Setting the record straight on precision agriculture adoption

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Setting the Record Straight on Precision Agriculture Adoption

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ABSTRACT

There is a perception that adoption of precision agriculture (PA) has been slow. This study reviews the public data on farm level use of PA in crop production worldwide. It examines adoption estimates for PA from completed surveys that utilized random sampling procedures, as well as estimates of adoption using other survey methods, with an objective to document the national or regional level adoption patterns of PA using existing data. The analysis indicates that Global Navigation Satellite Systems (GNSS) guidance and associated automated technologies like sprayer boom control and planter row or section shutoffs have been adopted as fast as any major agricultural technology in history. The main reason for the perception that PA adoption is slow is because PA is often associated with variable rate technology (VRT)—just one of many PA technologies, one of the first adopted by many farmers, but that now rarely exceeds 20% of farms. This level of adoption suggests that farmers like the idea of VRT, but are not convinced of its value. VRT adoption estimates for niche groups of farmers may exceed 50%. The biggest gap in PA adoption is for medium and small farms in the developing world that do not use motorized mechanization.

Core Ideas

- There is a perception that adoption of precision agriculture has been slow.
- Precision agriculture is not one technology but a toolkit from which farmers choose what they need.
- Global Navigation Satellite Systems guidance is being adopted rapidly.
- Variable rate technology adoption rarely exceeds 20% of farms.
- Use of precision agriculture technology on non-mechanized farms is almost nonexistent.

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Because precision agriculture (PA) is considered an approach that meets production and environmental goals simultaneously, both scientists and policymakers have been investigating techniques to overcome adoption barriers (Pierpaoli et al., 2013; Silva et al., 2015; Keskin and Sekerli, 2016; Paustian and Theuvsen, 2017; Kendall et al., 2017; and Thompson et al., 2018). For example, the World Agri-Tech Summit in London, UK, Oct. 17, 2018, had a session entitled, "Tackling Adoption Barriers: What Value is Digital Agriculture Bringing to the Farm"?, and in 2015 the UK Parliament Office of Science and Technology stated, "Precision farming uses technology to improve efficiency. It offers benefits for yields, profits and the environment. However, uptake by farmers has been slow" (POST, 2015:p. 1). The Italian Ministry of Agriculture, Food, and Forestry (2015) guidelines for PA make a similar comment. These reports suggest that there is an adoption barrier, which may or may not be accurate.

In spite of high profile reports, the data tells a different story. Some aspects of PA were adopted as quickly and as widely as any technology in history, while others have lagged behind for technical and economic reasons. The objective of this study is to set the record straight on PA adoption by reviewing the available data with an eye on data reliability and to hypothesize adoption trends. Because PA adoption data collection methods vary widely from country to country, there are limitations in making direct numerical comparisons. Consequently, the methodology is impressionistic comparison that looks at the big picture, rather than making quantitative comparisons. This study will be of interest to PA researchers and educators across all the disciplines involved, to agribusinesses involved in manufacturing and selling PA tools, and policymakers concerned about agricultural productivity and the environment.

The lack of a clear definition of PA makes tracking adoption more difficult. One aspect of this problem is how to distinguish PA from other terms describing agricultural technology (e.g.,

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Abbreviations: ARMS, Agricultural Research Management Survey; DEFRA, Department of Food and Rural Affairs; EC, electrical conductivity; EMBRAPA, Brazilian Agricultural Research Corporation; GM, Genetically Modified; GNSS, Global Navigation Satellite Systems; GPS, global positioning system; GRDC, Grain Research and Development Corporation; ISPA, International Society of Precision Agriculture; INTA, National Institute for Agricultural Technology; KFMA, Kansas Farm Management Association; PA, Precision Agriculture; TAM, Technology Acceptance Model; VRT, Variable Rate Technology; WCA, World Census of Agriculture.

site-specific farming, smart farming, and digital agriculture). From another perspective, there is no clear definition of what technologies are included in PA. There have been many attempts to define PA. The Lleida University Research Group in AgroTIC and Precision Agriculture lists 27 definitions from the scientific literature and the Internet (Lleida University, 2018). Some focus the definition on variable rate technology (VRT). Others concentrate on application of electronic information technology. The International Society for Precision Agriculture (ISPA) solicited input from their members on a definition. After the 2018 ISPA conference in Montreal, PrecisionAg.com posted three candidate definitions of PA (Sulecki, 2018). This study will use a slightly modified version of the third proposed definition:

> "Precision agriculture is a management strategy that uses electronic information and other technologies to gather, process, and analyze spatial and temporal data for the purpose of guiding targeted actions that improve efficiency, productivity, and sustainability of agricultural operations."

In this definition, "agriculture" should be broadly defined to include all types of biological production systems (e.g., arable cropping, perennial forages, forestry, orchards, vineyards, horticulture, livestock husbandry, and aquaculture). Unfortunately, adoption data for precision animal production is even more sparse than for crops. Consequently, this study focuses on crop PA, especially grain and oilseed production.

Site-specific crop management is ancient, but the idea of using electronic information technology to automate that process is relatively recent. From the dawn of agriculture, farmers instinctively managed crops site-specifically. For example, some crop varieties were planted in the lowlands and others in uplands. Manure was often applied on thinner or lighter soils or where the crop was less vigorous. In the 1920s, some US university researchers advocated grid soil sampling and spot application of fertilizer and lime to optimize soil nutrient levels (Linsley and Bauer, 1929), and most soil sampling protocols noted the importance of collecting different composite soil samples from areas with different characteristics. Depending on the information provided by the farmer, fertilizer recommendations would be made for each of these areas. Farmers applying fertilizers would often manually adjust the rates as they drove across the field.

The modern age of PA is often linked to the announcement by US President Ronald Reagan in 1983 that would allow global positioning systems (GPS) for civilian use. The term GPS refers to the US system; GNSS refers collectively to GPS plus other systems in use around the world. In the 1980s, soil scientists and agribusiness researchers in the United States and Europe started to develop equipment and methods for variable rate fertilizer application (Haneklaus and Schnug, 2002; Mulla and Khosla, 2016). The first commercially successful grain yield monitors were introduced in 1992. The combination of GNSS-enabled soil sampling, variable rate fertilizer applications, and yield monitoring was the "classic precision agriculture" package in the 1990s and some adoption studies focus on whether that classic package has been adopted.

Global Navigation Satellite Systems equipment guidance was commercialized in the late 1990s, first in Australia and shortly after in North America. In Australia guidance was closely linked with controlled traffic to reduce soil compaction, where farm equipment follows the same paths for various field operations (Quick, 2007), but in North America controlled traffic was a minor motivator for adoption. Soon after the introduction of guidance came a wave of related technology including automatic boom/nozzle control for sprayers and automatic row shut offs for planters.

During the 20th century, the technologies used to collect remote sensing information changed from visual observations of airborne individuals, to cameras mounted in planes, to high resolution satellites, to digital sensors mounted in unmanned aerial vehicles (Mulla, 2013). Use of unmanned aviation for crop monitoring began experimentally in the first years of the 21st century.

Proximal soil sensing started before the release of GNSS for civilian use (Shonk et al., 1991). Electrical conductivity (EC) was first used to measure soil salinity by USDA ARS researchers at the Riverside, CA, research site in the 1970s. On-the-go soil sensing to guide fertilizer use started with the "Soil Doctor" sensor, invented in 1982 and originally used without GPS to vary nitrogen application on the go within fields. (Colburn, 1999; Lowenberg-DeBoer, 2004). Global Navigation Satellite Systems technology was later used with EC and the Soil Doctor to create maps of the sensor readings that could be used to guide crop management decisions. Starting in the 1990s numerous optical, EC, mechanical, and ion soil sensors were developed and some have been commercialized (Adamchuk et al., 2004).

The history of proximal plant sensors is similar to that of soil sensors (Mulla, 2013). Development of optical sensors to diagnose plant conditions based on reflectance started several decades before PA was a concept (Markwell et al., 1995). With GNSS it became possible to use sensor readings to create fertilizer and pesticide application maps, or to create on-the-go sensor-algorithm-application equipment. In the mid-1990s competing research teams in Europe and North America created sensors which could guide nitrogen application. Those sensors, such as the Yara N-Sensor, CropCircle, and Greenseeker were eventually commercialized starting in the late 1990s.

To accompany the adoption information, a timeline of PA milestones and technology introduction was developed to provide points of reference (Table 1). Determining the year of technology introduction can be complicated, as inventions can exist in an entrepreneur's shop, a researcher's lab, or in prototype testing for many years with little documentation. As the commercial introduction is most relevant to adoption and is often better documented, the dates in the table below for specific technologies are the approximate year they came to the market.

Over the years, several studies have tried to provide a worldwide overview of PA adoption (Zhang et al., 2002; Griffin and Lowenberg-DeBoer, 2005; Say et al., 2018). Zhang et al. (2002) focused mainly on the technical issues associated with PA adoption and cited several adoption studies from the United States, United Kingdom, and Australia. They identify the following constraints to adoption: (i) the quantity of PA data exceeds the ability of farmers to analyze and use it for management, (ii) lack of scientifically validated procedures determining variable rate application of inputs, (iii) absence of evidence for the benefits of PA, (iv) labor intensive and costly data collection, and (v) need for improved technology transfer.

Griffin and Lowenberg-DeBoer (2005) summarized the worldwide data on PA adoption, reviewed the studies of PA

Table 1. Key precision agriculture milestones.

Year	Technology or activity†	Company/organization, product name	Reference
1983	Executive order that allowed civilian use of GPS	US government	Brustein, 2014 Rip and Hasik, 2002
1987	Computer-controlled VRT fertilizer	Soil Teq	Mulla and Khosla, 2016
1988	Handheld GNSS	Magellan	Smithsonian, 2018
1992	First conference dedicated to precision agriculture research	International Conference on Precision Agriculture	Khosla, 2010
1992	Impact plate grain yield monitor	Ag Leader, Yield Monitor 2000	Ag Leader, 2018
1995	First conference dedicated to precision agriculture industry	InfoAg	IPNI, 2010
1997	Auto guidance	Beeline	Rural Retailer, 2002
1997	On-the-go soil EC sensor	Veris	(Lund, E., personal communication, 13 Nov. 2018)
1997	Cotton yield monitor	Micro-Trak, Zycom	Vellidis et al., 2003
2000	End of GNSS selective availability	US government	Coalition to Save Our GPS, 2012
2002	Integrated optical sensor and variable rate nitrogen applicator	N-Tech Industries, Greenseeker	Rutto and Arnall, 2017
2003	On-the-go soil pH sensor	Veris, Soil pH Manager (MSP)	Lowenberg-DeBoer, 2003
2006	Automated sprayer boom section controllers	Trimble, AgGPS EZ-Boom 2010	Trimble, 2006
2009	Planter row shutoffs	Ag Leader, Sure Stop	Ag Leader, 2018
2017	First fully autonomous field crop production	Harper Adams University	Hands Free Hectare, 2018

† EC, electrical conductivity; GNSS, Global Navigation Satellite Systems; GPS, global positioning system; VRT, variable rate technology.

economics, and drew implications for Brazil. They reported detailed US PA survey information and on worldwide PA adoption in terms of the number of combine yield monitors being used in the United States, Australia, South Africa, several Latin American countries, and nine western European countries. Griffin and Lowenberg-DeBoer (2005) predicted strong PA adoption for higher value Brazilian crops like sugarcane and citrus. They noted that large-scale Brazilian farms would benefit from GNSS guidance and from use of PA to automate record-keeping, employee supervision, and quality control. On the negative side, they conclude that low land prices, low wages, a focus on commodity crops, and the high cost of imported technology would tend to discourage adoption of PA in Brazil.

Only a few studies focus on PA in the developing world. Mondal and Basu (2009) outlined the theoretical reasons why PA should be adopted by developing country farmers. Say et al. (2018) added to the literature by documenting the beginnings of PA adoption in middle and lower income countries. They confirm that guidance is the most commonly adopted PA technology in developing countries.

Numerous research efforts have focused on identifying factors that influenced individual farmers who adopted PA (Daberkow and McBride, 1998; Khanna, 2001; Fernandez-Cornejo et al., 2001; Roberts et al., 2002, 2004; Daberkow and McBride, 2003; Torbett et al., 2007; Larson et al., 2008; Walton et al., 2008; Isgin et al., 2008; Reichardt and Jürgens, 2009; Robertson et al., 2012; D'Antoni el al., 2012; Tey and Brindal, 2012; Pierpaoli et al., 2013; Silva et al., 2015; Keskin and Sekerli, 2016; Paustian and Theuvsen, 2017; Kendall et al., 2017; Kernecker et al., 2017; Jacobs et al., 2018; Tamirat et al., 2018; Thompson et al., 2018). They identified a long list of statistically significant quantifiable factors that influenced PA adoption. This list included age of the farm operator, education, years of farming experience, farm specialization, land tenure, farm size, full or part time farmer, debt-to-asset ratio, use of a crop consultant, perceived profitability of PA, use of a computer, and irrigation.

A small number of studies attempted to anticipate farmers' willingness to adopt PA technology, (Hite et al., 2002; Hudson and Hite, 2003; Adrian et al., 2005; Marra et al. (2010); Aubert et al., 2012). These studies used either a "Willingness-To-Pay" approach or the "Technology Acceptance Model (TAM)," which is a theoretical model often used to explain adoption. These studies focused on perceptions of PA technology, including profitability and ease of use.

Neither specific farm or farmer characteristics nor estimates of farmer willingness to adopt studies have been particularly useful in explaining or predicting national or regional PA adoption trends. Consequently, this study will focus on the adoption patterns in aggregate data at the national or regional level. The general objective is to use existing studies to document the national or regional level adoption patterns of PA for commodity crops, with the hypothesis being that adoption rates differ widely among PA tools, with GNSS guidance having become standard practice in most mechanized farming systems around the world and VRT fertilizer lagging in most cropping systems.

MATERIALS AND METHODS

Because there is no international consensus on a PA definition, PA is often referenced as "digital", "site-specific", "smart", etc. agriculture, PA involves numerous technologies, and much information exists outside academic journals and in a variety of languages, systematic review techniques would not ensure a thorough assemblage of PA adoption information. Consequently, the authors relied on their network of academic and business contacts, interactions at trade shows and scientific meetings, as well as Internet searches to assemble the data.

International adoption studies require comparisons of data collected with different survey methodologies and at various times. Consequently, the comparisons must be impressionistic, looking at the big picture, rather than strictly quantitative. Data quality varies widely. The United States, United Kingdom, Australia, and Denmark have PA adoption data collected by government agencies using standard random sampling techniques. Some phone surveys, notably in the United States and Brazil, have followed random sampling techniques but drawing on lists targeted to large-scale commercial farmers. Within Europe, many PA adoption surveys use volunteers who respond to a survey posted on the Internet or attendees at farm shows. In most developing countries, PA adoption information is anecdotal.

Most PA adoption information comes from surveys, but in the early period of PA, equipment inventories were sometimes used as a proxy for adoption (e.g., yield monitor data in Griffin and Lowenberg-DeBoer, 2005). Only Argentina has persisted in measuring PA adoption via equipment inventories (Melchiori and Garcia, 2018). It is very difficult to compare equipment inventories with percentage of farmers or farm area using a specific technology. Consequently, the Argentine equipment inventory data is used only in the trend section of this study.

Most PA adoption surveys measure adoption by percent of farms using the technology. This is often the easiest and clearest way to pose the question, but it does not measure intensity of use. It does avoid the problem of misreported or inaccurate area measurements. When using percent of farms to measure adoption, a farmer who uses VRT on one field is the same as a farmer who uses it on all fields. When the distribution of farm sizes is skewed and/or the sample is not representative, percent of farms may be misleading. If an area has many small farms who have not adopted but a few larger farmers that have, a survey reporting adoption as percent of farms will under-represent the use of the technology in the area. This study identifies which surveys used percentage of farmers vs. percentage of land area.

Randomness and representativeness are important when selecting the survey recipients so they accurately describe the total population (Babbie, 1990). Non-random selection of respondents often leads to a sample that is biased. But other problems can also create representativeness problems. For instance, if the initial list of farmers draws from a specific size, farm type, geography or other list, even a random sample will not be representative of all farmers; it will be representative of the farmers on the list. A systematic non-response can also create unrepresentativeness. For instance, if some farmers in an area consider PA to be a waste of time and money, they may be less likely to answer a PA survey and the results will be dominated by the farmers that consider PA useful. Internet surveys that distribute a survey link to thousands, and end up with a handful of responses are particularly problematic. Why did those few respond?

The methodology was to organize existing PA adoption data by region and country noting year of the data collection, collection method, and source of respondents. The data collected using standard random sampling methods is discussed first because it is probably the most reliable. Other surveys are discussed in the light of those random sample surveys.

Most PA adoption surveys are one-time studies that provide a snapshot of technology use at a specific time, but a few countries have surveys with similar methods repeated over time, which allow estimation of trend lines. Those trends are discussed after the snapshot data.

Included in this the discussion of trends is the CropLife-Purdue survey of PA technology use by agriculture retailers in the United States. This survey has been collected with consistent methods since the mid-1990s and is the longest PA adoption series available. Because of this it is probably the most cited PA adoption data, even though it represents adoption by dealers. The CropLife-Purdue data is useful because in the United States and Canada most farmers access PA (at least initially) through buying products and services from a dealer, not on their own. In most of the world, agriculture input dealer data would not be a good indicator of PA adoption because farmers buy their own PA equipment and the farmer or farm employees implement PA practices. In addition to tracking dealer use of PA in their business, the CropLife-Purdue survey also asks dealers to estimate farmer use.

The only other published PA dealer survey is the Guelph University study of agriculture input dealers in Ontario, Canada (Mitchell et al., 2017). The Ontario survey shows adoption patterns similar to the CropLife-Purdue survey, and is useful for comparison to other Canadian PA adoption surveys. But it was done once in 2017 and hence is not useful for showing adoption trends.

RESULTS

Government Studies Using Random Sample Methods

The United States, United Kingdom, Australia, and Denmark governments collect data on PA adoption by commodity crop farmers using standard random sample methods (Table 2). This data is probably the most reliable and representative PA adoption information available. Unfortunately, the sample selection procedures and questions asked differ substantially among countries:

The USDA Agricultural Resource Management Survey (ARMS) (USDA ERS, 2018a and USDA ERS, personal communication, 2019) is organized by crop for the continental United States. Crops surveyed include maize (*Zea mays* L.), rice (*Oryza sativa* L.), peanuts (*Arachis hypogaea* L.), soybean (*Glycine max* L.), winter wheat (*Triticum aestivum* L.), and cotton (*Gossypium hirsutum* L.), which are reported in this article. Precision survey information is also available for spring wheat (*Triticum aestivum* L.), durum wheat (*Triticum durum* Desf.), feed and malting barley (*Hordeum vulgare* L.), oats (*Avena Sativa* L.), and sorghum (*Sorghum bicolor* L.). The USDA definition of a farm is “any place from which (USD) $1000 or more of agriculture products were produced or sold, or normally would have been sold during the year.” Consequently, it includes a wide range of farm sizes. Data is collected and organized by state, and only in states where the focus crop is a major farm product. The maize survey is done in 20 states, but the peanut survey includes just five states. The schedule is irregular—it does not occur for each crop every year. Respondents are randomly selected from a list maintained by the USDA of all US farmers producing the focus crop. Response is voluntary, but the response rate is high because the mailed paper surveys are followed by a visit to the farm for non-respondents from a government staffer for a personal interview “at the kitchen table,” and because most commodity farmers interact regularly with USDA staff administering farm subsidy programs. The number of farmers surveyed each year depends on the focus crops in a given year and varies

Table 2. Precision farming adoption rates by year for government studies using random sample methods.

	Data collect. year	GNSS guidance†	Yield monitor	Yield map‡	VRT any§	VRT fert.	GNSS soil map¶	EC#
United States††		Percentage of planted area using the technology‡‡						
Maize	2016	59%	68%	45%	NA	29%	22%	NA
Rice	2013	53%	58%	NA	21%	21%	12%	NA
Peanuts	2013	49%	NA	NA	18%	18%	24%	NA
Soybean	2012	45%	63%	NA	22%	NA	19%	NA
Winter wheat	2009	35%	36%	6%	14%	11%	6%	NA
Cotton	2007	23%	5%	3%	5%	5%	5%	NA
United Kingdom§§		Percentage of holdings using the technology‡‡						
All farms	2012	22%	NA	11%	16%	NA	20%	NA
Cereals	2012	46%	NA	25%	31%	NA	38%	NA
Other crops	2012	40%	NA	18%	23%	NA	31%	NA
Pigs and poultry	2012	11%	NA	5%	8%	NA	7%	NA
Dairy	2012	19%	NA	5%	14%	NA	15%	NA
Extensive grazing	2012	3%	NA	2%	6%	NA	11%	NA
Lowland grazing	2012	6%	NA	2%	5%	NA	8%	NA
Mixed	2012	20%	NA	11%	17%	NA	16%	NA
Australia¶¶		Percentage of growers who have used the practice‡‡						
All respondents	2012	77%	NA	33%	15%	49%	NA	15%
New South Wales	2012	76%	NA	26%	11%	34%	NA	15%
South Australia	2012	79%	NA	30%	15%	52%	NA	13%
Victoria	2012	74%	NA	33%	16%	50%	NA	16%
Western Australia	2012	79%	NA	43%	17%	55%	NA	19%
Denmark##		Percentage of farms with cultivated land‡‡						
All farms	2018	23%	NA	NA	NA	NA	NA	NA
All farms	2017	16%	NA	NA	7%	NA	NA	NA

† For USDA ARMS survey, the Global Navigation Satellite Systems (GNSS) guidance prior to 2013 is "guidance or autosteer." For UK in 2012, the GNSS question was very general. It asked about GPS and gave autosteer and guidance as examples. Australia asked specifically about autosteer use. The Denmark survey asked specifically about "RTK GPS" where RTK stands for Real Time Kinematic.

‡ For USDA ARMS survey, "yield map created." UK DEFRA asked only if used "yield mapping" without explaining. For Australia, Llewellyn and Ouzman report data on "Yield map adopters."

§ "VRT any" indicates variable rate technology for any purpose including fertilizer, soil amendment, seed or plant protection chemicals.

¶ For USDA ARMS Survey through 2013 "GPS device used to create soil properties map." For UK DEFRA survey, asked only if used "soil mapping". The Australian survey asked about "soil testing" but this apparently was not necessarily GNSS linked.

For USDA ARMS survey, "soil properties map based on electrical conductivity." In Australia, electrical conductivity (EC) or Gamma. UK and Denmark surveys did not ask about EC.

†† Source: USDA ERS (2018a), except maize is USDA ERS, personal communication, 2019.

‡‡ NA = not available. Color formatting: Red-orange 0–19%, orange 20–39%, yellow 40–59%, yellow-green 60–79%, and green 80–100%.

§§ Source: UK DEFRA (2013).

¶¶ Source: Llewellyn and Ouzman (2014).

Source: Danish Statistics (2017 and 2018).

from 5000 to 30,000. Farmers report only for the crop specified, not their entire operation.

The UK Department of Food and Rural Affairs (DEFRA) farming practices survey in 2012 included questions on PA (DEFRA, 2013). The survey was implemented by paper mail only in England, not in Scotland, Wales, or Northern Ireland. To be included in the survey a farm must have at least one of the following: 50 cattle, 100 sheep, 100 pigs, 1000 poultry, 20 ha of arable crops, 20 ha of orchard, 5 ha of berries or other soft fruit, or 10 ha of nursery stock. For the 2012 survey DEFRA randomly selected 2900 farms from the roughly 60,000 English farms that fit the minimum size criteria. Under UK law, response to the farming practices survey is voluntary. The farm categories shown reflect the farm's primary enterprise; thus, the farms that focus on livestock are reporting for their accompanying cropping activities.

The Australian data in Table 2 was collected in 2012 by the Commonwealth Science and Industrial Research Organization (CSIRO) for the Grain Research and Development Corporation (GRDC) (Llewellyn and Ouzman, 2014). The CSIRO is an Australian government entity operating under the Ministry of Industry and Science. The voluntary survey was implemented via telephone in the major grain growing regions of Australia in the states of New South Wales, Victoria, South Australia, and Western Australia. Respondents were randomly selected from a comprehensive database of growers with over 500 ha of grain. Responses were obtained from 573 farmers. The Australian PA survey is not regular, but a similar survey was done in 2008 (Robertson et al., 2012).

Danish Statistics has collected data annually since 2017 on PA (Danish Statistics, 2017, 2018). A stratified sample is drawn from all farms with cultivated area registered with the government for administrative and regulatory purposes. The 2017 data are based on responses from 6281 farms from a total of 33,580 farms on the government list. In 2018 there were responses from 5708 of the 32,833 farms.

Key differences between the United States, United Kingdom, Australian, and Danish surveys include size and type of farm. The US survey includes some very small farms due to the USDA's definition of a farm, as previously discussed. Depending on the crop, price, and yield, (USD) $1000 of production might represent a farm of <1 ha. The UK arable farms must have at least 20 ha and the Australian respondents were selected from a list of farms with over 500 ha of grain. The Danish survey drew from a list of all farms registered with the government including horticultural producers and very small farms. In all four countries, the farm businesses surveyed may have included livestock and other enterprises. The US survey asks specifically for the technology used for the focus crop. By selecting from a list of farmers with over 500 ha of grain, the Australian survey may have chosen a sample more specialized in grain production. Because of the different types of farms included in the UK sample, the "Cereals" and "Other Crops" data may be the most comparable to the USDA ARMS data and the Australian information.

It should also be noted that the US ARMS data is provided on the USDA ERS (2018a) website in terms of percentage of area planted to the crop, while United Kingdom, Australia, and Denmark information is in terms of percentage of farms. Because PA technology is often adopted first on larger farms, the percent of area adopting is often higher than percent of farms. For example, in data for the 2016 maize survey obtained from the USDA the percent of farms using guidance is 40%, while the percent of area is 59%.

Auto Guidance Using Global Navigation Satellite Systems

The United States, United Kingdom, Australian, and Danish surveys show the widespread adoption of GNSS guidance by mechanized grain farmers. Even though the Australian survey is 6 yr ago, their guidance adoption percentages are highest (Table 2). This is consistent with the fact that the first auto guidance (also termed autosteer) systems were introduced in Australia in 1997, at least 3 yr before introduction in North America (Quick, 2007) and the relatively large size of the farms in the Australian sample. The US survey estimates show the growth of guidance use with the cotton survey in 2007, showing 23% of cotton area farmed with either light bar or auto guidance, to the 2016 corn survey with 59% of corn area farmed with guidance technologies. The 2012 DEFRA survey shows that 46% of cereal crop farms used some type of guidance, which is similar to the level of use in the US data at that time. The estimates for Denmark are exclusively for RTK GNSS guidance.

Yield Monitoring and Mapping

The yield monitor and yield map columns for the USDA ARMS data show that many US farmers have a yield monitor, but some do not take the next step to make yield maps. For example, the 2016 maize data indicated that 68% of the area was harvested with a combine equipped with a yield monitor, but only 45% of the area was yield mapped. In terms of percent of farms, 54% of farms had a combine equipped with a yield monitor, but only 32% of farms made yield maps. In some instances this may be because their system is not tied to GNSS. Yield maps are usually considered the first step in making management use of the yield monitor information, but possession of yield maps does not guarantee that the maps were used in management. The UK and Australian surveys do not ask about yield monitor equipment availability. Industry sources indicate that most new combines in these four countries come with yield monitors as standard equipment. The percentage of farmers making yield maps in the three countries is similar: United States, 45% of maize farmers in 2016; United Kingdom, 25% of cereal farmers in 2012; and Australia, 33% of grain farmers in 2012. The Danish reports did not include yield monitor adoption estimates.

Variable Rate Technology

In the four countries in Table 2, use of "VRT for any purpose" only exceeded 30% for cereal farms in the United Kingdom. More often the surveys estimate it at 20% or less. At 7% the Danish estimate is among the lowest in this group. Oddly, the percentage of farms in the Australian data using VRT fertilizer is higher than using VRT for any purpose. This is because of a quirk in the Australian data that includes manual variable rate in the VRT fertilizer estimates, but manual controls are not included in the "VRT for any purpose" estimates. With manual variable rate, the equipment operator changes the rate on the go or between field passes, not automatically via computer. The USDA estimates illustrate that in most cases computer controlled variable rate is fertilizer. The percentages in the VRT fertilizer column are the same or only slightly less than is the total VRT for any purpose column. In terms of percentage of farms, the maize survey in 2016 showed that 20% of farms used VRT fertilizer, but they occupied 29% of maize area.

Grid or Zone Soil Sampling

In many countries site-specific soil maps are commonly the foundation for VRT fertilizer recommendations, but the data indicates that only a modest proportion of farms have such maps. The highest percentage among this group is 38% for cereal farms in the United Kingdom. The Australian and Danish reports did not include GNSS soil mapping.

Electrical Conductivity

In the 2012 Australian survey an overall 15% of farms report using soil EC mapping. A question about soil EC maps was asked in some earlier USDA ARMS surveys. In the 2010 maize survey, the 2002 soybean survey, and the 2003 cotton surveys only 1% of area was managed with soil EC maps. The DEFRA and Denmark surveys did not ask about EC.

Other Adoption Studies

Precision agriculture adoption data from other studies around the world is listed in Tables 3 (the Americas) and 4 (Asia, Australia, and Europe). Because of differences in sampling, technology definitions and the questions asked, comparison among studies can provide only a rough impression of the trends. For example, for GNSS guidance some studies asked only about auto guidance, some asked about "GPS guidance" lumping light bar and auto guidance technologies in the same category, and others asked only about light bars. Similarly, the "Yield monitoring" column contains estimates primarily of farmers who report using a yield monitor, others asked about making yield maps, and yet others asked if yield monitoring equipment was available. For

Table 3. Precision agriculture adoption rates by year for North America and South America farmers with other methodologies.†

Location	First author	Collection year	Collection method	Source of list	GNSS guidance	Yield monitor‡	VRT fertilizer or soil amendment	GNSS linked soil test mapping	EC	Remote sensing imagery
					Percent of farmers, unless noted§					
Argentina	Melchiori	2018	Web	INTA list	60%	78%	42%	51%	26%	80%
Various US states	Thompson	2017	Phone	Purchased farmer list	91%	93%	73%	66%	NA	56%
Various US states	Erickson¶	2017	Web	CropLife	60%	43%	38%	45%	9%	19%
Canada	Steele	2017	Web	Link sent to farm groups	79%	48%	48%	43%	19%	28%
US Cotton States	Zhou	2013	Post	Cotton Inc.	67%	20%	25%	22%	5%	6%
Brazil	Molin	2013	Phone	Commercial list	23%	12%	26%	36%	NA	NA
Argentina	Melchiori	2013	Web	INTA list	40%	84%	30%	48%	18%	60%
Brazil	Borghi	2011–2012	Web	EMBRAPA PA Network list	56%	56%	89%	100%	22%	22%
Alabama	Winstead	2009	ARS#	Conf. audience	60%	28%	37%	28%	NA	NA
Florida	Winstead	2009	ARS#	Conf. audience	40%	20%	80%	80%	NA	NA
US Cotton States	Mooney	2009	Post	Cotton Inc.	47%	10%	22%	29%	4%	10%
US Cotton States	Cochran	2005	Post	Cotton Inc.	21%	6%	23%	18%	NA	2%
Ohio	Isgin	2003	Post	Ohio State Univ.	7%	14%	15%	17%	NA	5%
Indiana	Fountas	2002	Post	Purdue Univ. Ext. contacts	NA	67%	59%	86%	12%	6%
US Cotton States	Roberts	2001	Post	Cotton Inc.	NA	2%	8%	12%	NA	0%

† GNSS, Global Navigation Satellite Systems; VRT, variable rate technology; EC, electrical conductivity.

‡ Yield monitoring is reported for all studies except Fountas et al. (2005), Steele (2017), and Borghi et al. (2016), where the question was yield mapping.

§ NA = not available. Color formatting: Red-orange 0–19%, orange 20–39%, yellow 40–59%, yellow-green 60–79%, and green 80–100%.

¶ Yield monitoring was not reported for 2017; 43% is from 2015. Percent of acres as reported by retailers.

ARS = audience response software.

VRT fertilizer or soil amendments some studies asked specifically if variable rate fertilizer was applied. Other studies asked about VRT for specific soil nutrients and amendments (e.g., N, P, K, lime). In that case Tables 3 and 4 report the estimate for the fertilizer or soil amendment material most commonly applied with VRT. Yet other studies asked whether VRT was used for any input (i.e., fertilizer, soil amendment, seed, pesticide). The GNSS linked soil testing column shows similar variability in definitions and questions. Some studies asked about “GPS soil sampling” or “georeferenced soil sampling”. Others asked specifically about the type of sampling (i.e., grid, zone). In that case the tables report the adoption estimate for the most commonly used sampling method. In the “Remote sensing” column some studies asked simply about use of remotely sensed images. Other asked specifically about use of satellite, aerial, or drone images. Electrical conductivity seems to be the only technology for which all the studies seem to have used a common definition, but many studies did not ask about EC use. And there can be confusion surrounding specific technologies and how they are defined. For instance with EC, a respondent may have answered about EC, EM (electromagnetic) induction, electrical resistance, or other related technologies. For more information on the methodology used in each study readers should consult the original documents.

Some of the studies in Tables 3 and 4 use standard or almost standard random sample techniques and should have reliably representative data. For instance, the 2008 Australian national survey reported by Robertson et al. (2012) used methods similar to Llewelyn and Ouzman (2014). The two other surveys reported in the same article were based on personal interviews with members of farm associations. The yield mapping (25%) and variable rate fertilizer (20%) estimates in the 2008 Australian survey are consistent with those found 4 yr later in the 2012 survey.

Similarly, the Lawson et al. (2011) data for Germany, Denmark, and Finland seems to have been collected with random sampling methods. In Denmark and Finland, questionnaires were mailed to a random sample of farms registered with their governments. In Denmark the list was from arable, dairy, and swine farms, omitting horticultural operations unlike the Danish Statistics surveys (2017, 2018) previously discussed. In Germany, farms were randomly selected from a list of farms receiving over €40,000 in EU farm support. The PA adoption reported by Lawson et al. (2011) fits with the patterns seen in Table 2. GNSS guidance is the highest, with modest adoption in the other PA technologies. Some of the other studies were conducted using unconventional methods and often had unexpected results.

North America

Isgin et al. (2008) reported on a farming practices survey of randomly selected Ohio producers by The Ohio State University. The survey had 816 respondents of which 36% reported using some type of PA technology in an area where maize and soybeans are the most common crops. The most frequently reported PA technology was soil mapping. Even though GNSS guidance had only been commercially available in Ohio a couple of years when the survey was done, 7% reported using some kind of guidance. This Ohio data fits the general picture created by the USDA ERS (2018a) corn surveys in 2001 and 2005, and the soybean survey in 2002.

Winstead et al. (2010) used audience participation software to collect data from 42 farmers attending a PA workshop in 2009. The fact that those farmers were at a PA workshop may indicate that they were more interested in PA than the average

Table 4. Precision agriculture adoption rates by year for Asia, Australia, and Europe farmers with other methodologies.†

Location	First author	Collection year	Method	Source of list	GNSS guidance	Yield mapping‡	VRT fertilizer or Soil amendment	GNSS soil test mapping	EC	Remote sensing images
					Percent of farmers§					
Australia	Bramley	2017	Web	AGRDC members	84%	50%	52%	NA	26%	40%
UK	Pickthall	2016	Web	Author contacts	20%	13%	14%	15%	NA	NA
Turkey	Keskin¶	2015	In person	Individuals with PA interest known to researchers	5%	3%	0%	0%	NA	0%
Italy	Cavallo¶	2010	In person	Farm show participants	46%	NA	NA	NA	NA	NA
WA, Australia	Robertson	2009	In person	Farmer group	66%	47%	14%	NA	0%	0%
Australia	Robertson	2008	Phone	Commercial famer list	NA	25%	20%	NA	NA	NA
Germany	Lawson	2008	Post	EU Farm support > 40,000€	37%	12%	8%	20%	1%	11%
Denmark	Lawson	2008	Post	Government registered farmers	9%	3%	4%	6%	1%	1%
Finland	Lawson	2008	Post and web	Government registered farmers	1%	1%	3%	1%	0%	0%
WA, Australia	Robertson	2006	In person	Farmer group	46%	45%	NA	NA	0%	0%
Germany	Reichardt#	2006	In person	Farm show participants	NA	6%	3%	6%	1%	NA
Germany	Reichardt#	2005	In person	Farm show participants	NA	3%	1%	4%	0%	NA
Germany	Reichardt#	2003	In person	Farm show participants	NA	3%	1%	3%	1%	NA
Denmark	Fountas	2002	Post	Industry contacts	NA	92%	52%	75%	42%	NA
Germany	Reichardt#	2001	In person	Farm show participants	NA	3%	1%	4%	1%	NA

† GNSS, Global Navigation Satellite Systems; VRT, variable rate technology; EC, electrical conductivity; PA, precision agriculture.

‡ Yield mapping is reported for all studies except Lawson et al. (2011), where the question was yield monitoring.

§ NA = not available. Color formatting: Red-orange 0–19%, orange 20–39%, yellow 40–59%, yellow-green 60–79%, and green 80–100%.

¶ 2015 is assumed, as collection date is not specified. Results published in 2016.

Adoption rates are approximated from figures in the publication.

producer and maybe more likely to be already using it. The sample was also relatively small with 36 respondents from Alabama and only six from Florida. The relatively high rates of VRT fertilizer, and GNSS linked soil testing and mapping may be related to the Winstead et al. (2010) data collection methods.

Thompson et al. (2018) did a random sample phone survey from a Purdue University list of large US commercial grain and cotton farmers with over 400 ha. They reported that 91% used auto guidance, 93% did yield mapping, 73% used VRT fertilizer, 66% reported GNSS linked soil testing and mapping, and 56% used remote sensing images. The high PA adoption may be related to the type and size of the farms in the sample.

Fountas et al. (2005) mailed paper questionnaires to a contact list of farmers interested in PA generated by Purdue University extension staff. The relatively high yield mapping (67%), VRT fertilizer (59%), and GNSS soil mapping (86%) adoption among this group is probably related to their prior expressed interest in the technologies.

The 2001, 2005, 2009, and 2013 PA surveys funded by Cotton Incorporated (Zhou et al., 2017; Mooney et al., 2010; Cochran et al., 2006; Roberts et al., 2001) are random sample surveys done with standard statistical sampling methods. The cotton surveys used a list of cotton producers provided by Cotton Incorporated, which is funded primarily by producer levies. The PA adoption measured in these surveys is consistent with the USDA ERS (2018a) cotton surveys in 2003 and 2007.

For Canada, the Steele (2017) web survey provides information on PA adoption by farmers in the Prairie Provinces. A web link was provided to farmers through 31 grower associations, agribusiness, provincial government agriculture staff, and academics. The link was also circulated to farmers through the farm media and social media. The total number of respondents was 261 out of almost 100,000 farms in the region. The report states that "The survey responses reflect a younger than average farm demographic, operating larger acreage farms which generate higher than average gross revenues and reflect more incorporated farm business operating structures than the average western Canada farm in general." (Steele, 2017:p. 5). This may have something to do with the relatively high adoption rates reported. The VRT fertilizer adoption rate of 43% is almost double the highest percent of farmers VRT adoption estimate found across the border in the United States by USDA ERS (2018a). The 2017 dealer survey in Ontario by Mitchell et al. (2017) found that dealers estimated that in their market area 13% of land area used VRT fertilizer.

One of the few places where VRT fertilizer has become a standard practice is among sugar beet growers in the Red River Valley of the North, in Minnesota and North Dakota. In 2016, 53% of the sugar beet area in the Red River Valley was managed with VRT nitrogen fertilizer (Franzen, 2017), not shown in Table 3. This VRT adoption estimate is from a beet processing cooperative survey. Sugar beets incomes are affected by both yield and quality, influenced by soil nitrogen, and the universities and beet processors in that region have worked to determine the optimal site-specific nitrogen application given soil test levels.

South America

Precision agriculture started in Latin America simultaneously with North America. In the 1990s, Argentina led the world in yield mapping. Quantitative PA data is available for Brazil and Argentina.

One source of PA adoption in Brazil comes from information collected by phone interviews in 2013 and reported by Molin (2016). The sample was composed of 992 large-scale commercial grain farmers selected by an agribusiness consulting group. Among that group of farmers, 45% reported using some PA. The GNSS guidance estimate in Table 3 is auto guidance. Another 14% reported using light bars, but the light bar and auto guidance estimates cannot be summed for an overall GNSS guidance estimate because some farmers may have used both on different equipment. The yield monitor estimate is the percent that used a combine yield monitor; mapping was not asked. The percentage of farmers reporting VRT fertilizer is quite high (i.e., 26%), but it should be noted that the soil testing on which that VRT is based is quite sparse. Only 16% of the farmers reported using a soil grid of 1 ha or less.

Another PA adoption survey in Brazil was reported by Borghi et al. (2016). This study surveyed both farmers and PA related businesses. The farmer side of the survey was drawn from the Brazilian Agricultural Research Corporation (EMBRAPA) Precision Agriculture Network email list. The EMBRAPA is a state-owned research corporation affiliated with the Brazilian Ministry of Agriculture. They received 25 responses from farmers in Goiás, Rio Grande do Sul, Parana, Maranhao, and Tocantins states. Very high rates of PA adoption were reported including 100% using grid soil sampling, 89% using light bar guidance and 56% using yield mapping. Like the survey reported by Molin (2016), the grid soil sample size was relatively large. Only 11% reported using a 1 ha grid; the other used larger grid sizes with 22% over 5 ha. The high PA adoption rates reported by Borghi et al. (2016) may have been influenced by the small number of respondents obtained from the members in a PA network.

The primary source of the percent of farmers using PA in Argentina is the web surveys done by the National Institute for Agricultural Technology (INTA) researchers in 2013 and 2018 (Melchiori and Garcia, 2018). The INTA is an Argentina federal agricultural research and extension agency. The survey was emailed to farmers based on lists obtained from the INTA Precision Agriculture Project, agronomy professional associations and university faculties of agricultural sciences. The number of respondents in the INTA surveys was substantial: 488 in 2013, and 306 in 2018. The respondents were concentrated in the Pampas region, but also represented other parts of the country. The relatively high PA adoption rates may be related to the survey participants' association with the INTA PA Project.

One interesting aspect of the Argentine survey data is the high level of yield mapping compared to yield monitor use. In the United States, less than one-half of the farmers who have a yield monitor on their combine take the next step to make a yield map. Anecdotal information suggests that the situation is similar in Europe. In Argentina more farmers report processing yield data than collecting it. For example, in the 2018 survey about 73% of farmers reported grain yield monitoring, but well over 80% reported processing yield data. The difference may be yield data received from contractors harvesting on their farms. Historically, Argentine farmers were leaders in yield mapping (Bongiovanni and Lowenberg-DeBoer, 2005; Griffin and Lowenberg-DeBoer, 2005). That was attributed to the value of the yield map information on large Argentine farms managed by farm managers who rarely drove a tractor or combine. Yield maps were new information for them. In comparison most farmers in the United States, even those with large farms, spend some time in the field on the tractor or combine. Consequently, those US farmers knew something about within-field variability from personal observation before yield mapping.

Australia

For Australia, several less formal surveys complement the information provided by the national surveys in 2008 (Robertson et al., 2012) and 2012 (Llewelyn and Ouzman, 2014) (Table 4). Robertson et al. (2012) reported on interviews done with members of the Liebe Group of farmers in Western Australia in 2006 and 2009. The Liebe Group interviews confirmed the strong interest in GNSS guidance (46 and 66% respectively) and showed a strong interest in yield mapping (45 and 47% respectively). The VRT question was asked only in 2009 and showed a 14% adoption which is consistent with the national surveys. No farmers in the Liebe group reported use of EC or remotely sensing images, surprising compared to Australia's relatively high adoption of other PA technologies.

In 2017, Bramley and Ouzman (2018) provided a questionnaire link via email to the 49,000 growers on the GRDC list. They received 203 responses. Like the Steele survey in Canada which used a similar methodology, they found relatively high PA adoption with 84% using GNSS guidance, 50% yield mapping, 52% VRT fertilizer spreading, 26% using EC, and 40% using satellite images. Perhaps those with an interest in PA were more likely to volunteer and respond. Much of the PA research in New Zealand has been focused on improved pasture and forage management, but adoption statistics have not been published.

Europe

For Europe, in addition to the data reported by Lawson et al. (2011), Fountas et al. (2005) performed a mail survey using a list of PA farmers provided by industry partners. This study also included a survey of US farmers described above. In both Denmark and the United States, it intentionally sourced farmers more likely to use PA to obtain information on their experience. Fountas et al. (2005) argued that a random sample survey of all farmers would have yielded little information on PA because at that time few farmers were using the technology. They report that among those "PA farmers" 92% were yield mapping, 52% practiced VRT fertilizer, 75% used GNSS linked soil mapping, and 42% had tried soil EC. That confirms that they were probably among the most experienced PA farmers of their day, but unfortunately, these data are sometimes cited to show high PA adoption rates in Denmark and the United States. The Fountas et al. (2005) data is useful information, but misleading when comparing overall adoption rates.

Reichardt and Jürgens (2009) interviewed agricultural show attendees in Germany in 2001, 2003, 2005, and 2006, totaling 6183 farmers. The objective of the study was to document PA adoption patterns, with adoption expressed as a percent of PA users. To make them more comparable to the other studies the estimates in Table 4 are expressed as percentages of all respondents. Results varied from year to year, but about 3 to 6% of respondents used yield mapping, 1 to 3% did VRT P and K fertilization, some 3 to 6% of respondents indicated that they did GNSS linked soil mapping, and roughly 1% used soil EC.

The adoption levels in terms of percentage of all respondents estimated by Reichardt and Jürgens (2009) are consistent with the somewhat higher estimates from Lawson et al. (2011) data gathered several years later. Unfortunately, the Reichardt and Jürgens (2009) estimates of adoption by PA users is sometimes misinterpreted as percent of all farmers. Their adoption estimates were approximated from figures in their publication.

Cavallo et al. (2014) interviewed more than 300 Italian visitors at the International Exposition of Agricultural Machinery (EIMA) in Bologna in 2010. Most of the respondents were farmers, but the sample included contractors, farm workers, agricultural equipment dealers, students, and others. The size of the farms where respondents worked were larger than the Italian average farm of 7.9 ha. Over one-half of the respondents worked on farms of over 20 ha. Cavallo et al. (2014) asked a wide range of questions about agricultural machinery including use of GNSS guidance. They found that about 46% used guidance. This is larger than the guidance adoption rate reported by Lawson et al. (2011) in northern Europe, but consistent with the fact that larger farms were over represented.

Pickthall and Trivett (2017) conducted a web-based survey of UK farmers and found PA adoption levels very similar to those in the 2012 DEFRA survey (Table 2) in spite of the fact that the respondents tended to be younger than most UK farmers. The survey was sent via email and social media to contacts known to the authors. They received 77 responses. The mean age of respondents was 34 yr, while the average age of UK farmers was 59 yr. Over 50% of the Pickthall and Trivett (2017) respondents were in the 18 to 29 yr old category. The DEFRA statistics showed that only 3% of UK farmers were under 35 yr old in 2016 (DEFRA, 2018).

Asia

Precision agriculture adoption data for Asia is scarce. Mondal and Basu (2009) summarize the opportunity for PA in India, but do not provide adoption estimates. Kendall et al. (2017) does the same for China. Some Turkish universities have initiated PA research initiatives, but information on farm level adoption of the technology is scarce. Keskin and Sekerli (2016) reported on interviews with selected farmers, government staff, and farm equipment dealers in the Cukuova region of south central Turkey. Among the 39 farmers interviewed, 3% used yield mapping and 5% used auto guidance. None used VRT or soil mapping technologies. A substantial number indicate that they use GNSS, but Keskin and Sekerli explained that this was for measuring field areas. The Kesin and Sekerli (2016) interviews are useful because they provide a benchmark for future comparisons.

Africa

There is very little statistical evidence of PA technology use in Africa. Anecdotal evidence suggests that GNSS guidance is used by large-scale grain farmers and on tea (*Camellia sinensis* L.), rubber (*Hevea brasiliensis* Muell. Arg), oil palm (*Elaeis guineensis* Jacq.), and other plantations. Government and philanthropically funded projects are offering information and communication technologies and web/phone based agricultural information to farmers throughout the developing world (Haworth et al., 2018). Entrepreneurs are starting to offer sensor, drone, and data analysis services to farmers (Ekekwe, 2017). African research is starting to adapt PA technology to both large-scale farming (Maine et al., 2007, 2010) and smaller scale agriculture (Teboh et al., 2012). One of the main uses of GNSS in developing countries is mapping of farm and field boundaries to establish land tenure. Deininger (2016) provides an overview of how geospatial technologies are used in to improve land registration, markets and planning. Tamrakar (2013), Ganou et al. (2017), Sommerville et al. (2017) and Barnes et al. (1998) provide examples of GNSS used for farmland tenure systems. The GNSS mapping substantially reduces the cost of cadastral maps.

Chlorophyll/Greenness Sensor Adoption

Some technologies attract substantial research attention and are commercialized, but are only occasionally included in adoption surveys. For example, sensor-based nitrogen application has been the subject of many research projects (Diacono et al., 2013; Colaço and Bramley, 2018). Sensor based fertilizer systems have been touted by agricultural economists as potentially the most cost effective solution to soil nutrient management (Lowenberg-DeBoer, 2008). Companies advertise testing their nitrogen sensors worldwide, but these technologies are only rarely included in farm level adoption surveys. The USDA ERS data, the 2012 DEFRA study, and the Australian national surveys (Robertson et al., 2012; Llewelyn and Ouzman, 2014) do not include sensor-based nitrogen application. Based on farm show visitor data from 2001 to 2005, Reichardt and Jürgens (2009) in Germany reported that about 10 to 23% of their respondents use a nitrogen sensor. In 2013, Söderström and Rydberg (2013) wrote that 20% of wheat in Sweden was managed by a nitrogen sensor. Bramley and Ouzman (2018) reported that 12% of the Australian grain growers in their survey used "proximal canopy sensing". Erickson et al. (2017) reported that the percentage of US agriculture input dealers offering "chlorophyll/greenness sensor" services had risen from 4% in 2011 to 9% in 2017. Mitchell et al. (2017) reported that 15% of Ontario agriculture dealers used a proximal chlorophyll sensor on a pickup or applicator to collect data for nitrogen application maps, and 5% of their custom application area was applied based on the chlorophyll sensors.

Precision Agriculture Adoption Trends

Only in a few countries has enough data been collected over time to estimate PA adoption trends. One of the most widely cited longitudinal studies of PA adoption is the CropLife Purdue survey which has been done regularly since the mid-1990s (Erickson et al., 2017). Even though the CropLife-Purdue survey collects data from agricultural input suppliers, not farmers, it is useful in tracking PA adoption because in the United States and Canada many farmers access PA in the form of services provided by input suppliers. This is in contrast to the rest of the world, where PA is more often implemented by farmers with equipment that they own.

The CropLife-Purdue survey is a joint project between Meister Media and Purdue University. Meister publishes trade magazines for agricultural input suppliers and consequently has an almost exhaustive mailing list of input suppliers in the United States. Each time the survey has been implemented, a paper copy has been sent to a subset of those input suppliers. In 2017, respondents also had the option of going on-line to complete the

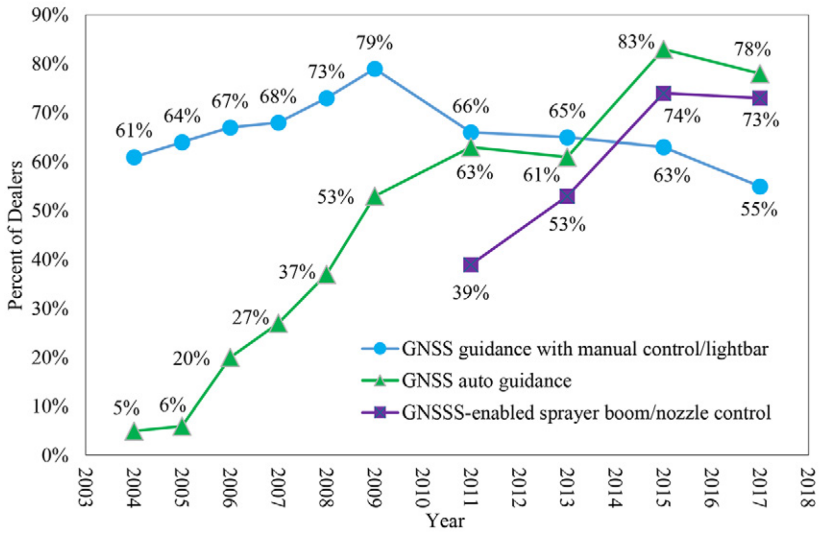

Fig. 1. United States dealerships using Global Navigation Satellite Systems (GNSS) guidance and sprayer section controllers, 2004 to 2017.

questionnaire. Typically the response has been 200 to 250 out of an initial list of input suppliers numbering about 2500.

The CropLife-Purdue data clearly shows the rapid adoption of GNSS guidance (Fig. 1). In 2004 when the survey first asked about light bar guidance use, over 60% of dealers already reported using the technology–it was introduced in the United States in the late 1990s. Light bar use peaked among input suppliers in 2009, probably being replaced by auto guidance. The adoption curve for auto guidance use among the input dealers almost forms a classic adoption curve, rising from almost 0 in 2004 to over 80% by 2015. The small decline in reported use of auto guidance in 2017 is probably the result of sampling variation and limited sample size, 209 in 2017. The CropLife-Purdue Survey is not a panel, respondents differ from year to year. Since 2011, the survey included a question on sprayer boom section control. Figure 1 shows that boom control adoption has increased at the same rate as auto guidance, but at an adoption level 5 to 10% below the auto guidance curve.

Figure 2 provides a perspective on the evolution of VRT services offered to farmers. In the first survey in 1997, 20% of suppliers offered single nutrient VRT spreading. That rose quite steadily over the next 20 yr to over 81%. Until 2017, the survey asked about single nutrient and multiple nutrient VRT separately. In 1997, the multiple nutrient offer was only at 3%, substantially less than the single nutrient VRT service. By 2015, the single nutrient and multiple nutrient services offers were almost equivalent in the upper 60% range, in part attributed to changes in equipment. In the mid-1990s, dealers were often using retrofitted spinner spreaders which could only handle VRT for a single nutrient. By 2015 many had acquired purpose-built machines with factory installed VRT hardware and software capable of handling multiple nutrients.

VRT lime, a soil amendment, follows a trajectory similar to that of VRT fertilizer, but about 10% lower. It should be noted the lower rate for lime does not necessarily mean that lime is less likely to be spread with VRT. The lower rate may simply reflect the structure of the industry in which lime is often spread by specialized companies separate from a farmer's local agriculture retail input supplier. Many fertilizer dealers handle the more costly pelleted lime which can be spread with ordinary fertilizer equipment, but not always the common agricultural lime which is finely ground. The CropLife-Purdue survey does not pick up much of the VRT done by those companies applying agricultural lime.

Since the mid-1990s, some input suppliers have offered VRT seed prescription services that help farmers create the recommendation maps for VRT seeding (Fig. 2). Dealers often also help with hybrid/variety placement among fields, and sometimes within fields if the farmer has a planter capable of planting more than one variety on the same pass across a field. The percentage of suppliers offering VRT seed prescriptions has expanded rapidly since 2013. Note that custom seeding is not as common as custom fertilizer applications, as most dealers are only providing the recommendations.

The CropLife-Purdue survey shows that dealer VRT pesticide application has muddled along in the 10 to 25% range since 2002. Farmers and input dealers struggle to create reliable recommendation maps for most pesticides. Some pests can be mobile, and their development and potential damage can be hard to reliably quantify. Many pesticides work best as a preventive treatment before the pest is even present. Also, label rates which were developed for uniform broadcast applications may be difficult to follow for VRT. In addition, some farmers (or their landowners) have little tolerance when it comes to pest damage; they may be willing to use full uniform pesticide rates across a field rather than taking a chance on escapes.

For many years the CropLife-Purdue survey asked dealers about the farm level use of PA technologies in their trade areas (Erickson et al., 2017). These reports usually followed the trends reported in other data sources (see Table 2, 3; Fig. 3, 4), but in some cases they have been more optimistic about farmer adoption than the USDA ARMS data suggests. For example, dealers estimated farm level use of VRT fertilizer to be almost 40% of crop area, while the USDA data suggests it at most in the upper 20% range. This difference may be in part related to how the question is asked in the CropLife-Purdue survey. The question asks dealers about PA use in in terms of, "acreage in your market area." Most dealers offer VRT fertilizer services and they would be best acquainted with the farmers who are their loyal customers, drawn in part by the interest in trying VRT and other PA services. The dealers may be less well informed about farmers

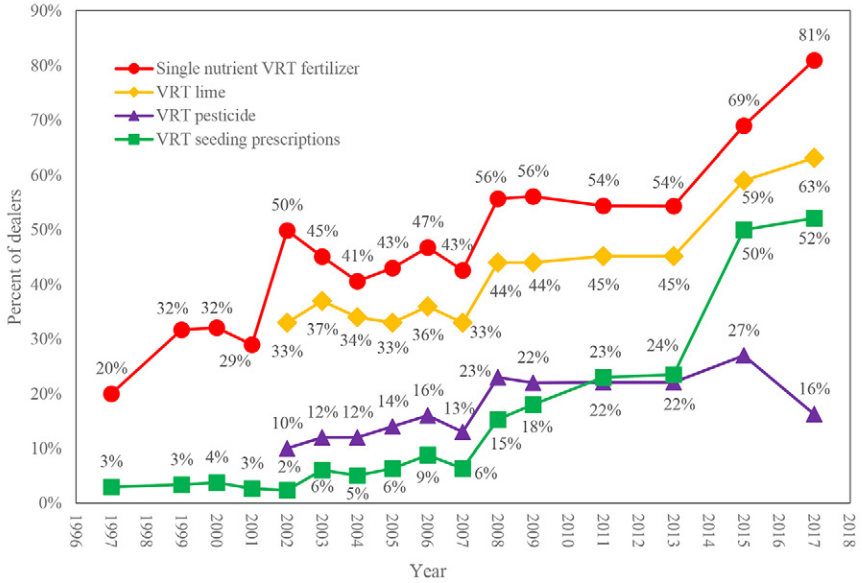

Fig. 2. United States dealers providing variable rate technology (VRT) services for fertilizers, lime, pesticides, and seeds, 1997 to 2017.

who are focused on short term cost control and consequently are not loyal to one dealer because they shop around for the lowest fertilizer price and who are reluctant to invest in the information gathering aspect of PA (e.g., grid soil sampling).

The USDA ERS (2018a) farm level data portrays a similar GNSS guidance adoption trajectory for farmers as the CropLife-Purdue data did for dealers (Fig. 3). Unfortunately, because the USDA data is by crop and not every year, the trend is not just a matter of connecting the dots. Strictly speaking only data points should be connected by crop. Some crops have only two data points, others four. It is more instructive to observe the "cloud" of data points of various crops that created a very clear linear trend of guidance adoption. That farmer adoption trend is only slightly below the dealer adoption trend line for guidance shown in Fig. 1. Dealers can probably justify investing in guidance earlier than farmers because they are covering more area, and the reduction in skip and overlap is a larger benefit for their business. Many farmers are more likely to wait for the normal equipment replacement cycle to upgrade to machines with guidance.

The USDA ERS data for VRT is more diffuse (Fig. 4). Until 2010, the data shows an indistinct collection of data points at less than 15% adoption rate, rather than a trend line. After 2010 during the high commodity price years from 2010–2014, reported VRT use edged up into the 20% range. Some anecdotal evidence suggests that with the persistent lower commodity price trends of recent years, some farmers have sought to cut costs by reducing their VRT use.

While the questions on the USDA ARMS survey differ slightly from year-to-year and crop-to-crop, it would be possible to create data cloud figures for yield monitor use, yield mapping, GNSS linked soil mapping, soil EC, remote sensing, and VRT for specific uses (e.g., nitrogen, phosphorus, potassium, seeding, pesticide). Those figures would help visualize the pattern of adoption for various PA technologies, but they would not substantially change the insights from observing the most recent adoption levels in Table 2.

Some researchers that have not collected data over time have relied on farmer recall to sketch out adoption curves. Llewelyn and Ouzman (2014) generated curves using the respondent's, "stated first year of use of a particular practice." The Australian adoption curves are similar to those estimated from USDA data, except that the VRT fertilizer curve rises more rapidly and achieves higher adoption levels because manual variation of fertilizer, where the applicator changes the rate, is included in the Australian data.

In 2013, Zhou et al. (2017) asked a random sample of US cotton producers which PA technologies they used from 2000 to 2012. Based on this data they estimated adoption curves. They fitted Sigmoidal adoption curves and estimated that the maximum adoption rates for GNSS guidance was reached in 2010 at 7%, for VRT in 2010 at 4% and for information gathering technologies like yield monitoring and remote sensing in 2008 at 4%.

Griffin and colleagues generated adoption curves for farmers in the Kansas Farm Management Association (KFMA) by asking them to specify the year of adoption of PA technologies, and the year of abandonment if that technology was no longer used (Griffin et al., 2017). They used that information to identify PA technology packages that were more likely to be used together, and transition probabilities from one technology package to another using a Markov chain methodology. For example, one common package in the KFMA data is the use of a yield monitor, GNSS soil testing and VRT fertilizer. The Griffin et al. (2017) analysis shows a 99% probability that a farm using that technology package would continue to use it in the following year. While the KFMA data represents farms that are larger than the Kansas average farm and probably are more intensively managed, the Griffin et al. (2017) study adds insight on the time path of adoption.

Since the late 1990s researchers at INTA have maintained a tally of the number of PA machines (e.g., yield monitors, light bar, and auto guidance) in Argentina. These are very useful in visualizing trends in Argentine PA equipment. The trend lines by type of equipment were most recently charted by Melchiori and Garcia (2018). Unfortunately, it is very difficult to compare

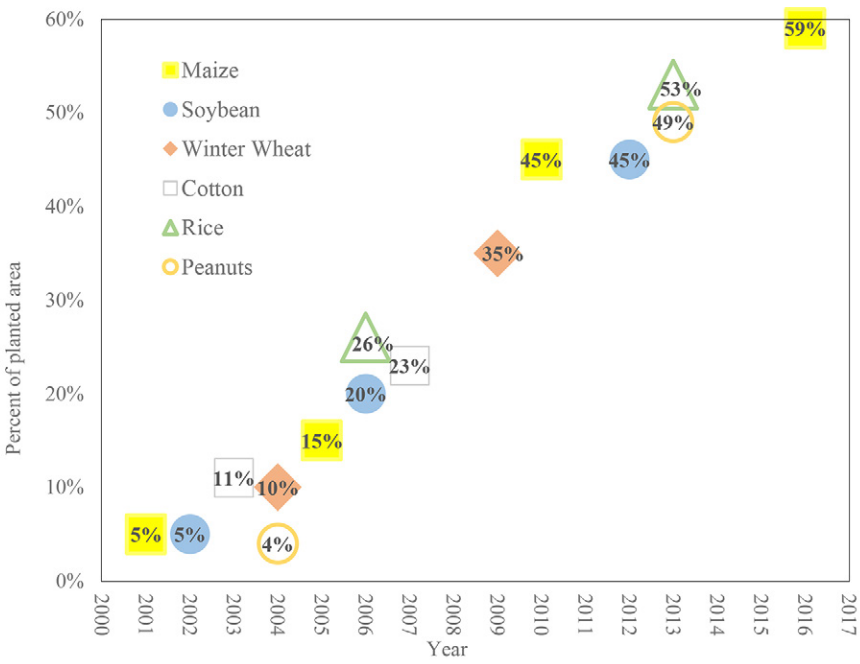

Fig. 3. Planted area by crop in the United States where Global Navigation Satellite Systems (GNSS) auto guidance was used, 2000 to 2016.

machine numbers with the adoption estimates in terms of percentage of farmers or percent of crop area reported in other countries.

DISCUSSION

From the confusing mass of data collected from surveys that used several different sampling methods and were analyzed in a variety of ways emerges a picture of rapid adoption of GNSS guidance and related technologies like sprayer boom control and seed shutoffs, and slower adoption of VRT of all kinds. Adoption of information gathering technologies like yield and soil mapping and remote sensing, which are the foundation of VRT, has also been relatively slow.

Lowenberg-DeBoer (1998) compared PA adoption speed to that of previous agricultural technologies in the United States. The first successful internal combustion engine tractor was commercialized by the Hart-Parr company in 1902, but fully motorized farms did not become common in the United States until after 1932, when pneumatic tires for tractors were introduced. Tires were an important breakthrough because they allowed tractors to operate on roads and for use hauling produce to market. Hybrid maize took about 20 yr from first commercialization in the late 1920s to widespread adoption in the US Midwest in the late 1940s. International Harvester commercialized the first till planter (i.e., the M21) in 1955, but it took until the late 1990s for no-till adoption to reach about a quarter of US corn and soybean area. No-till planting has continued to increase since the 1990s and reached about 35% of US grain area in 2010 (Horowitz et al., 2010).

Genetically modified (GM) seeds for soybeans, corn and cotton were commercialized in 1996. In the United States, GM soybeans were planted on over 50% of the crop area by 1999 and 90% by 2007 (USDA ERS, 2018b). Herbicide tolerant cotton exceeded 50% of cotton area by 2001 and 90% by 2017. Herbicide tolerant maize area reached 50% in 2007, and 90% in 2018. The pattern of adoption of GM seed in Argentina was similar (Trigo, 2016). However, in spite of the rapid adoption of GM seeds in some countries they are hardly universal. They are grown in only 28 of the 195 countries in the world mainly because of legal and regulatory constraints put in place due to public resistance (James, 2005).

In comparison to other 20th Century agricultural technologies, GNSS guidance has been adopted relatively quickly. In the United States, light bar and auto guidance reached about 80% of the agriculture dealer market in a decade. Guidance is standard practice for commercial commodity crop farmers and the most common PA technology wherever adoption data is available. It has rapidly been adopted wherever motorized mechanization is used. The GM seeds may have been adopted more rapidly in the countries where they are permitted, but they are prohibited in most countries.

In many ways the adoption pattern of VRT is similar to that of motorized mechanization at the beginning of the 20th century or conservation tillage in the second half of the century. In both cases, an immature technology was put on the market and gradually improved until it found a significant market share (Lowenberg-DeBoer, 1998). The widespread pattern of 20 to 30% adoption rates for VRT fertilizer suggests that farmers like the idea and are willing to try, but relatively few of them are willing to make it their standard practice.

Almost every PA adoption study cited in this article has a hypothesis about VRT improvements needed to speed VRT adoption. Those hypotheses might be summarized in three points. (i) Reducing cost of VRT: Manual soil testing, laboratory analysis, and map based VRT systems with human beings in the decision loop are probably too expensive (Lowenberg-DeBoer, 2018). The economics of crop production all point to a sensor based approach, but it is not yet clear if that is proximal soil sensors, some type of optical sensor, or remote sensing. (ii) More reliable VRT decision rules: Whether VRT is implemented via a map-based approach in which an agronomist makes a recommendation, or an algorithm in a computer, farmers want to know that it will result in a high probability that the resulting

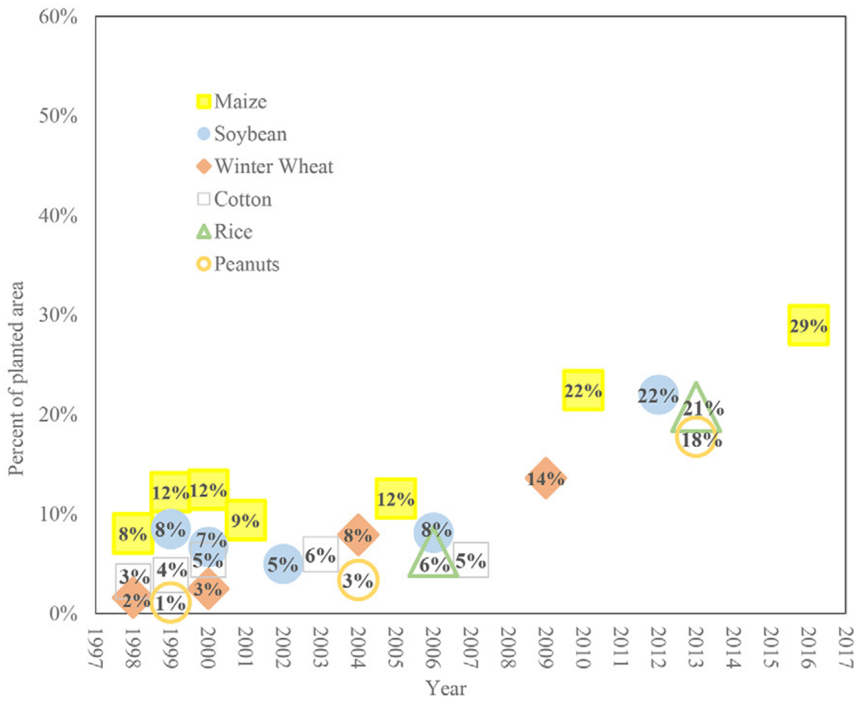

Fig. 4. Planted area by crop in the United States where variable rate technology (VRT) was used for any purpose, 1998 to 2016.

application is the most profitable. This is especially a problem for nitrogen application because nitrogen response is sensitive to moisture, temperature, soil organic matter, and a range of other factors. And finally, (iii) Demonstrated value: Farmers need to see differences in the crop and in their profit margin. The first review of the profitability of VRT fertilizer raised questions about the economics of this practice and most subsequent VRT fertilizer studies have come to the same conclusion (Swinton and Lowenberg-DeBoer, 1998; Lowenberg-DeBoer, 2018).

Good science starts with good problem definition and good problem definition usually starts with accurate observations on the system in question. Comparable data on PA adoption from major agricultural countries would make it much easier to diagnose PA issues and zero in on key constraints. For most other technologies the United Nations Food and Agricultural Organization (FAO) provides guidelines on how to collect data through the World Census of Agriculture (WCA) program (FAO, 2017). This helps researchers, policymakers, and agribusiness compare technology use between countries, identify problems, and develop solutions. The WCA definitions contain a section on collecting data on agricultural practices (i.e., Section 8.6.1). For instance, it specifies how to collect data on use of pesticides, GM seed, and farm machinery. The WCA program has a standardized list of farm equipment types in Annex 7. Is it time for the WCA to add PA technology?

CONCLUSIONS

This study reviews the publicly available data on farm level adoption of PA worldwide. The definition of PA used for the study focuses on the use of information and other technology to improve the spatial and temporal management of agricultural production. The study considers PA as a toolkit from which farmers pick and choose. It examined the adoption estimates for specific crop PA technologies in surveys done with standard random sampling procedures and considered how estimates using other sampling methods may differ. Based on that analysis the study sets the record straight on PA adoption as follows.

(i) Rapid adoption of some PA technologies worldwide: GNSS guidance and associated technologies like sprayer boom control and planter row or section shutoffs are becoming standard practice for mechanized agriculture. They are being adopted as fast as any agricultural technology in recent memory, just as fast as GM seed and over a wider area because GNSS guidance has not faced the regulatory hurdles and political/social concern that has restricted use of GMs in some parts of the world.

(ii) Slow adoption of VRT: The main reason for perceiving that PA adoption is slow is that PA is sometimes thought as strictly VRT. In spite of the fact that VRT fertilizer was part of the classic PA introduced commercially in North America in the early 1990s, adoption at the regional level rarely exceeds 20% of farms. This level of adoption suggests that farmers like the idea of VRT and are trying it, but are not convinced of its value. The VRT adoption estimates for specific groups of farmers may exceed 50% and approach the standard practice level. High VRT adoption estimates also occur because survey sampling is not representative. For example, farmers attending a PA workshop or a farm technology show may be self-selecting for PA interest and consequently a high percentage of them may have tried VRT.

(iii) And finally, very little use of PA on non-mechanized farms in the developing world: The biggest gap in PA adoption is for medium and small farms in the developing world that do not use motorized mechanization. They do not use PA technology to improve spatial and temporal management because research has developed very few PA technologies that might be cost effective on non-mechanized medium and small farms, and because

> entrepreneurs have not commercialized those few technologies developed for these uses. The typical commercial strategy of multi-national business is to try to sell simplified, cheaper versions of industrialized country technology in the developing world. Technology history suggests that rarely is successful. More often entrepreneurs must go back to the science and re-engineer technologies that solve developing country problems.

The relatively slow adoption of VRT should not be interpreted as a failure any more than motorized mechanization should not be considered a failure because the steam tractors developed in the 1880s and 1890s were never generally adopted. Technology historians consider steam traction to have been a useful first step in the process of motorized mechanization. Historians of the future may look back and realize that the VRT equipment and services marketed starting in the early 1990s were a useful first step, but not the last word in spatial management of crop inputs. A new wave of technology may be required to apply the right input, at the right place, at the right time, and in the right manner. For example, it may require robots equipped with AI doing individual plant management.

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