ADOPTION, PROFITABILITY, AND MAKING BETTER USE OF PRECISION FARMING DATA

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Abstract

Precision agriculture (PA) technology has been on the market for over ten years. Global Positioning Systems (GPS), Geographic Information Systems (GIS), yield monitors, variable rate technologies (VRT) and other spatial management technologies are being used by farmers worldwide, but questions remain about the profitability of the technology and its future. This paper summarizes: 1) data on adoption of PA technology worldwide, 2) review of PA economics studies and 3) efforts to make better use of yield monitor and other sensor data in crop management. The adoption estimates are based on reports by an international network of collaborators. This paper draws on USDA ARMS data to update U.S. PA adoption numbers. The PA profitability summary goes beyond previous reviews by including a large number of publications from the last three years, a more detailed breakdown of results by technology type and new technologies. The data analysis section focuses on efforts to make use of the yield monitor and other data that farmers are collecting routinely, including spatial analysis of on-farm comparisons and alternative on-farm trial designs that take advantage of PA technology. Conclusions outline our vision of the future of precision agriculture and the role of farm management extension.

Keywords: precision agriculture, adoption, profitability, experimental design, yield monitor analysis

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Introduction

Precision agriculture (PA) is an application of spatial information technologies to crop production. PA technologies such as Global Positioning Systems (GPS), Geographic Information Systems (GIS), yield monitors, variable rate technology (VRT) and other spatial management technologies have been on the market for about 15 years and are used by farmers worldwide, but questions remain about the profitability of these technologies and their future. This paper summarizes: 1) data on adoption of PA technology in the United States (U.S.) and worldwide, 2) a literature review covering more than 200 studies reviewing PA profitability, and 3) efforts to make better use of yield monitor and other sensor data for crop management decisions. These overlapping themes can be thought of as what we have learned, what we are doing, and where we go from here.

Adoption estimates are based on reports from an international network of collaborators, and publicly available literature, such as refereed journal articles, technical magazines, and conference proceedings. United States PA adoption numbers draw on USDA Agricultural Resource Management Survey (ARMS) data. The PA profitability summary extends the review of 108 documents by Lambert and Lowenberg-DeBoer (2000), with an additional 126 studies from the last 15 years, and a breakdown of technology profitability by type and new technologies. Following the adoption section, the paper focuses on efforts to make better use of yield monitor and other data that farmers are collecting routinely, including analysis of on-farm comparisons and alternative on-farm trial designs that take advantage of PA technology. Conclusions outline our vision of the future of PA and the role of farm management extension. Some explanations of the constraints impeding PA adoption are offered.

Current Adoption Trends

Several studies have examined PA adoption since its debut in the late 1980s (Daberkow et al., 2002; Daberkow and McBride, 1998; Fountas et at, 2003; Griffin et al., 2000; Khanna, 2001). PA has slowed in recent years compared to the mid- and late 1990's (Daberkow et al., 2002; Popp et al., 2002). Still others present possible constraints impeding PA adoption (Fountas et al., 2003; Kitchen et al., 2002; Popp et al., 2002; Wiebold, 1998).

The USDA ARMS survey provides the most detailed information with respect to PA adoption in the U.S. The survey is a collaborative effort by the Economic Research Service (ERS) and the National Agricultural Statistics Service (NASS). Since 1996, the ARMS Survey has provided information on production practices and resource use of America's farmers through

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Footnote: The opinions and conclusions expressed here are those of the authors and do not necessarily represent the views of the U.S. Department of Agriculture.

face-to-face interviews. The 2002 ARMS survey targeted soybean production. This section reports results of the updated 1996 through 2002 ARMS.

1. Yield Monitor Adoption

Yield monitor adoption is often the yardstick by which PA is measured. Around the world yield monitors are the single most common PA technology (Lowenberg-DeBoer, 2003 a). About 90% of the world's yield monitors are in the U.S. Corn and soybean yield monitor adoption rates have steadily increased since the introduction of yield monitors. Corn and soybean yield monitors were used on 15.6% and 13.3% of planted acres in 1996 (Table 1.). Yield monitor use exceeded 35% of planted corn acreage in 2001. However, the soybean acreage harvested with a combine yield monitor was still less than 30% by the end of 2002. Wheat and cotton acres have not experienced the same level of adoption as corn and soybean. Approximately 9% and 1% percent of the acres planted to wheat and cotton respectively were harvested with machines equipped with yield monitors by the end of 2000.

One might expect high value crops like cotton to have higher adoption rates. One reason for the lag in yield monitor adoption in cotton acres is the uniqueness of the crop's harvesting machine. The cotton picker is used only for cotton, as opposed to the grain combine, which is used for corn, soybean, wheat, and other grain and oilseed crops. While a combine harvests multiple crops and can have costs spread over many acres, the cotton picker has its costs spread over cotton acres only. The cotton yield monitor became commercially available in 1998, at a time when over 20% of corn and soybean acres were harvested with yield monitors.

Worldwide Yield Monitor Adoption

Cross-country technology comparisons are important for tracking global trends in competitive advantage and in understanding the underlying economics of the technology. Watching which technologies do well in different economic environments can tell us something about the perceived benefits and costs. To make this comparison it is essential to count yield monitors the same way everywhere. Some observers report only yield monitors used with GPS because it is only with GPS that full use can be made of the data, but to be consistent with the USDA ARMS data we have tried to count all yield monitors and report separately on the percentage used with GPS. It is also important to understand yield monitor numbers relative to the total crop acreage.

In 2000, the U.S. had about 136 yield monitors per million acres of grain or oilseeds (Table 2). Anecdotal information suggests that the situation is similar in Canada. The only country that may have had a higher level of yield monitor use is Germany, with over 200 yield monitors per million acres of grain and oilseeds. Denmark had approximately 100 yield monitors per million acres, while the U.K. and Sweden had only 43 and 48 yield monitors per million acres, respectively. Outside U.S., Canada and Western Europe the highest density of yield monitor use is in Argentina and Australia, with an estimated 17 yield monitors per million acres. It should be noted that because of differences in farm size and combine ownership (more custom

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Footnote: ARMS point estimates for any specific year are subject to sampling error. Hence, year-over-year comparisons are not as meaningful as data over multiple years.

Table 1. Share of U.S. Corn, Soybean, All Wheat, and Cotton Acres on Which Precision Agriculture Technologies Were Used, 1996-2002.[1/]

Technology/year	Corn	Soybeans	All wheat	Cotton
Yield monitor	(percent of planted acres)			
1996	15.6	13.3	5.9	NA
1997	19.9	16.1	7.4	NA
1998	26.0	20.2	8.5	*
1999	32.0	21.6	NA	1.7
2000	34.2	25.4	9.1	1.3
2001	36.5	NA	NA	NA
2002	NA	28.7	NA	NA
Yield map (Yield monitor with GPS)				
1996	NA	8.1	*	NA
1997	9.5	5.2	*	NA
1998	12.7	10.2	*	*
1999	18.4	9.9	NA	1.0
2000	13.8	7.8	*	*
2001	13.7	NA	NA	NA
2002	NA	10.7	NA	NA
Geo-referenced soil map [2/]				
1998	18.6	14.4	6.6	3.1
1999	23.8	16.7	NA	7.6
2000	25.0	18.5	12.2	14.2
2001	25.0	NA	NA	NA
2002	NA	11.2	NA	NA
Remotely sensed image [3/]				
1999	12.7	6.9	NA	NA
2000	7.3	4.4	3.9	NA
2001	3.4	NA	NA	NA
2002	NA	1.7	NA	NA

* = less than 1 percent NA= not available

1/ These estimates are revised from previously published estimates based on updated weights from the ARMS.

2/ Prior to 2002, respondents were asked if the soil characteristics of this field had ever been geo-referenced. Beginning in 2002, respondents were asked about geo-referencing in the current and previous year.

3/ The question was reworded in 2002 to better define the term “remotely sensed".

For more information, go to http://www.ers.usda.gov/Briefing/ARMS/

cutters in Argentina), a combine in that country may cover as much as five times as many acres annually as a similar machine in the U.S. Thus, the use of yield monitors in Argentina probably surpasses that of most Western European countries and approaches that of the U.S. in the late 1990s. Yield monitors are being used on some larger farm operations in Brazil and Mexico (Norton and Swinton, 2001). Informal reports indicate that in Australia about 800 yield monitors were used for the 2000 harvest. Some fifteen farmers used yield monitoring in South Africa for the 1999-2000 crop season (Nell, 2000).

Table 2. Number of Yield Monitors by Country

Country	Estimated Number	Year of Estimate	Source of Estimate	Yield Monitors Per Million Acres
Americas:				
United States	30000*	2000	Daberkow et al. (2002)**	136*
Argentina	1000	2003	Bongiovanni	17
Brazil	100	2002	Molin	1
Chile	12	2000	Bragachini	8
Uruguay	4	2000	Bragachini	3
Europe				
U.K.	400	2000	Stafford	43
Denmark	400	2000	Stafford	100
France	50	2000	Stafford	2
Germany	4250	2003	Wagner	212
Netherlands	6	2000	Stafford	11
Sweden	150	2000	Stafford	48
Belgium	6	2000	Stafford	7
Spain	5	2003	4ECPA participants	0
Portugal	4	2003	Conceicao	3
Other				
Australia	800	2000		17
South Africa	15	2000	Nell	1

* U.S. combines with yield monitors calculated from data provided by Daberkow et al. (2000)
** @gInnovator (2000) also estimates 30,000 combine yield monitors in North America

2. Variable Rate Technology Use by Farmers

The second most common yardstick to measure PA adoption is variable rate technology (VRT). In the later part of the 1990's, VRT was used to manage soil fertility (mainly nitrogen, phosphorous, potassium, and lime) on nearly 18% of planted corn acres (Table 3). However, ARMS data indicate that this rate was less than 10% of corn planted acres in 2001. Soybeans showed a similar trend, albeit a lesser magnitude. Soybean acres fertilized with VRT peaked at 8% in 1999, but fell to 5% in 2002. Part of the difference is that soybeans require no applied nitrogen, the nutrient that is most widely applied using VRT in corn acres (see Lambert and Lowenberg-DeBoer, 2000). These fluctuations are in part explained by soil mapping adoption rates in those years since VRT applications are coincident with soil mapping. Corn acres with VRT seeding declined steadily, while soybean VRT seeding fell to below 1% of planted acres in 2002. Some studies have concluded that VRT seeding is not profitable in corn (Lowenberg-DeBoer, 2003 b; Bullock et al., 1998). However, other studies suggest that VRT seeding for cotton shows some profit potential (Larson et al., 2004). VRT for pesticides seems to be increasing for corn, soybean, wheat and cotton, even though overall rates are still low at 1% to 3% in the most recent ARMS data.

Table 3. Share of U.S. Corn, Soybean, All Wheat, and Cotton Planted Acreage on Which VRT was Used by Input, 1998-2002.

	Fertilizer	Seed	Pesticides	Fertilizer	Seed	Pesticides
Year	Corn			Soybean		
	percent of planted acres					
1998	12.3	4.1	2.4	6.7	*	*
1999	17.5	4.2	1.1	8.3	2.0	1.7
2000	14.5	4.5	3.8	5.8	2.5	1.0
2001	9.8	2.4	3.8	NA	NA	NA
2002	NA	NA	NA	5.0	*	1.3
	All wheat			Cotton		
1998	2.6	1.5	1.7	2.0	1.3	1.5
1999	NA	NA	NA	1.0	1.8	2.0
2000	3.1	*	*	3.8	2.4	2.7

* = less than 1 percent NA= not available

Source: ARMS

3. Variable Rate Technology Services Offered by Agricultural Industry: The Whipker and Akridge Surveys

The Precision Agricultural Services Dealership Survey Results has been published yearly by Whipker and Akridge since 1996. In 2004, 439 useable respondents from 40 states were included in the survey. Of the service providers who offered custom applications, 67% expected to offer VRT services by the end of 2004 (Whipker and Akridge, 2004). They reported controller-driven single product application was offered by 40% of dealers in 2004, down from 45% and 50% in 2003 and 2002, respectively. Controller-driven multi-product application was offered by 23% of service providers in 2004, approximately the same levels as in 2002 and 2003 when 20% and 26% of service providers, respectively, offered the service (Whipker and Akridge, 2004). Only 28% of providers expect to offer multi-product applications by 2005 (Whipker and Akridge, 2004). By the end of 2004, nearly half (48%) of agricultural service dealers expect to offer single nutrient VRT in the Midwest, compared to only 18% of dealers from other states. Although single nutrient application is the most common use of VRT, the %-increase in VRT multi-nutrient application offered was greater than for single nutrient. Whipker and Akridge found that the agricultural industry is not as interested in VRT seeding as in other PA services, with less than 10% of dealerships offering the service.

Commercial applicators are increasingly using PA technology to deliver conventional services. Pierce and Nowak (1999) segregate PA technologies into one of two groups. One group deals with yield monitors, soil mapping, and other sensors that provide spatial information and the second group deals with using PA technologies such as GPS to control or improve conventional applications. Sixty-one percent of applicator services use GPS guidance with manual control or light bar navigation, however only 5.3% use GPS auto-guidance (Whipker and Akridge, 2004). GPS guidance has become standard practice on aerial applicators.

4. Yield Mapping Adoption (Yield Monitor plus a GPS)

Most crop management uses of yield monitor data are only possible if the sensor is linked to GPS to provide location information. The yield maps which have become the icon of PA are only possible with GPS. However, yield-mapping adoption seems to be occurring at a much slower pace than yield monitoring. Although the percentage of acres of corn and soybeans harvested with a yield monitor-equipped combine gradually increased since 1996, corn and soybean acres harvested with a combine yield monitor attached to a GPS did not follow the same trend as yield monitor adoption. In the U.S., corn acres yield mapped peaked in 1999 at 18.4% and decreased to 13.7% in 2000. Since 1998, mapped soybean acres dipped to 9.9% and 7.8% in 1999 and 2000, respectively. Soybean acres yield mapped had the highest reported rate in 2002 at 10.7%, breaking the previous high of 10.2% set in 1998.

There may be several reasons why yield mapping adoption rates lag behind yield monitor adoption rates. Many combine manufacturers offer yield monitors as standard equipment on their larger machines, but GPS is often not included (Griffin, 1999; Lowenberg-DeBoer, 2003 a). Thus, some combine owners acquire yield monitors whether they want the sensors or not. In some of those cases, the yield monitor is not even switched on. In other cases, it is used uncalibrated to provide rough yield differences. Some combine owners who do not wish to use the yield monitor themselves will buy it in a new combine because it is perceived that combine trade-in values are higher with a yield monitor. Logistical reasons for having a yield monitor without a GPS is that yield monitors can be used for the associated moisture measurements. Some growers use the yield monitor moisture readings to decide whether grain can be sold directly from the field or needs to be dried before sale. Case studies by Urcola (2003) showed that some farmers use the combine yield monitor as a replacement for weigh wagons by recording “loads” of field, block or strip averages rather than within-field variability.

The most often cited reason provided by farmers for not yield mapping are problems associated with data analysis. Yield map analysis requires substantial time and skill. Either the farm operator or a crop consultant must devote time to learning analysis skills and data manipulation. Interpretation of yield maps is still as much an art as a science. Uncertainty about the reliability of yield maps for crop management reduces their perceived value. Thus, the cost of yield map analysis in terms of management time is perceived to be high, while the benefit is uncertain.

Some countries appear to have higher rates of yield mapping than the U.S. Some 70% of combines with yield monitors in Argentina use GPS compared to only about one-third in the U.S. (Lowenberg-DeBoer, 2003 a). For northern Europe, some evidence suggests that the number of combines with yield monitors, but no GPS, is similar to that of the U.S. (Lowenberg-DeBoer, 2003 a). Part of the difference is due to farm structure. United States and northern European farms are often run by owner-operators who do some of their own fieldwork. In contrast, many Argentine farms are run by managers who have less direct experience with field conditions because they hire custom operators to do most of the fieldwork. Therefore, yield data may provide more new information for Argentine managers than it does for U.S. or European owner operators. Because of high unemployment in Argentina and downward pressure on wages, management time may be less expensive there than in the U.S.

5. Soil Mapping Adoption

Leading up to 2000, a positive general trend for soil mapping was observed for corn and soybean with approximately 2% increase in number of acres each year for soybean (Daberkow et al., 2002). One-fourth of the acres planted to corn had soils that were geo-referenced. This trend appears to be leveling off for the time being. The proportion of acres planted to wheat has values comparable to corn, cotton, and soybeans at 12.2% in 2000. The number of cotton acres soil mapped has doubled each year between 1998 and 2000, starting at 3.1% and rising to 14.2%. Similar to the problems associated with yield map interpretation, understanding the spatial and temporal dynamics between soil test variables and yield is difficult. Linking soil test information to yield maps over space and time is still more of an art than science.

Coupled with the expenses associated with grid sampling, this uncertainty with respect to data processing and application may be another constraint with respect to soil mapping adoption. A related problem is that of resolution. How fine of a grid is needed before solid recommendations can be made? Mallarino and Wittry (2004) and Peone (2004) have recently tackled some of these questions with respect to soil test resolution. Unfortunately, like site-specific management in general, optimal soil sample resolution tends to be field-specific. However, on-the-go technologies such as the Veris Technologies Mobile Sensor Platform (MSP) automate high-resolution electrical conductivity and pH sampling at relatively low costs (Lowenberg-DeBoer, 2003 c). These technologies collect data on almost a continuous basis rather than on discrete grids.

6. Remote Sensing

Anecdotal accounts indicate that remotely sensed (RS) images are being widely used for management of fruits and vegetables. For grains and oilseeds, RS images were the least adopted technology among the group reviewed in the ARMS data set (Table 1). In 2002, only 1.7% of acres planted to soybeans had RS images or photographs made during the growing cycle. This was the lowest reported use of RS images for any crop in any year since data collection began in 1999. The trend for both corn and soybeans was the same; fewer RS images were used over time.

One reason for the decrease in the use of RS maps is the lack of perceived usefulness of mapping growing crops. A second reason is that maps of bare soils do not change over time and are only needed once. A third reason for low RS adoption rates is that there are relatively few reliable RS analysis or consulting firms.

The way in which RS images have been marketed may also discourage adoption by grain and oilseed growers. In the past, RS providers have tried to market subscriptions with an image every week or ten days. This may be good for orchards, vegetables and cotton, but not for corn and soybean for which most decisions are made around planting time. Although the ARMS survey did not examine RS in cotton production, it is suspected that RS image use for cotton exceeds that of corn and soybean substantially.

In spite of the long history of research on use of RS images in agriculture, the economics of this technology are not well researched. Tenkorang and Lowenberg-DeBoer (2004) reviewed 10 articles reporting RS economic benefits (Table 4). Seven of the ten report positive returns. Many studies did not report the budgeting details. Very high returns appear to be gross value, with no deductions for RS image cost and analysis, or implementation of VRT management plans based on the image. Tenkorang and Lowenberg-DeBoer (2004) argue that to make progress in understanding the economics of RS for agriculture, researchers need to report yield and budget details. In addition, they advocate repeated testing of multiple locations of the same management approach to RS use. The ten RS economics studies seem to be one-of-a-kind trials that are hard to compare.

Table 4. Studies Citing Returns to Use of Remote Sensing in Agriculture

Authors	Type of Imagery	Crop	Input Managed	Average Return $/acre
Zone Determination using Images from Previous Seasons:				
Carr et al. (1991)	Aerial & Satellite	Wheat, Barley	P & K Fertilizer	$0.87
OSU (2002)	Aerial	Cotton	Fertilizer, Insecticide, Growth Regulator	$60.00 - $150.00*
Larson et al., (2004)	Aerial	Cotton	Fertilizer, Insecticide, Growth Regulator	-$2.31 to -$14.96
Seelan, et al. (2003)	Satellite	Wheat, Sugar Beet	Nitrogen	$98.78*
In-Season Management				
Copenhaver et al. (2002)	Aerial	Soybeans	Herbicide	$1.68
Long (2002)	Aerial	Wheat	Herbicide	$0.92
Reynolds & Shaw (2002)	Aerial	Cotton, Corn	Herbicide	$27.47 to $74.65*
Watermeier (2003)	Aerial	Corn	Nitrogen	$13.00
White et al. (2002)	Aerial	Wheat	Nitrogen	-$1.21
White and Gress (2002)	Aerial	Corn	Nitrogen	-$1.06

* No details given on how benefit was estimated. Appears to be gross benefits without subtracting costs of images, analysis and VRA implementation.
SOURCE: Tenkorang and Lowenberg-DeBoer, 2004.

7. Auto-guidance

Auto-guidance systems (AGS) have become commercially available in the last two years. However, benefits from this technology are not yet established. AGS makes use of GPS information automatically controlling steering of farm equipment, effectively reducing human error. This technology works in various adverse conditions including dust and nighttime dark. Accuracy differs between systems and so do costs (Watson and Lowenberg-DeBoer, 2003). As with most new technologies, initial costs are relatively high, but will become less expensive over time. Benefits include allowing the operator to safely work more hours in a day, increasing ground speed, and reducing overlap. In some cases, AGS allows more acres to be farmed with the same equipment set. Some studies estimate that AGS could increase net revenues above variable and technology costs by $28 to $30 per acre (Watson, 2003). Because the technology is new, there are at present no reliable adoption numbers available, although local individual systems are gaining attention from the agricultural community in demonstrations or farm use in Denmark, Germany, Argentina, Brazil, Australia and the U.S.

8. On-the-go technologies

In the last two years, several on-the-go technologies have been introduced. These technologies are new enough that little adoption information has been documented and usefulness continues to be debated. The Veris Technologies Mobile Sensor Platform (MSP) automates pH sampling in addition to its electrical conductivity readings. Veris MSP's were sold in at least five states since being offered in the fall of 2003 (Lowenberg-DeBoer, 2003 c). It is anticipated that on-the-go lime applicators will be coupled with similar devices to apply appropriate rates of lime in the future. Measurements of resistance of electrical flow through soil are being made by electrical conductivity (Veris and Soil Doctor) and electromagnetic induction (Geonics EM38) giving information about soil chemical levels and physical properties on a nearly continuous level. Greenseeker technology was originally developed for on-the-go changes in nitrogen application rates in wheat. In addition, active normalized difference vegetative index (NDVI) readings from Greenseeker have been found to be useful in determining management zones in cotton (Sharp et al., 2004). Other innovations for Greenseeker are currently being developed. Herbicide sprayer sensors are being developed which allow the identification and treatment for weeds.

What We've Learned in the Last 15 Years

This section summarizes publicly available studies of the profitability of PA. It is an update of the PA profitability review by Lambert and Lowenberg-DeBoer (2000). Studies since 2000 are summarized by Peone et al. (2004). The information sources are refereed articles from scientific journals or proceedings, and non-technical or non-refereed magazines and monographs specializing in agribusiness services. Of the 210 of the 234 reviews reporting losses or benefits, 68% reported benefits from some sort of PA technology. Approximately half (52%) of those studies reporting benefits were written or co-authored by economists.

Profitability by Technology - Of the technologies specifically mentioned in the articles, PA summaries were most frequent, appearing in one-third of the literature (34%) (Table 5). GPS was mentioned in 6.4% of the articles. This does not include articles mentioning the combined use of GPS and other technologies, like yield mapping and VRT. VRT was mentioned with GPS in 4% with VRT/Yield Monitor and VRT/Seed mentioned in roughly 3% of the articles each.

Crops – Thirty-seven percent of the articles reviewed discussed economic returns from PA experiments with corn alone, and 73% of those reporting some benefit from using PA (Table 6). The second most common crop mentioned was wheat at nearly 11% of the articles, with half of those reporting PA benefits. Other crops mentioned were corn and soybean studies accounting for 9%, however three-fourths of those reported PA benefits. All soybean, barley and oats studies reported benefits. Corn and cotton combination studies reported no benefits to PA.

Partial Budget Components Reported in PA Studies

Time Scale and Discount Rate – Factors relating to time scale include the period of test validity (soil tests, yield maps), whether costs were spread out over an acres per time period, and the net revenue period. When these details were mentioned in articles, they were noted. Twenty-nine percent of the articles reviewed included one or more of these factors.

Input and VRT/PA Costs – Input costs considered in this review were fertilizer costs, seed costs, application costs, and any variable and fixed costs mentioned in the article. Variable rate technology and PA costs were considered separately for comparative purposes to verify whether benefits espoused by the authors(s) included PA technology costs, other farm input costs, and crop yield. Seventy-one percent of the articles included farm inputs in the budget analyses while 62% included PA technology costs. One-fourth mentioned equipment costs. Forty percent mentioned yield monitors. One-third of the articles reported environmental costs and benefits associated with PA.

Table 5. Frequency (%) of PA Technologies Reviewed in Articles.

Technology	*Frequency*	*Percent*
VRT, N	28	11.97
VRT, Seed	7	2.99
VRT, Weeds/Pests	7	2.99
VRT, Irrigation	2	0.85
VRT, P,K	7	2.99
VRT, GPS	10	4.27
VRT, Yield Monitor	8	3.42
VRT, Lime	4	1.71
Soil Sensing	5	2.14
GPS	15	6.41
PA(Summary)	82	34.94
VRT(General)	59	25.21
Total	234	

Table 6. Percent of Studies Reporting PA Benefits for Specific Crops.

Crop	*Percent*	*Percent Reporting Benefits from PA*
Corn	37.0	73
Potato	2.1	75
Wheat	10.9	52
Soybean	2.1	100
Sugarbeet	2.6	80
Barley	1.0	100
Oats	0.5	100
Corn & Cotton	0.5	0
Corn & Soybean	8.9	76
Soybean, Corn & Rice	1.6	33
Mixed	9.4	62
Sorghum/Millet	2.6	60
Cotton	1.6	33
NA	19.3	

Human Capital and Information Costs **–** Conventional economic feasibility studies of PA technology have often failed to include human capital and information costs in budget analyses. In all, nearly 21% of the articles reviewed mentioned human capital costs. Although this may be a difficult cost to compute, it should always be addressed in economic analyses since PA is generally human-capital intensive.

Table 7. Crop and Technology-Specific Benefits from PA Technology.*

Crop	*Technology*	*Percent Reporting Benefits*
Corn	VRT, N	72
Potato	VRT, N	NO
Wheat	VRT, N	20
Sugarbeet	VRT, N	YES
Barley	VRT, N	YES
Corn & Soybean	VRT, N	YES
Corn	VRT,Seed	86
Corn	VRT, Weed/Pests	100
Wheat	VRT, Weed/Pests	50
Soybean	VRT, Weed/Pests	100
Corn	VRT, Irrigation	YES
Corn & Cotton	VRT, Irrigation	NO
Corn	VRT, P & K	60
Potato	VRT, P & K	YES
Corn & Soybean	VRT, P & K	YES
Corn	VRT,GPS	100
Wheat	VRT,GPS	YES
Corn & Soybeans	VRT,GPS	100

*Entries with ‘YES’ or ‘NO’ are based on a single article.

Table 7. (cont) Crop and Technology-Specific Benefits from PA Technology.*

Crop	*Technology*	*Percent Reporting Benefits*
Corn	VRT, Lime	100
Corn & Soybean	VRT, Lime	YES
Corn	Soil Sensing	33
Sugarbeet	Soil Sensing	NO
Corn & Soybean	Soil Sensing	YES
Corn	GPS	50
Wheat	GPS	50
Corn & Soybeans	GPS	YES
Sorghum/Millet	GPS	NO
Cotton	GPS	NO
Corn	PA Technology (In General)	67
Wheat	PA Technology (In General)	YES
Soybean	PA Technology (In General)	YES
Barley	PA Technology (In General)	YES
Corn & Soybean	PA Technology (In General)	50
Corn, Soybeans, Rice	PA Technology (In General)	50
Sorghum/Millet	PA Technology (In General)	100
Corn	VRT, Yield Monitor	33
Sorghum/Millet	VRT, Yield Monitor	NO
Cotton	VRT, Yield Monitor	50
Corn	VRT, General	81
Potato	VRT, General	100
Wheat	VRT, General	60
Sugarbeet	VRT, General	100
Oats	VRT, General	YES
Corn & Soybean	VRT, General	60
Corn, Soybeans, Rice	VRT, General	NO
Sorghum/Millet	VRT, General	YES

*Entries with 'YES' or 'NO' are based on a single article.

Information costs are associated with grid soil sampling, lab testing, GPS services, or any PA activity that generates data conducive to becoming useful information. Information costs were mentioned in 34% of the articles reviewed. In Table 7, benefits to specific crops from different PA technologies are presented. This table summarizes results from articles where a mention of a specific crop(s) was explicitly managed by a specific PA technology. It omits reports that reported benefits to PA but were not explicit which technology corresponded to a particular crop (for example, whole-farm PA benefits), or reports that were not specific about which crops directly benefited from a PA technology in the article.

Discussion - Future Directions: Where Do We Go From Here?

Recognizing the Fundamental Constraints to PA Adoption

It is important to identify key constraints before anticipating the future of new technologies. Fernandez-Cornejo et al. (2001) contrasted adoption patterns of biotechnology and

PA. The question that remains with PA users and those considering PA is whether 'information-intensive' management is profitable, or whether we continue with the 'embodied knowledge' approach. 'Information-intensive' management refers to strategies that depend on farm and field level data to make decisions about input application and cropping practices. That data may be collected manually or electronically. VRT soil fertility management and integrated pest management are examples of information intensive approaches. In embodied knowledge technologies, information is purchased in the form of an input. The manager requires minimal additional data. An example of 'embodied knowledge' is hybrid corn. When it was introduced in the U.S. in the 1920s, hybrid corn was a new technology, but the knowledge needed to implement the technical package was already well-established. Two other good examples of 'embodied knowledge' are Bt Corn and Round-up Ready soybeans. The skill needed to successfully apply these new technologies is relatively small in that the technological packages are 'self-contained', requiring no new equipment purchases, or additional cultivating skills.

The 'information-intensive' technologies that characterize many PA technologies not only require time-costs, but they are scale-sensitive as well. For a producer willing to spend $150,000 to $200,000 on a combine, the extra $3000 for GPS equipment is negligible. However, how far these costs can be spread over the acreage operated makes a difference. Spreading capital over acres is probably less important than being able to spread *human capital* over the same acreage. For example, someone who learns how to interpret yield maps for a 2,000-acre farm can probably interpret yield monitor data for a 20,000-acre farm. Fountas et al. (2003) note that a key constraint to 'spreading of human costs' over farm acres is that of learning new software and other analysis skills. The opportunity cost of time may often be sufficiently high to discourage producers from learning how to accumulate, store, process, and interpret electronically generated data in the field or office computers.

Though the human cost of information intensive processes limit use, crop producers seem to be skeptical of 'closed-looped' approaches that automate decision-making. An example of a closed loop process in agriculture is the use of automated chicken feeders which adjust feed rations by average bird weight. In this instance, the producer spends less time worrying about matching feed requirements with the bird growth: rations are adjusted automatically over the course of bird growth. Crop farmers argue that a 'human touch' is still needed in cropping because crop management is still more of an art than a science. The environment of a chicken house is very controlled compared to field conditions for rain fed crops. Some farmers might feel they are giving up production control by handing over their human-made decisions to the 'black-box' decision-making processes.

Recognizing the Fundamental Incentives of PA Adoption

Earlier mentioned studies outline reasons for non-adoption, but few give alternative encouragement for PA adoption. Overall, information technology software and hardware costs are continually declining at the same time its capacity is increasing. In a broader view, society is readily incorporating technology in everyday life such as personal computers, GPS in cars, and cell phones. People are becoming more comfortable with technology. USDA FSA and NRCS agencies have moved to a GIS based system to replace aerial imagery, potentially increasing producer awareness of PA benefits. Identity tracking (IT) and identify preservation (IP) of agricultural commodities from seed production through farmer fields site-specifically, all the way through the marketing, processing, and distribution chains can either offer premiums for specialty crops or segregation of transgenic varieties. Another motivation for PA adoption may be through environmental regulations for monitoring input use that could potentially affect water quality and wetlands. PA could assist in pesticide recordkeeping in much the same way as with grain with IT and IP. In addition, cost sharing of PA technologies may entice farmers to adopt. This may occur by way of studies documenting environmental benefits from PA use.

When understanding adoption trends, cultural and socio-economic factors certainly come into play. For example, anecdotal evidence suggests that auto-guidance will be adopted by grain producers in South Africa (S.A.) for very different reasons than those in Brazil or the U.S. In S.A., farm workers specialized in combine and tractor operations have been lost to the AIDS epidemic (Nell, 2004). In response, some owner-operators are considering purchasing auto-guidance to replace years lost in driver skill. On the other hand, in Brazil 100,000 contiguous acres might be used in soybean production. The advantages of auto-guidance with respect to reduction in skip and overlaps over vast production surfaces are clear in this case. Additional examples of PA technologies being adopted in different parts of the world because of differing environmental, economic, and social conditions include:

- Auto-guidance is popular in Australia for controlled traffic because their soils are particularly susceptible to compaction and they do not have freezing and thawing to counteract that compaction.
- Outside of North America most farmers apply their own fertilizer and pesticide, so there has not been the growth of PA services.
- In South Africa and Argentina most phosphorus and potassium is applied with the planter. For farmers using air seeders it is relatively easy to modify their equipment for VRT.
- Grid soil sampling is used commercially mainly in the U.S. and Canada, in part because soil analysis is relatively cheap there.
- Agronomic skills are relatively inexpensive in Latin America, so knowledge-intensive management may catch on there more than the U.S.
- Much of the VRT in Europe has focused on nitrogen because of the environmental rules regulating nitrogen application.

Potential for PA Analysis and Consulting Groups

The network externality framework from information technology theory plays an important role in understanding adoption. Varian (1996, page 591) defines network externalities as “a special kind of externality in which one person’s utility for a good depends on the number of other people who consume this good.” Classic examples of these goods are fax machines, cell phones, and computer modems. Varian states that indirect effects of network externalities arise with complementary goods and services. He uses video rental stores and video cassette players as an example. In areas where there are no video rental stores, video players have low values to consumers and vice versa (Varian, 1996). This can be extended to PA technologies and consulting services as a complementary service with respect to using PA in production agriculture. If there are no services that analyze PA data and report recommendations to the farmer, there is no incentive for farmers to adopt the technology. Conversely, if farmers are not adopting PA, there is no incentive for firms to offer PA analyses and consulting services, especially startup firms. An example of 'consulting groups' might be a consortium of producers pooling farm-specific information. For example, Lowenberg-DeBoer and Urcola (2003) outlined a protocol for combining site-specific information across site-years, giving more value to localized yield monitor data. They discuss the problems of ranking the importance of station data to farm operations closer or farther away from station sites. With no standard for deciding which experiment station data to place the most weight, on-farm experimentation appears to be promising.

Better Experimental Designs

PA technology has reduced the cost of data collection, but most on-farm comparisons continue to be large block, split field or paired field comparisons with little or no replication. Citizen access to GPS and associated monitoring equipment has presented opportunities for revisiting the notion of on-farm experimental trial designs. In the early 20th century, the experimental designs used in agronomic studies focused on blocking techniques and replication. These techniques are effective, controlling for experimental unit heterogeneity. However, they require time, resources, and careful planning, thus limiting the producer's willingness to conduct on-farm trials. For logistical reasons, relatively few farmers use strip trials or other on-farm designs derived from classical small plot experimental methodology. Recent advances in spatial statistics may provide an alternative to blocking and numerous treatment replications commonly associated with classical agronomic trials. At Purdue, current research focuses on how replication with spatial statistical methods affects the quality of information from on-farm testing of categorical treatments such as hybrids, tillage, and herbicides (Lowenberg-DeBoer, Lambert, and Bongiovanni, 2003; Griffin, Lambert, and Lowenberg-DeBoer, 2004). Preliminary results suggest that fewer replications may be needed when spatial information is incorporated in estimation. The upshot is that producers may be able to conduct on-farm trails with fewer replications, saving time and money in terms of experimental protocol.

Spatial Analysis Workshops at the Purdue Top Farmer Crop Workshop

Alternative on-farm experimental designs are currently being tested on farmer-cooperator fields in four states. These designs are evaluated for ease of farmer implementation and data collection, data quality, and conduciveness to differing statistical methods. As a service to farmers, a first of its kind program has been implemented to analyze on-farm planned comparisons. In the process, a standardized protocol is being developed to consistently handle the analysis across farms and years, plus to make the analysis replicable. The service of yield monitor data analyses will be a part of Purdue annual Top Farmer Crop Workshop.

Conclusions: The Role of Extension and Farm Management

A major question remains as to what form information-intensive agriculture will take in the future. However, the objective for extension farm management is not to promote PA or any other technology but to educate producers and other clients when given the opportunity. In order to do this, it is important to have firm understanding of PA and understand farmer's reasons for non-adoption. A detailed literature review of PA profitability can be found in Lambert and

Lowenberg-DeBoer (2000) and Peone et al. (2004). A few recent studies have outlined reasons for non-adoption by topic and specified which ones were educational in nature (Kitchen et al., 2002; Wiebold, 1998). Among other things they listed time to learn equipment and software, lack of electronic skills, lack of training for producers and industry, linking data collection and decision making, lack of technical assistance, lack of local experts, working with data of differing formats, yield data analysis for limiting factors of production, difficulty in maintaining data quality, basic research on yield and soil relationships, and need for a PA equipment, techniques, software do's and don'ts or pro's and con's (Kitchen et al., 2002; Wiebold, 1998). These barriers to adoption are an opportunity for extension farm management to provide beneficial educational programming to farmers and industry.

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