Global Adoption of Precision Agriculture: An Update on Trends and Emerging Technologies

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Abstract.

The adoption of precision agriculture (PA) varies greatly around the world according to region, crop, farm type and size, and other factors. This research provides an update on PA adoption and poses hypotheses on likely adoption patterns in the next decade. The major challenge with estimating PA adoption levels is that statistically robust PA adoption surveys are conducted in few countries worldwide. The availability of estimates from national statistical offices (NSOs) of 48 countries and other international sources was rigorously assessed. Survey results are reported from the Grains Research and Development Corporation (GRDC) of Australia, United States Department of Agriculture (USDA), the CropLife-Purdue Precision Dealer Survey, Denmark Statistics, the Hungarian Central Statistical Office, the United Kingdom Department for Environment, Food and Rural Affairs, Statistics Canada, Statistics Estonia, Statistics Portugal, Mexican National Institute of Statistics and Geography, and other organizations. Results are disparate, so summary statements are difficult. Global Navigation Satellite System (GNSS) guidance has been adopted rapidly worldwide on large, mechanized grain and oilseed farms. No survey results from any country, region, or crop show variable rate technology (VRT) applications of fertilizers, seeds, or pesticides at more than half of farmland, and in many regions much less. Use of uncrewed aerial vehicles (UAVs)/drones, satellites, and/or aerial imagery adoption varies broadly by country, with highest adoption at 30% of Danish farmland in 2023. New and more advanced technologies based on robotics, UAVs, machine vision, and artificial intelligence (AI) more broadly are in the process of being commercialized. Use of UAVs by U.S. farmers for spraying herbicides, fungicides, or insecticides was less than 10 percent of farmland. Adoption may grow over time as technological complexity declines, while accuracy and use cases increase. Evidence on crop robotics in arable farming from certain countries (e.g., USA, Canada, Denmark, Hungary) is starting to be statistically detectable. Extensive robotics research and development (R&D), initial commercial offerings, and increasing robotization in other sectors suggest their use could rise. Similar expectations could exist for certain AI applications like precisely targeted weed management enabled by machine vision and possibly combine operator assistance.

Keywords.

Adoption, first-generation technologies, machine vision, robotics, artificial intelligence (AI), uncrewed aerial systems (UAV), automation

1. Introduction

Considerable uncertainty exists regarding the uptake and diffusion of precision agriculture (PA) technologies in most countries. To be sure, researchers and various organizations throughout the world have calculated and continue to calculate estimates of PA adoption, many of which have aided our understanding about the status of these technologies, especially in local contexts. However, not all adoption estimates stem from randomly-sampled farmers (or retailers, custom service providers), with a sufficient sample size to ensure they are statistically-reliable and representative of the population being considered. In particular, there is a notable gap in our knowledge of countries' adoption on a national scale, and such estimates that do exist are often challenging to locate, not publicly available, and/or not widely circulated among interested parties (e.g., researchers, industry professionals, policymakers)—likely hindering a fuller realization of PA benefits and further technological improvement. We help fill this void by 1) gathering and presenting among the most rigorous estimates available to document the status of PA adoption—for Australia, Canada, Denmark, Estonia, France, Hungary, Mexico, Poland, the United Kingdom, and the United States, and 2) providing a contextual discussion that serves as a launching point for facilitating meaningful comparisons across countries.

This lack of reliable and representative adoption data is occurring at a time of substantial strain on global agricultural production. Domestic food security issues due to international conflict, farm profitability and farm household incomes, climate change adaptation, and supply chain traceability, among others, are major concerns worldwide. Some of these have the potential, at least partly, to be mitigated by PA technologies and increasingly digitalized production (e.g., McFadden et al., 2023), though the extent to which these technologies can offer lasting solutions across a wide range of countries has not been fully explored. Improved international data collection on adoption would undoubtedly benefit research that explores the role of technologies in addressing some dimensions of these pressing challenges.

This is brought into sharper focus when attempting to consider the significant heterogeneity of agricultural production and PA technology use between and within countries. Where rigorous adoption data do exist, they point to large differences in PA usage across countries as a function of soil quality and topography, climate, the kinds of commodities produced, technology pricing and availability, farm size, and national agricultural policies—to name only few (e.g., McFadden et al., 2022). These criteria also have explanatory power when seeking to understand regional adoption differences inside a country's boundaries, with the caveat that local circumstances (e.g., technology availability and costs, operation type and scale, regional policies) are likely to matter even more. In the absence of such data, researchers can attempt to use information on uptake of foundational technologies like high-speed internet and global navigation satellite systems (GNSS) to roughly sketch bounds on PA adoption, but this is fraught with methodological pitfalls and will tend to be highly inaccurate. This reinforces the need for accurate national and sub-national estimates when seeking to analyze the net benefits of these tools at a more macro level.

Despite such gaps, a large and growing literature continues to evolve in characterizing the international dimensions of PA use. This body of work has addressed major economic issues associated with these technologies, including adoption, even as precision agriculture has grown increasingly sophisticated and garnered increasing attention as a bedrock of the ongoing digital transformation of agriculture (e.g., Schroeder et al., 2021). Some of this expanding research focus has been facilitated by improvements in the availability, ease, and affordability of online surveying methods, leading directly to new hypotheses and estimates—and new lines of inquiry. Instances of non-existent information about PA penetration have given way to useful estimates or meaningful approximations for some countries. Yet, some of this additional information has the potential to cause confusion throughout the global agricultural sector, especially when estimates from small, biased, or otherwise non-representative samples of PA technology users are regarded as authoritative. A question that naturally arises is: using the best available evidence, what is the current status of PA technology use worldwide?

Our research aligns most closely with two past studies that systematically document PA adoption in various countries. Lowenberg-DeBoer and Erickson (2019) catalog use of PA technologies worldwide, with estimates for certain countries in North and South America, Asia, Australia, and Europe. The set of technologies considered is comprehensive, including some that are often overlooked, such as electrical conductivity, and the study provides estimates from government surveys that use rigorous survey designs and large samples, in addition to estimates from university analyses and other sources. Our study focuses primarily on government surveys, adding information from a larger set of countries and for a greater number of years, with some emphasis on sub-national estimates and a (descriptive) focus on newly commercialized technologies incorporating elements of machine learning. Likewise, McFadden et al. (2022) documents adoption trends for select countries using similar data sources, with additional information provided about the technological status of the livestock and specialty crop sectors, though the analysis is restricted to OECD countries. To our knowledge, this work contains estimates for the most exhaustive collection of countries (ten) using rigorously-designed government surveys of representative samples, which are intended to inform both domestic and international agricultural policymaking.

2. Methods

An investigation of publicly available data on adoption rates of PA technologies worldwide was undertaken, seeking nationally representative, rigorously undertaken surveys of agricultural production practices. In many cases this was a country's census of agriculture, or a survey conducted by a government agency or university. Emphasis was placed on compiling adoption estimates for PA technologies adopted by individuals for use on farms, rather than agricultural businesses (e.g., contractors, cooperatives, processors). In several instances, the relevant national statistics office (NSO) is the main agency within the country's central government tasked with performing major national surveys (e.g., household censuses, manufacturer surveys). However, the relevant NSOs in several other countries are the central government's agriculture agency (e.g., Ministry of Agriculture).

All of the 27 countries currently comprising the European Union (EU) and the 21 countries making up the Asia Pacific Economic Cooperation (APEC) were contacted. Of these 48, the NSOs of 41 countries responded, suggesting an 87% "response rate" to our communication efforts. The most common responses were: 1) a redirection to the central government's agricultural agency because the relevant data and documentation resided with them, or 2) no data are recorded about uptake of PA technologies.

With the general lack of precision farming adoption information, there were few pre-specified limits underlying the study's inclusion criteria. That is, to avoid potential bias, national estimates were not excluded based on: 1) specific unit of observation (e.g., field, farm, farm household), or 2) perceived digital sophistication of the PA technologies. Rather, the approach was designed to be as broadly representative as possible, while focusing mainly on advanced technologies to assist site-specific agricultural management (McFadden and Schimmelpfennig, 2019; McFadden et al., 2023).

It was unclear for some countries if missing estimates of farmers' PA adoption were: 1) available based on the creation of a special tabulation for a fee, 2) accessible only to qualified researchers, 3) ambiguous due to questionnaire wording or lack of a publicly posted questionnaire, or 4) completely unavailable because questions about the use of PA technologies, specifically, had not been incorporated into the relevant survey(s).

3. Analysis

Our analysis proceeds in three sections. Below, we present national adoption estimates of first-generation technologies for select countries, followed by geographically disaggregated estimates (e.g., province, state, or other region). We close with a presentation and discussion of newly commercialized technologies.

3.1 National Adoption Estimates

Our study focuses on the following six countries for which there are statistically reliable, representative adoption estimates for technologies of interest: Australia, Canada, Denmark, England, Hungary, and the United States. The current adoption landscape in four additional countries (Estonia, France, Mexico, and Portugal) is briefly summarized.

3.1.1 Australia

The Grains Research and Development Corporation (GRDC) of Australia has included several PA technologies in its periodic farming practices survey of large grain farms (Table 1). The GRDC is a quasi-governmental, levy-supported agricultural research and development organization, and its farming practices survey is a random sample of the GRDC Customer Relations Management database which includes most commercial Australian grain farms. In the 2008 to 2021 period, the average farm size of respondents has ranged from 3,475 ha to 3,991 ha. Other than autosteer, PA technology adoption levels on large Australian grain farms are modest.

Table 1. Adoption of PA Technology on Large Grain Farms in Australia.

	Percent of area in large grain farms						
Year	**Yield Monitoring**	**VRT**	**VRT Seeding**	**VRT Fertilizing**	**Autosteer**	**Sensing using EM38 or NDVI**	**Controlled Traffic**
2008	13.5	8.7			46.7		15.1
2012	21.8	8.1			66.7		21.1
2014	29.0		6.5	9.0	80.1	1.8	21.4
2016	34.9		6.5	7.4	86.0	5.1	29.3
2021	44.0			11.0			34.0

Source: GRDC Farm Practices Survey Report for years 2012, 2015, 2017 and 2021.

Australia was the first country where GNSS guidance was commercialized (in 1997), and large grain farms adopted it quickly. By 2016, 86% of GRDC respondents were using autosteer. This is quicker adoption than in the USA, Canada, England or Denmark. However, it should be noted that the GRDC sample does not include smaller farms and mixed livestock-crop-horticulture farms that are included in the USA, Canadian or Danish samples. Worldwide, the rate of GNSS guidance adoption on small and mixed farms has lagged behind that of larger grain farms.

Variable rate technology (VRT) fertilizer was used by only 11% of large Australian grain farms in 2021. Use of VRT fertilizer has increased only slightly over the last decade. VRT seeding was used by only 6.5% of the respondents in 2016.

Yield sensors are standard equipment on most combine harvesters sold in Australia and many farmers see yield estimates on their yield monitor screens. The GDRC data do not clarify how many farmers make yield maps and use them for farm management purposes.

In 2016, only slightly over 5% of large grain farms were using NDVI from remote sensing or data from EM38 proximal sensors.

Controlled Traffic Farming (CTF) is used by over a third of the GDRC respondents. Adoption of CTF has more than doubled over the last 15 years. The interest in CTF may be linked to soil compaction observed in many Australian soils and the lack of freezing and thawing which counteracts compaction in many parts of North American agriculture.

3.1.2 Canada

Statistics Canada performed an agricultural census in 2016 and 2021, with somewhat different questions on use of digital and precision agricultural technology (Table 2). The technology questions were binary and had no indication of intensity of use. Autosteer and GIS mapping were the only technologies for which data were collected in both censuses. Use of autosteer rose from 21% of all farms in 2016 to 27% of all farms in 2021. Use of GIS mapping rose from 8% in 2016 to 13% in 2021.

Table 2. Precision and Digital Technology Adoption Estimates for Canada, 2016 and 2021.

Technology	Number of farms using this technology	Percent of all farms*
2016 Census of Agriculture		
Computers/laptops for farm management	108,655	56
Smartphones/tables for farm management	83,071	43
Automated steering (auto-steer)	39,708	21
GPS technology	58,166	30
GIS mapping (e.g., soil mapping)	15,801	8
Greenhouse automation	1,579	1
Robotic milking	1,063	1
Automated environmental controls for animal housing	8,695	4
Automated animal feeding	9,405	5
2021 Census of Agriculture		
Automated guidance systems (auto-steer)	50,917	27
Geographic Information System (GIS) mapping	25,058	13
Variable-rate input application	30,657	16
Drones	6,781	4
Soil sample test	60,687	32
Slow-release fertilizer	44,484	23
Fully-robotic milkers	2,197	1
Robotic greenhouse equipment	348	<1

Source: Statistics Canada, Census of Agriculture for 2016 and 2021.

* Statistics Canada gathers data on all farms that report farm income or expenses for income tax purposes. The total was 193,492 in 2016 and 189,874 in 2021.

In 2016, the majority of Canadian farms used computers (56%), and many used smartphones or tablets (43%). The percentage using greenhouse automation, robotic milking, automated environmental controls for livestock housing, and automated animal feeding was 5% or less.

In 2021, an estimated 16% of Canadian farms used variable rate applications (VRA). The 2021 census questionnaire defined VRA to include "variable rate seeders, sprayers and fertilizer applications." That year, 32% had soil samples tested, and 23% used slow-release fertilizer, but the soil samples and slow-release fertilizer use may have been on a whole field basis. Use of drones, robotic milkers and robotic greenhouse equipment was estimated at less than 5%.

3.1.3 Denmark

Denmark Statistics regularly collects data on PA technology use on all farms in Denmark that report crop production (Table 3). The crop area managed with PA has increased rapidly, while the number of farms using the technology has grown more slowly. The data indicate that 78% of Danish crop area is managed with PA, but that represents only 40% of farms because disproportionally larger farms adopt the technology. Similarly, 67% of crop area is farmed using RTK GNSS guidance, but that is 27% of farms. In the Denmark data, only RTK GNSS guidance with at least 2 cm accuracy is counted. About 57% of crop area is managed with sprayer section control, but on only a quarter of farms. Use of crop sensors has stagnated, with the percentage of farms at 2% and in 2023 only 6% of crop area.

Table 3. Precision Agriculture Estimates for Denmark, 2019-23.

	Percent of farms or area									
	2019		2020		2021		2022		2023	
Technology	Farms	Area	Farms	Area	Farms	Area	Farms	Area	Farms	Area
All Precision Agriculture	28	66	32	68	36	73	37	76	40	78
RTK GNSS Guidance	24	59	23	58	24	61	26	66	27	67
Sprayer Section Control	14	40	20	48	23	53	25	57	25	57
Software for N	7	21	8	21	9	22	10	26	13	37
Satellite/Drone Images	5	15	4	12	7	19	8	26	10	30
Crop Sensors	2	8	2	5	2	4	2	5	2	6

Source: Denmark Statistics, Agricultural and Horticultural Survey, years 2019-2023.

As with other countries, use of PA in Denmark differs by crop. The percentage using some type of PA was higher among farms producing seed (93%), potatoes (92%) and sugar beet (92%). On farms producing mainly cereals, pulses and oilseeds, PA use was only slightly over the average (83%). Farms producing mainly forages had lower use of PA (67%).

3.1.4 England

The UK Department of Environment, Food and Rural Affairs (DEFRA) has regularly collected data on PA in England since 2009 (Table 4). Note that these data are for England only; other nations of the UK may have different adoption levels. The DEFRA estimates use a broad definition of "precision agriculture" which includes first-generation PA technologies like GPS, soil mapping, yield mapping and VRA, but also controlled traffic, pasture measurement and some precision livestock technology.

Table 4. PA Adoption Estimates for England, 2009, 2012, and 2019.

	Percent of farms		
Technology	**2009**	**2012**	**2019**
GPS (Global Positioning System)	14	22	
Soil mapping	14	20	29
Variable rate application	13	16	25
Yield mapping	7	11	17
Telemetry (remote measuring)	1	2	10
Controlled traffic farming			8
Breeding indices or estimated breeding values			32
Regular weighing to measure livestock growth rates			42
Automated heat detection systems			8
Pasture measurement (e.g. plate meters, probes)			9

Source: Farm Practices Survey, DEFRA, years 2009, 2012, and 2019.

In England, livestock information technology, such as breeding indices and regular weighing to measure growth rates, is the most commonly used. Most farms in England were classified as predominately livestock farms (57%) in 2023, and by global standards, most farms in England are small or medium sized. The relatively "low-tech" livestock information technology adopted fits those relatively modest sized English farms.

Use of first-generation PA technology has increased slowly over time, with soil mapping estimated at 29% in 2019 and VRA at 25% in that same year. The DEFRA PA questions are also binary, and the survey does not provide information on the intensity of use. For example, a farmer might answer "yes" even if soil mapping or VRA is used only on some fields or not every year. There is often motivation to answer "yes" if at all possible because of peer pressure and subsidy-granting government agencies that tend to view farmers who use soil mapping and VRA as better stewards of the land. The way that the question is asked by DEFRA may tend to inflate VRA and soil mapping estimates.

Controlled traffic farming (CTF) is considered PA because it contributes to spatial management of the operation. CTF has attracted farmer interest because, as in Australia, many English soils are vulnerable to compaction.

3.1.5 Hungary

In 2020, the Hungarian Central Statistical Office (HCSO) started collecting data on precision agriculture in the country. In that year, 12% of the farms used some type of PA (HCSO, 2020). In 2023, PA adoption estimates were updated by the HCSO as part of the Integrated Farms Statistics (HCSO, 2023). During that time, the proportion of farms using plant sensor information from satellites, drones or proximal sensors decreased from 5.6% in 2020 to 2.3%. Note that the plant sensors may have been owned by the farm or used as a service. The use of general environmental sensors decreased from 2.7% to 2.6% and yield mapping from 2.4% to 1.6%. The proportion of farms using VRT for any input rose from 2.8% to 4.9% over three years. The most common specific VRT uses in 2023 were nutrient application (3.8%), sowing and planting (3.5%), and plant protection (3.7%). The proportion of guided/automatic steering was up from 4.0% in 2020 to 5.3% in 2023.

Table 5. Precision and Digital Technology Adoption Estimates for Hungary 2020 and 2023.

	2020			2023			
	With own tools	As a service	Total	With own tools	As a service	Total	Increased/ decreased ↑↓
Technology/Category	Percent of farms						
Plant sensors	3.3	2.3	5.6	0.7	1.6	2.3	↓
Guided/automatic steering	2.8	1.2	4.0	3.1	2.2	5.3	↑
Input VRT	1.8	1.0	2.8	2.3	2.6	4.9	↑
General environmental sensors	1.9	0,8	2.7	1.4	1.2	2.6	↓
Yield mapping	1.5	0.9	2.4	0.5	1.1	1.6	↓
Fleet tracking	0.7	0.8	1.5	0.7	1.4	2.1	↑
Use of drones	0.7	0.7	1.4	0.3	0.6	0.9	↓
Use of robots	0.4	0.3	0.7	0.7	1.0	1.7	↑

Source: Hungarian Central Statistical Office (KSH) Integrated Farm Statistics data collection – IFS 2023, preliminary data

3.1.6 United States

The U.S. Department of Agriculture's (USDA) Agricultural Resource Management Survey (ARMS) is among the most detailed sources of information to the USDA and the U.S. Congress about the technology use, production practices, and financial health of U.S. farm businesses and farm households (USDA, 2024a). Through USDA's Economic Research Service (ERS), data from this survey are used to produce the Congressionally-mandated national and regional cost of production estimates for 12 commodities (USDA, 2024b) and USDA's official farm income forecasts (USDA, 2024c), among other authoritative estimates. Since 1996, the surveys have been carried out annually in three phases, although only the second phase of the surveys inquires about farmers' PA adoption. In this phase, a representative sample of farmers who are producing that year's target commodities are surveyed in person; the target commodities recur on a rotating basis typically every 4-6 years.

Use of guidance autosteering in the production of seven major U.S. field crops has steadily increased since 2001 (Figure 1). In these early years, adoption was generally 5-15% of crop-planted area. However, rapid growth in adoption in these intervening years has led to the use of autosteer on the majority of planted area in all of these major field crops, except rice, since 2016. This stands in contrast to the 26-year time path of VRT adoption (Figure 2). Early use of VRT was quite low (1%-12% of crop planted area) and expanded only modestly through 2013, with adoption appearing to currently plateau at 31-37% of corn, soybeans, and winter wheat area and 21-23% of cotton, rice, and peanuts area.

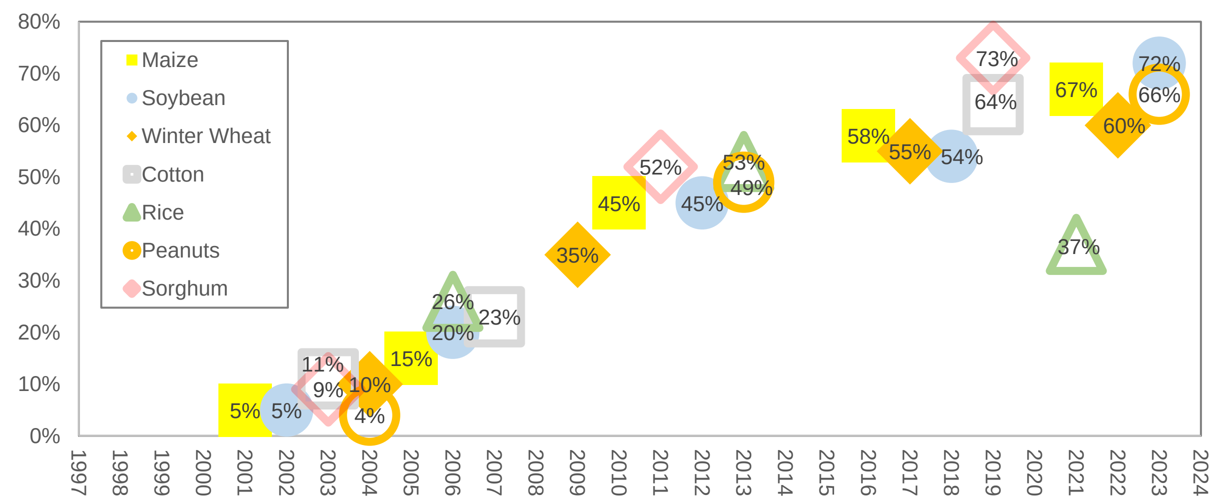

Figure 1. Estimates from Farmers of Percent of Crop-Planted Area Managed with Guidance Autosteering, 2001-23.
Source: Agricultural Resource Management Survey (ARMS), USDA – Economic Research Service and National Agricultural Statistics Service, years 2001-07, 2009-2013, 2015-2019, 2021-22.
Note: The ARMS samples a set of target commodities on a rotating basis every 4-6 years.

Similar dynamics are apparent when examining the data for several other technologies in the three most recent survey years (Table 6). For several field crops, yield monitoring is widely

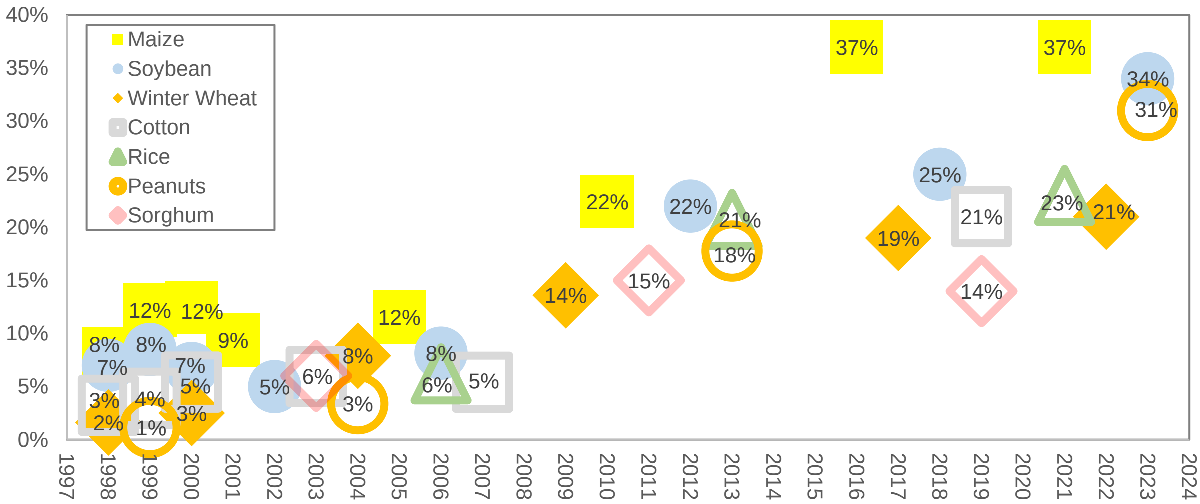

Figure 2. Estimates from Farmers of Percent of Crop-Planted Area Managed with VRT for Any Purpose, 1998-2023.
Source: Agricultural Resource Management Survey (ARMS), USDA – Economic Research Service and National Agricultural Statistics Service, years 2001-07, 2009-2013, 2015-2019, 2021-22.

used, as are yield mapping and soil core testing, though significant variability exists across crops. Adoption in oats production remains low, in part because it tends to be grown on less fertile land and increasingly as a cover crop, with relatively low variable inputs applied. The use of drones/UAVs for commercial agricultural purposes remains quite low, perhaps inconsistent with the level of media coverage to date about their current potential.

Table 6. PA Adoption Estimates from Farmers for the United States, 2021-23.

	Percent of cropland area					
	2021	2021	2022	2023	2023	2023
Technology	Corn	Rice	Winter Wheat	Soybeans	Oats	Peanuts
Yield monitoring	70	33	37	79	19	11
Yield mapping	54	13	21	48	8	5
Soil core testing	21	7	14	27	14	60
Variable rate applicator	37	21	21	34	7	31
Autosteer	67	37	60	72	28	66
Drones/UAV use	5	3	4	6	2	5

Source: Agricultural Resource Management Survey, USDA – Economic Research Service and National Agricultural Statistics Service, years 2021-23.
Note: The ARMS samples a set of target commodities on a rotating basis every 4-6 years.

The CropLife/Purdue Precision Dealer Survey has been conducted at least every other year since 1996. While the survey focuses primarily on the technologies used by ag retailers and precision services offered, dealers are asked about the share of acres in their local market area that are managed with various precision technologies.

Table 7 shows the estimated market area of an array of precision technologies for the last six surveys, ranked from highest to lowest for 2023. There was no survey in 2018, and the 2024 survey did not include farmer adoption. GPS autoguidance and yield monitors have the highest farmer adoption, with dealers reporting around three-fourths of the acres in their market areas managed using these technologies. By mistake, yield monitors and spray section controllers were not on the survey in 2017.

Operators on more than half of farm acres use sprayer section controllers, planter row controllers, and precision soil samples. Similar to Figures 1 and 2, changes over time in the retailer-estimated percent of market area of various PA technologies used by farmers are shown in Figures 3 and 4. Both time series do not include all technologies to provide for visual clarity (see reports online).

Some notable increases in recent years have been in cloud storage, going from 14% in 2017 to 40% of acres in 2023, planter variable down pressure, from 14% to 38%, and the use of any type of data analysis service, from 13% to 30%.

Table 7. PA Adoption Estimates from Retailers for the United States, 2017-23.

Technology	Percent of cropland area					
	2017	2019	2020	2021	2022	2023
Guidance/Autosteer	60	66	66	76	69	77
Yield Monitor		69	65	75	68	72
Sprayer Section Controllers		56	62	65	63	64
Planter Row or Section Shutoffs		45	46	52	51	54
Grid or Zone Soil Sampling	45	52	52	60	57	51
VRT Lime Application	40	41	44	56	52	43
VRT Fertilizer Application	38	39	44	51	49	43
Cloud Storage of Farm Data	14	21	29	36	42	40
Variable Down Pressure on Planter	14	29	31	40	41	38
Electronic Records/Mapping for Quality Traceability		20	21	21	34	31
Any Data Analysis Service	13	26	25	33	38	30
VRT Seeding	13	19	19	23	22	22
Satellite or Aerial Imagery	19	26	31	27	31	21
Soil EC Mapping	9	10	14	17	19	15
Variable Hybrid Placement Within Fields	7	11	17	15	14	12
UAV or Drone Imagery	6	9	12	10	17	10
Wired or Wireless Sensor Networks					18	9
VRT Pesticide Application	3	8	7	8	9	6
Autonomous Support Vehicle (grain cart) for Harvest				0	5	6
Selective Harvest for Quality Improvement		4	7	7	15	5
Crop Inputs Applied with a UAV/Drone						5
Chlorophyll/Greenness Sensors for N Management	3	5	5	6	8	4
Robotics/Automation on Harvester		0	1	1	3	3
Machine Vision Weed Detection on Sprayer						2
Robotics/Automation for Scouting				1	3	1
Robotics/Automation for Weeding		0	0	0	3	1

Source: CropLife/Purdue Precision Dealer Survey, years 2017-23.
Note: These are not random sample estimates, but the opinions of ag retailers in the Midwestern United States responding to the CropLife survey. There was not a survey in 2018.

One decade ago, there were no precision technologies being tracked by the CropLife/Purdue Survey that were used on more than half of farm acreage. Since then, many technologies have rapidly expanded in use, but some have been plateauing in the last few years. A plateau is generally inevitable after adoption has become widespread, but some practices that are not widely adopted have also shown recent downward trends.

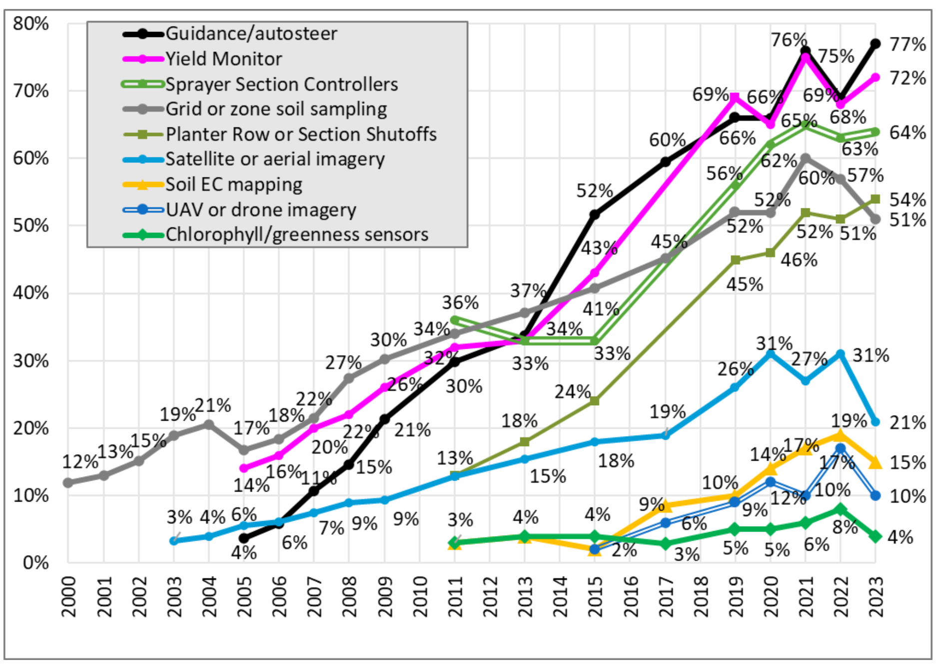

Figure 3. PA Adoption Estimates from Retailers for the United States, 2000-2023.
Source: CropLife/Purdue Precision Dealer Survey, years 2000-23.
Note: Yield monitor, sprayer section controllers, and planter row/section shutoffs were inadvertently omitted in the 2017 survey.

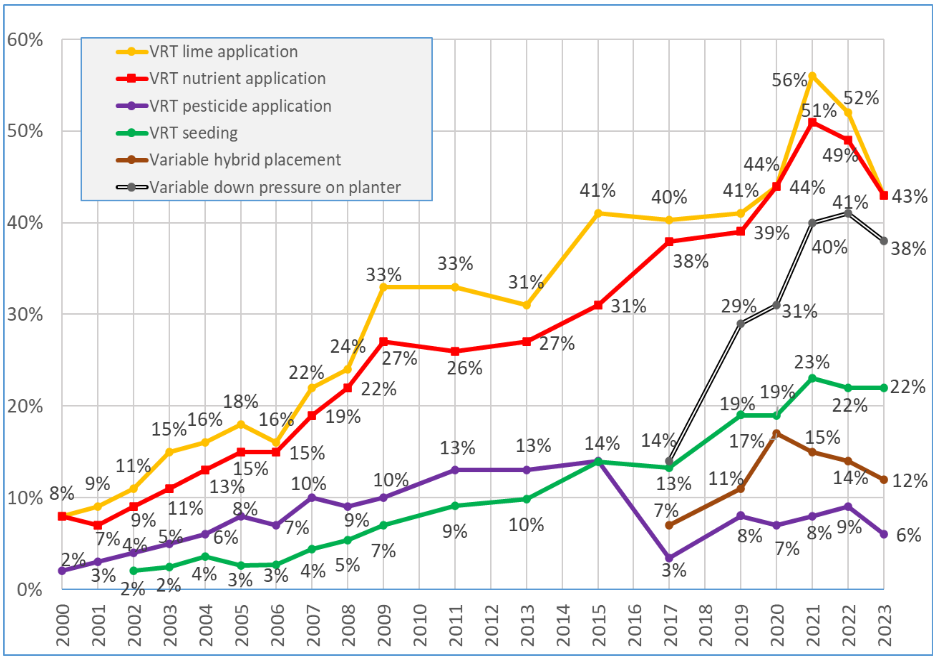

Figure 4. Adoption Estimates of VR Application/Placement/Pressure from Retailers for the United States, 2000-2023.
Source: CropLife/Purdue Precision Dealer Survey, years 2000-23.

Over the past 20 years, the percent of acres receiving grid or zone sampling has been higher, by a few points, than the percent of acres receiving VRT fertilizers, indicating that not all acres with precision sampling follow up with a precision application. Most PA practices show growth on farms in recent years, with the exception of VRT pesticide applications which fell back in 2017 and have partially rebounded.

3.1.7 Other Countries

A brief review of PA in four other countries is as follows:

- *France*: Various non-government surveys suggest that about 20% of farmers used yield monitors (2019-20), 10% of farmers used VRT (2018), and use of satellite-based remote sensing occurred on roughly 8% of area (2020). However, 50% of farmers used GNSS-based geolocation on their operations in 2019 (Observatoire des Usages de l'Agriculture Numérique, 2024).
- *Portugal (2019)*: The Census of Agriculture revealed the following adoption rates, in units of utilized agricultural area: georeferenced farm data (4%), soil moisture sensors (4%), VRT (2%), NDVI charts/vegetation indices (2%), and soil electrical conductivity charts (1%) (National Statistics Institute of Portugal, 2021).
- *Mexico (2018-19)*: The National Agricultural Survey indicated that 4% of farms used soil analysis and 1% used humidity sensors (National Institute of Statistics and Geography, 2019).
- *Estonia*: Data from Estonia's Information Technologies in Enterprises database are only available in aggregate for operations in the Agriculture, Forestry, and Fishing sector. In 2019, 5% of operations performed their own analysis of data from smart devices/sensors (rather than hiring external firms to perform the data analysis), while purchase of cloud computing services in 2020 was 67% (Statistics Estonia, 2024).

3.2 Subnational Adoption Estimates

To shed more light on the national estimates presented above, we provide estimates that are representative at a finer geographic scale.

3.2.1 Australia

Adoption of PA technology varies widely within Australia. Yield monitoring in 2011 ranged from 11% in Tasmania, the northeast area of New South Wales, and southwest Queensland to 41% in the northern area of Western Australia. By 2021, that range had moved up to 20% in Tasmania to 68% in the Western Australia Mallee/Sandplain. CTF has also increased in many agroecological zones. In 2021, CTF varied from 14% of cropped area in the Mallee area of South Australia and Victoria, up to 64% in the northeast area of New South Wales and southwest Queensland.

In most agroecological zones of Australia, the adoption of VRT fertilizer has varied mostly under 20% without any clear trend since the first GDRC survey that included this technology (Table 8). One exception is the northern wheat area of Western Australia near Geraldton, where use of VRT fertilizer almost doubled from 2014 to 2021. The 2021 adoption in that area is estimated at 38%. Some case studies indicate that productivity of soils in that area is highly variable, and farmers are using VRT to maximize productivity on the higher potential soils and avoid overfertilizing low potential areas (GRDC, 2017).

Table 8. VRT Fertilizer Use by Agroecological Zone in Australia, 2014, 2016, and 2021.

	Percent crop where VRT fertilizer used		
Agroecological Zone*	**2014**	**2016**	**2021**
NSW Central	13	8	5
NSW NE / QLD SE	7	4	10
NSW NW / QLD SW	1	0	3
NSW / VIC Slopes	7	8	7
QLD Central/Northern	3	0	14
SA Mid North / Lower EP	10	8	13
SA / VIC Bordertown, Wimmera	7	4	9
SA / VIC Mallee	22	21	23
TAS*	0	0	4
VIC High Rainfall	4	1	15
WA Central	9	7	8
WA Eastern	5	24	16
WA Mallee/Sandplain (Esperance	17	7	9
WA Northern	21	14	38
National Average	9	7	11

Source: GRDC Farm Practices Survey Report for years 2012, 2015, 2017 and 2021.
* Australian state abbreviations are: NSW = New South Wales; QLD = Queensland; VIC = Victoria; SA = Southern Australia; WA = Western Australia; TAS = Tasmania.

3.2.2 Canada

The Canadian PA adoption estimates show substantial variation from one province to another (Table 9). Autosteer adoption is highest in the prairie provinces of Manitoba, Saskatchewan and Alberta, where there are many large farms producing grains and oilseeds. Prairie province autosteer use is similar to that observed in the US. Autosteer use is much lower in provinces where farms are smaller and produce a wider range of products including fruit and vegetables (e.g., Newfoundland and Labrador, Nova Scotia, New Brunswick and British Colombia).

Table 9. Canadian Provincial Estimates of PA Adoption, 2021.

Province	Percent of farms with auto-steer	Percent of farms with VRA
Newfoundland and Labrador	NA	13
Prince Edward Island	20	21
Nova Scotia	7	12
New Brunswick	8	14
Quebec	12	9
Ontario	23	18
Manitoba	41	16
Saskatchewan	48	22
Alberta	31	16
British Colombia	4	9

Source: Statistics Canada, Census of Agriculture for 2021.
NA = Too unreliable to be published.

Consistent with estimates worldwide, VRA adoption is substantially lower than that of autosteer and varies over a narrower range among provinces. VRA use varies from 9% in Quebec and British Colombia, to 22% in Saskatchewan and second highest in Prince Edward Island (PEI). Percent VRA adoption in Ontario, Manitoba, and Alberta is in the high teens.

The Canadian census does not separate out technology use by farm type, but relatively high VRA adoption in PEI seems to be related to potato production. Though PEI is a relatively small province that plays a modest role in overall Canadian agriculture, PEI has more potato farms than any other Canadian province, and PA technology can substantially improve profitability of potato production.

3.2.3 England

Adoption of crop PA in England is highest in East of England (i.e., East Anglia), which is the leading area in England for production of cereals, oilseeds and other broadacre arable crops (Table 10). For soil mapping and yield mapping, the adoption rates in most regions are too small to be reliable. CTF estimates are reported for all regions, with the highest percentage (18%) in the East of England.

Table 10. Adoption of Crop PA by Region in England, 2019.

	Percent of farms			
Region	**Soil Mapping**	**Yield Mapping**	**Variable rate application**	**Controlled traffic farming**
North East	NA	NA	NA	9
North West	20	6	18	5
Yorkshire and The Humber	NA	NA	26	7
East Midlands	NA	NA	NA	6
West Midlands	NA	NA	23	6
East of England	48	38	42	18
South East including London	NA	NA	28	12
South West	21	NA	19	5

Source: Farm Practices Survey, DEFRA, year 2019.
NA = indicates that data have been suppressed to prevent disclosure of information about individual holdings.

3.2.4 United States

Sub-national differences in the ARMS-based adoption estimates occur at the level of "farm resource regions," groupings of U.S. counties with similar production characteristics (Table 11). For any crop-year, there are only minor differences across regions in use of VRT, though this technology tends to be adopted at the highest rates in the Prairie Gateway, which tend to have relatively large wheat- and corn-growing farms in Texas, Kansas, and surrounding areas. In any year, cross-regional differences in autosteer are larger. Roughly 93% of 2023 soybean acres in the Northern Great Plains region (Montana, North and South Dakota, and other areas) were managed using autosteer, consistent with the fact that some of the largest U.S. farms are located here.

Table 11. Adoption of Crop PA by Farm Resource Region in the United States 2021-23.

	Percent of regional crop area					
	2021 Corn		2022 Winter Wheat		2023 Soybeans	
Region	**VRT**	**Autosteer**	**VRT**	**Autosteer**	**VRT**	**Autosteer**
Heartland	37	69	18	49	35	71
Northern Crescent	33	52	22	56	30	58
Northern Great Plains	32	78	18	68	31	93
Prairie Gateway	47	73	16	56	44	72
Eastern Uplands					25	69
Southern Seaboard	34	40			35	50
Mississippi Portal					30	64

Source: Agricultural Resource Management Survey, USDA – Economic Research Service and National Agricultural Statistics Service, years 2021-23.
Note: Empty cells represent areas with lower sample sizes. In general, the Heartland includes areas of the U.S. Midwest, the Northern Crescent is the northern Great Lakes and Northeastern states, the Northern Great Plains are the northern areas of the Plains states, the Prairie Gateway includes the lower Plains states, the Eastern Uplands includes parts of Appalachia, the Southern Seaboard extends across the coastal South, and the Mississippi Portal contains counties near the lower Mississippi to the Gulf.

3.3 Newly Commercialized Technologies

The most detailed data on more recently commercialized technologies, such as drones for imagery and input application, robotics, and machine vision for targeting pesticide applications, comes from the USA. For example, USDA ARMS data show that, among operations using drones, an estimated two thirds of surveyed corn fields used the imagery for weed analysis in 2021, and over 40% of drone-adopting, surveyed wheat fields in 2022 and drone-adopting, surveyed soybean fields in 2023 (Table 12). Likewise, USDA ARMS estimated that, among operations using drones, in 2021 18% of corn fields and in 2022 9% of wheat fields used drones to apply pesticides. Because of the small number of farms reporting drone use, the confidence intervals for these drone use estimates are wide. The CropLife/Purdue Survey respondents report in 2023 that 10% of cropland in their market areas was managed using drone imagery and 5% used crop inputs applied with a drone (Table 7). Danish Statistics asks about satellite and drone imagery use in a combined question. In 2023, satellite or drone images were used by 10% of Danish farms on 30% of crop land (Table 3). The Hungarian Central Statistical Office (HCSO) estimates that the use of drones dropped from 1.4% in 2020 to 0.9% in 2023 (Table 5). Drone use change in Hungary may be due to regulations becoming stricter.

Table 12. Drone Use Purposes on U.S. Fields Managed with Drones.

	Percent of farms using drones					
	2021 Corn		2022 Wheat		2023 Soybeans	
Drone purpose	**Estimates**	**95% CI**	**Estimates**	**95% CI**	**Estimates**	**95% CI**
Weed analysis	66	[34, 88]	40	[13, 74]	45	[29, 61]
Spraying herbicide or fungicide	18	[6, 44]	9	[1, 43]		
Insect analysis	13	[4, 37]	29	[7, 68]		
Insect control	2	[1, 9]	8	[1, 50]		
Yield analysis	36	[13, 68]	34	[10, 70]	29	[15, 48]
Moisture analysis	24	[10, 49]	3	[0.3, 26]	18	[9, 33]
Equipment check	26	[10, 55]	12	[3, 34]		

Source: Agricultural Resource Management Survey, USDA – Economic Research Service and National Agricultural Statistics Service, years 2021 and 2022.

Note: As a measure of uncertainty in the estimates due to the small number of U.S. surveyed fields that report using drones, 95% confidence intervals are reported for both crop-years.

Robotics are starting to be used on farms around the world but are not widely tallied in national statistics. For the first time, in 2023, the Danish survey included a question about crop robotics. It showed that 1% of farms, representing 3% of crop area, used autonomous machines. The Hungarian Central Statistical Office (HCSO) reports that 0.7% of farms used robots in 2020 and that reached 1.7% by 2023 (Table 5). Information which rely on business sources show substantial growth in use of robotics. The 2024 FutureFarming crop robot catalogue shows 60 robots being marketed by some 50 medium and small companies, plus two companies with tractors that can be operated autonomously and seven companies with retrofit kits to convert conventional tractors for autonomous use. Major farm machinery companies like John Deere and CNH are commercializing autonomous crop equipment. Respondents to the 2023 CropLife/Purdue Survey indicated that 6% of the cropland in their market area was farmed using autonomous grain carts at harvest (Table 7). That same survey showed that 3% of cropland was managed with robotics/automation on the harvester, 1% with robotic/automation scouting and 1% robotic/automation weeding. The Observatory for Use of Digital Agriculture shows 600 robots being used in French agriculture, mostly for mechanical weeding (Observatoire des Usages de l'Agriculture Numérique, 2024).

Similar to crop robotics, machine vision weeding and targeted pesticide application is beginning to be used commercially but has not yet attracted the attention of national statistical agencies. Business media reports the potential for 90% reduction in the amount of herbicide applied with targeted application technology (Economist, 2024). In the USA, respondents to the 2023 CropLife/Purdue Survey indicated that 2% of crops in their market area was managed using a sprayer equipped with machine vision.

4. Discussion and Implications

Precision agriculture has been compared to a toolbox from which farmers pick the technologies that they need. The data continue to show farmers being selective in their technology choices. Some of the first-generation PA technologies introduced in the 1990s, like GNSS guidance, have become standard practice worldwide wherever there is mechanized farming in large field crop/broadacre crop operations. Adoption of other aspects of the PA vision have been successful in niche applications but have not achieved widespread, high-level adoption. For example, some data suggest that VRT fertilizer has been widely adopted for sugar beet production in the Red

River Valley of Minnesota, USA, and in certain watersheds in Ohio, but overall VRT fertilizer adoption has been modest, with the highest national statistics showing 30%-40% adoption for certain regions and/or crops. This adoption pattern has been attributed largely to differences in profitability and ease of use of the first-generation technologies (Lowenberg-DeBoer, 2018).

Among the second wave of PA technologies commercialized in the first decade of the 21st century, the pattern has been similar. Some technologies have been widely adopted, while others stagnate. Widely adopted technologies among this second wave are GNSS sprayer boom control and seeder row shutoffs. Drones for imagery and data collection are widely used in certain areas, but spraying and other input application using drones is less common. One of the major constraints to drone use for input application is regulatory in nature. Where the rules are flexible, drone spraying is growing rapidly. Anecdotal information suggests this is the case in China and Brazil. In the European Union and the United Kingdom, drone spraying is highly regulated and allowed only in specific circumstances. For example, in the United Kingdom, drone spraying has been allowed for control of bracken on steep hillside pastures in inaccessible areas where the alternative would have been application by a person on foot using a backpack sprayer. In the EU, drone pesticide application is sometimes allowed for steeply sloped vineyards. Drone input application is growing in the USA as a more flexible regulatory framework is developing.

Commercial experience with crop robotics and machine vision technologies in agriculture is still limited. Research suggests that these technologies have great economic potential (e.g. FAO, 2022; Lowenberg-DeBoer, 2024), but reliability, cybersecurity, and other practical aspects remain to be shown. As with drones, the regulatory framework may strongly influence adoption patterns for crop robotics (Lowenberg-DeBoer et al., 2021). Notably, the US state of California and the EU have required that crop robots must have on-site human supervision. The economics of robotics suggest that, with current technology, it is often more profitable for an on-site human to *operate* the machine rather than *supervise*. The United Kingdom has tried to proactively guide crop robot use by developing a code of practice for mobile autonomous agricultural machines that encourages risk management plans to mitigate potential risk (BSI, 2023).

5. Conclusion

Using information primarily derived from publicly-accessible sources, we have sought to provide a comprehensive and more accurate depiction of the current state of PA use worldwide than currently exists. Emphasis has been placed on estimates from nationally-representative, reliable surveys administered by national statistics offices (NSOs) so as to 1) minimize ambiguity from estimates based on small, unrepresentative samples, and 2) highlight data sources that are more likely to be used to inform agricultural policymaking in some settings. Our findings suggest automated steering systems and some related GPS technologies (e.g., section controllers and shutoffs) are among the most commonly used components of PA in countries where they are feasible. Yield monitoring, soil mapping, and VRT are used to a lesser extent and exhibit substantial variation between and across countries. Drone use is limited but may be expected to increase to the extent that the number of cost-effective use cases expand, and regulatory oversight further develops. Robotics and full automation technologies remain in the early stages of commercialization but are growing increasingly sophisticated, reliable, and economically viable.

Our study points to the utility of accurate, objective estimates of PA adoption and highlights the necessity of large-scale data collection efforts by NSOs as a prerequisite for better understanding the net benefits of these technologies to farmers worldwide. Fortunately, such data collection efforts continue to be bolstered by major national and international survey initiatives. For example, increased reporting requirements from the European Commission on digital agriculture, resulting in new data collection via the EU's Integrated Farm Survey, will generate a set of harmonized, country-level adoption estimates for the first time in EU history. Inasmuch as researchers will be able to access the operation-level microdata underlying these and similar estimates, the discipline will benefit from studies using data expected to be more detailed and less prone to bias.

Several directions for future research emerge from our study. Our methodology did not allow for a thorough review of NSOs in the greater part of Central and South America, Africa, and the Middle East. Research that broadens the geographic scope of our analysis, with adjustments to the set of precision technologies deemed feasible and appropriate for agriculture in these regions, is a necessary addition to a literature that has tended to focus on large-scale farming among high-income countries. In a similar vein, publicly-available datasets and documentation from national *agricultural* offices should be systematically explored so as to include any adoption estimates that may have been unintentionally omitted in our study. Estimates from these agencies—if backed up by large-sample, unbiased data from rigorous statistical methods—are clearly valuable for expanding our knowledge base, as are similarly-sourced estimates from universities and other research organizations.

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