., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. "Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen." *Issues in Ecology* 3. http://etmd.nal.usda.gov/bitstream/10113/78/1/IND21636988.pdf

El-Osta, H.S., and A.K. Mishra. 2001. "Adoption and Economic Impact of Site-Specific Technologies in U.S. Agriculture." Paper presented to *American Agricultural Economic Association* Annual Meeting at Chicago, IL, Aug. 5-8. http://ageconsearch.umn.edu/bitstream/20593/1/sp01el01.pdf

El-Osta, H.S., and M. Morehart. 1999. "Technology Adoption Decisions in Dairy Production and the Role of Herd Expansion," *Agricultural and Resource Economics Review* 28(1):84-95.

Feder, G., and G. O'Mara. 1981. "Farm Size and the Diffusion of Green Revolution Technology," *Economic Development and Cultural Change* 30:59-76.

Fernandez-Cornejo, J., S. Daberkow, and W.D. McBride. 2001. "Decomposing the size effect on the Adoption of Innovations: Agrobiotechnology and Precision Agriculture," *AgBioForum* 4(2):124-136. Available at: http://www.agbioforum.org.

Fernandez-Cornejo, J., A. Mishra, R. Nehring, C. Hendricks, M. Southern, and A. Gregory. 2007. *Off-Farm Income, Technology Adoption, and Farm Economic Performance*. Economic Research Report Number 36, U.S. Dept. of Agriculture, Economic Research Service. http://ageconsearch.umn.edu/bitstream/7234/2/er070036.pdf

Frisvold, G.B. 2000. “Data, Information, and Rural Environmental Policy: What Will the Next Ten Years Bring?” *Review of Agricultural Economics* 22(1):237-44.

Gebbers, R., and V.I. Adamchuck. 2010. “Precision Agriculture and Food Security,” *Science* 327:828-31.

Goolsby, D.A., W.A. Battaglin, B.T. Aulenbach, and R.P. Hooper. 2001. “Nitrogen Input to the Gulf of Mexico,” *Journal of Environmental Quality* 30:329–336.

Goolsby, D.A., W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulenbach, R.P. Hooper, D.R. Keeney, and G.J. Stensland. 1999. “Flux and Sources of Nutrients in the Mississippi-Atchafalaya River Basin,” Topic 3 Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico, National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce.

Griffin, T.W., and J. Lowenberg-DeBoer. 2005. “Worldwide adoption and profitability of precision agriculture: implications for Brazil,” *Revista de Política Agrícola*, 4. http://www.embrapa.br/publicacoes/tecnico/revista-Agricola/rpa-de-2005/pol_agr_04-2005-p-pg-embrapa.pdf

Griffin, T.W., J. Lowenberg-DeBoer, D.M. Lambert, J. Peone, T. Payne, and S.G. Daberkow. 2004. “Adoption, Profitability, and Making Better Use of Precision Farming Data.” Staff Paper Number 04-06. Purdue University, Dept. of Agricultural Economics. http://ageconsearch.umn.edu/bitstream/28615/1/sp04-06.pdf

Griliches, Z. 1957. “Hybrid Corn: An Exploration in the Economics of Technological Change,” *Econometrica* 25(4):501-522

Hatfield, Jerry L. 2000. “Precision Agriculture and Environmental Quality: Challenges forResearch and Education.” Research summary prepared for The National Arbor Day Foundation following national workshop, *Precision Agriculture and the Environment: Research Priorities of the Nation*, held in cooperation with the USDA’s Natural Resources Conservation Service and Agricultural Research Service.

Heisey, P.W. 2009. “Science, Technology, and Prospects for Growth in U.S. Corn Yields,” *Amber Waves* 7(4):10-13, Economic Research Service (USDA).

Horowitz, John, Robert Ebel, and Kohei Ueda. 2010. *’No-Till’ Farming Is a Growing Practice*. Economic Research Service (USDA), Economic Information Bulletin Number 70, Nov.

Huang, W. 2009. *Factors Contributing to the Recent Increase in U.S. Fertilizer Prices, 2002-8*, AR-33, U.S. Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/Publications/AR33/AR33.pdf

Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment Report (Climate Change 2007). Working Group III (WGIII): Mitigation of Climate Change, Summary for Policymakers. http://www.ipcc-wg3.de/activity/assessment-reports/ar4

Just, R., D. Zilberman, and G. Rausser. 1980. "A Putty-Clay Approach to the Distributional Effects of New Technology Under Risk," in *Operations Research in Agriculture and Water Resources*, D. Yaron and C. Tapiero (eds.). New York: North Holland Publishing Company.

Klemme, R.M. 1985. "A Stochastic Dominance Comparison of Reduced Tillage Systems in Corn and Soybean Production under Risk," *American Journal of Agricultural Economics*. 67(3):550-57.

Lybbert, T.J., and A. Bell. 2010. "Why Drought Tolerance Is Not the New Bt," *Nature Biotechnology* 28(6):553-4.

Luh, Y-H., and S.E. Stefanou. 1993. "Learning-by-Doing and the Sources of Productivity Growth: A Dynamic Model with Application to U.S. Agriculture," *Journal of Productivity Analysis* 4(4):353-70.

Monsanto. 2011. "Industry Leaders Collaborate on Precision Agriculture," Feb. 8, news release available at: http://monsanto.mediaroom.com/industry-leaders-collaborate-on-precision-agriculture.

National Research Council (NRC). 1997. *Precision Agriculture in the 21st Century: Geospatial and Information Technologies in Crop Management*, report by the Committee on Assessing Crop Yield: Site-Specific Farming, Information Systems, and Research Opportunities, ISBN-10: 0-309-05893-7

Patterson, Paul. 2009. "The Economics of Growing Sugarbeets in Southern Idaho: A Short Run Gross Margin Analysis," University of Idaho, Department of Agricultural Economics and Rural Sociology, Moscow, Idaho, http://www.ag.uidaho.edu/aers.

Paxton, Kenneth W., Ashok K. Mishra, Sachin Chintawar, James A. Larson, Roland K. Roberts, Burton C. English, Dayton M. Lambert, Michele C. Marra, Sherry L. Larkin, Jeanne M. Reeves, and Steven W. Martin. 2010. "Precision Agriculture Technology Adoption for Cotton Production." Selected Paper, Southern Agricultural Economics Association Annual Meeting, Orlando, FL, Feb. 6-9.

Prokopy, L.S., K. Floress, D. Klotthor-Weinkauf, and A. Baumgart-Getz. 2008. "Determinants of agricultural best management practice adoption: Evidence from the literature," *Journal of Soil and Water Conservation* 63(5):300-311.

Rahm, M.R., and W.E. Huffman. 1984. "The Adoption of Reduced Tillage: The Role of Human Capital and Other Variables," *American Journal of Agricultural Economics*. 66(4):405-13.

Skinner, J., and D. Staiger. 2005. *Technology Adoption From Hybrid Corn to Beta Blockers*. National Bureau of Economic Research, Inc., NBER Working Papers: 11251.

Stenberg, P., M. Morehart, S. Vogel, J. Cromartie, V.E. Breneman, and D.M. Brown. 2009. “Broadband Internet’s Value for Rural America.” Economic Research Report Number 78. U.S. Department of Agriculture, Economic Research Service.

U.S. Department of Agriculture, Economic Research Service. 2006. *Agricultural Resources and Environmental Indicators (AREI)* Economic Information Bulletin 16:144-50.

U.S. Department of the Interior, U.S. Geological Survey. 2009. *Nutrient Delivery to the Gulf of Mexico among Highest Measured*, June 16. http://www.usgs.gov/newsroom/article.asp?ID=2240

Whelan, B.M., and A.B. McBratney. 2000. “The ‘Null Hypothesis’ of Precision Agriculture Management,” *Precision Agriculture* 2:265-279.

Whipker, L.D., and J.T. Akridge. 2006-09. “Precision Agricultural Services Dealership Survey Results.” Working Paper Number 09-16. Purdue University Department of Agricultural Economics. http://www.agriculture.purdue.edu/ssmc/

Zinser, L.D., J.A. Miranowski, J.S. Shortle, and M.J. Monson. 1985. “Effects of Rising Relative Energy Prices on Soil Erosion and Its Control,” *American Journal of Agricultural Economics* 67(3):558-62.