GAO

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Report to Congressional Committees

January 2024

TECHNOLOGY ASSESSMENT

Precision Agriculture

Benefits and Challenges for Technology Adoption and Use

GAO-24-105962

The cover image displays examples of precision agriculture technologies being used on farm fields.

Cover source: GAO (illustrations). | GAO-24-105962

Highlights of GAO-24-105962, a report to congressional committees

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Why GAO did this study

Precision agriculture involves collecting, analyzing, and taking actions based on data. It can help the agricultural sector meet increasing demand for food products, while also helping farmers improve efficiencies such as through reduced input costs.

The Advancing IoT for Precision Agriculture Act of 2021, contained in what is commonly referred to as the CHIPS and Science Act of 2022, included provisions for GAO to conduct a technology assessment and review federal programs.

This report examines (1) emerging precision agriculture technologies and precision agriculture technology adoption; (2) federal programs providing support for precision agriculture; (3) benefits and challenges of adopting and using precision agriculture technologies; and (4) policy options that could address challenges or help enhance benefits of adopting and using precision agriculture technologies.

To conduct this technology assessment and review, GAO reviewed scientific literature and other key reports; interviewed officials and representatives from government, industry, academia, and associations; conducted two site visits to observe technology operations and obtain stakeholder perspectives; and convened a 3-day virtual expert meeting in collaboration with the National Academies of Sciences, Engineering, and Medicine. GAO is identifying policy options in this report.

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What GAO found

Precision agriculture technologies can improve resource management through the precise application of inputs, such as water, fertilizer, and feed, leading to more efficient agricultural production. Precision agriculture can be implemented through a suite of technologies that can be used in isolation or in conjunction with other technologies. Examples of emerging precision agriculture technologies are in the table below.

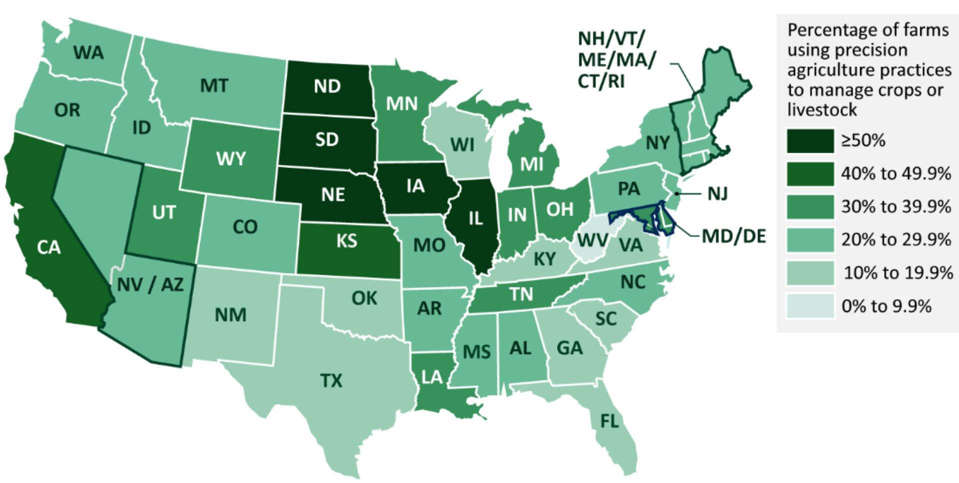
Examples of emerging precision agriculture technologies

Technology	Description
Remote sensing platforms	Drones and ground robots can provide new ways to provide measurements on crop conditions.
In-ground sensors	Provide farmers near-real-time information on soil and plant properties such as temperature, moisture, and nutrients.
Targeted spray systems	Use machine learning to precisely spray in a specific spot.
Automated mechanical weeders	Use machine learning to start and stop weeding blades to avoid damaging the growing crops.

Source: GAO summary of literature, interviews, and agency documentation. | GAO-24-105962

While precision agriculture technologies, such as variable rate fertilizer applications and yield monitoring, have been available since the 1990s, only 27 percent of U.S. farms or ranches used precision agriculture practices to manage crops or livestock, based on 2023 U.S. Department of Agriculture (USDA) reporting.

Use of precision agriculture practices by U.S. farms, June 2022–June 2023



Source: GAO summary of data reported in 2023 by the U.S. Department of Agriculture; Map Resources (map). | GAO-24-105962

Federal agencies support precision agriculture adoption, research and development, education, and training. USDA supports precision agriculture technology adoption with financial assistance and loan programs, such as through payments for implementing practices that provide a conservation benefit. USDA and the National Science Foundation (NSF) have provided almost $200 million for precision agriculture research and development funding in fiscal years 2017—2021. This funding includes partnerships between the two agencies to support artificial intelligence (AI) research institutes.

Benefits to using precision agriculture technologies include:

- **Increased profits**. Farmers can increase yields and thus profits with the same amount of inputs or achieve an equivalent yield with fewer inputs.
- **Reduced application of crop inputs.** Technologies can reduce the application of crop inputs such as fertilizer, herbicide, fuel, and water. They can also address water scarcity by promoting the efficient use of water in agriculture.
- **Environmental benefits**. Technologies can prevent excessive use of chemicals and nutrients in a field, potentially reducing runoff into soil and waterways.

Challenges limiting the broader adoption and use of precision agriculture include:

- **High up-front acquisition costs**. Acquisition costs for the latest technologies can be prohibitive for farmers with limited resources or access to capital.
- **Farm data sharing and ownership issues**. Concerns regarding farm data sharing and ownership can pose obstacles to the widespread use of AI in agriculture.
- **Lack of standards**. An absence of uniform standards can hamper interoperability between different precision agriculture technologies.

GAO examined three policy goals and associated options that could help address adoption challenges or enhance the benefits of precision agriculture technologies. These policy options identify possible actions by policymakers, which include Congress, federal agencies, state and local governments, academic and research institutions, and industry. In addition, for each policy goal, policymakers may choose no additional policy interventions, maintaining the status quo by continuing existing activities.

Policy Goals and Options That Could Address Challenges or Help Enhance Benefits of Adoption and Use of Precision Agriculture Technologies

Policy goals and options	Implementation approaches	Opportunities and considerations
Encourage greater adoption and use (report p. 43)		
Provide additional incentives or other financial support	• Consider modifying eligibility criteria for existing governmental financial assistance programs. • Consider expanding levels of financial assistance through new or existing programs.	• Consider what types of programs to provide to farmers, such as loan guarantees or grants. • Overall program cost, the extent to which equipment acquisition and operating costs are covered, and the potential trade-off with other agricultural programs could be factors. • Programs could be devised to realize goals, such as environmental protection and food insecurity.
Better understand and quantify benefits and costs	• Support development of analytical tools and models to quantify benefits and costs.	• Analytical tools could be configured for farm geography, soil type, and other factors. • Farmer confidence could increase if estimates of benefits are data-driven and based on real-world experiences.
Promotion and outreach to farmers	• Consider expanding Extension services to enable development of more expertise and technical support to farmers. • Increase on-field demonstrations.	• The extent to which federal agencies could provide more training, such as through USDA service centers. • Technology companies and dealerships could assume more of a role in educating or helping farmers.
Encourage further innovation (report p. 48)		
Conduct research and development to improve on-farm data gathering and analysis	• Support research for in-ground sensors for measuring soil conditions. • Examine ways that remote imagery, such as from drones, can be more effectively used to gather data.	• In-ground sensors can provide more detailed information on soil conditions, which can enable farmers to further optimize the application of inputs to increase yields and minimize costs. • New remote imagery sensors from drones or ground robots promise to provide greater resolution, more frequent data, and quicker data delivery than traditional satellite sources.
Promote the development and use of standards	• Promote data standards that could improve equipment interoperability. • Financial assistance programs could consider specifying that precision agriculture equipment comply with certain standards.	• Standards can improve interoperability and compatibility among different devices and platforms. • A lack of standards could result in challenges assessing the quality of the data derived from farm measurements. • Consider the level of federal involvement in standards development and use.
Manage greater amounts of data (report p. 52)		
Enhance data analysis	• Support the development of software to help farmers better manage their farms. • Examine how AI and machine learning could help facilitate analysis and interpretation of data.	• Data analytics and high-performance computing approaches promise to generate valuable information for farmers but are dependent on the availability of large amounts of data. • Farmers may have tools, such as yield monitors, to help identify outcomes of decisions, but few analytical tools and software are available to enhance analysis and translate farm data into actionable decisions.
Encourage data sharing	• Develop a governance framework to manage and store agricultural data and its access. • Establish easy-to-understand data license agreements and codes of conduct to enable better flow of data.	• Farmers often do not trust the ways farm data are being collected and managed; thus, terms and conditions regarding data use should be simple, transparent, and accountable. • Farmer concerns about data sharing include a potential loss of competitive advantage, data security, and additional regulatory scrutiny may increase as AI is increasingly used for data analysis.

Source: GAO. | GAO-24-105962

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Abbreviations

AFRI	Agriculture and Food Research Initiative
AI	artificial intelligence
AMS	automated milking system
ARMS	Agricultural Resource Management Survey
ARS	Agricultural Research Service
CEAP	Conservation Effects Assessment Project
CES	Cooperative Extension Service
CSP	Conservation Stewardship Program
EPA	Environmental Protection Agency
EQIP	Environmental Quality Incentives Program
ERS	Economic Research Service
FCC	Federal Communications Commission
FMIS	farm management information system
FSA	Farm Service Agency
GPS	global positioning system
NASA	National Aeronautics and Space Administration
NASS	National Agricultural Statistics Service
NIFA	National Institute of Food and Agriculture
NRCS	Natural Resources Conservation Service
NSF	National Science Foundation
R&D	research and development
UAS	Uncrewed aircraft system
UGV	Uncrewed ground vehicles
USDA	United States Department of Agriculture

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
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Congressional Committees

With the world's population estimated to grow to nearly 10 billion by 2050, global demand for agricultural products of food, fuel, and fibers is increasing. The ability of farmers to meet this increasing demand is hindered by several factors, including a shrinking agricultural workforce, environmental impacts, and rising production costs.

Precision agriculture technologies can be part of the solution to help the agricultural sector meet the increasing demands. These technologies are designed to collect and analyze data and provide suggestions to farmers on ways to increase farm efficiencies, such as reducing input costs while increasing yield or reducing on-farm labor requirements. The "classic" precision agriculture package in the 1990s of GPS-enabled soil sampling, variable rate fertilizer applications, and yield monitoring has advanced over the years to take advantage of new sensors and analysis techniques such as artificial intelligence.

We prepared this report in response to provisions in the Advancing IoT for Precision Agriculture Act of 2021, included in what is commonly referred to as the CHIPS and Science Act of 2022.[1] We examined (1) precision agriculture technology adoption and emerging precision agriculture technologies, (2) federal programs providing support for precision agriculture, (3) benefits and challenges of adoption and use of precision agriculture technologies, and (4) policy options that could help enhance benefits or address challenges related to adoption and use of precision agriculture technologies.

To address these objectives, we conducted a literature search; interviewed officials and representatives from government, industry, academia, and associations; conducted two site visits; and convened a 3-day expert meeting from May 2 to 4, 2023. See appendix I for the full objectives, scope, and methodology used in this report and appendix III for the list of participants in our expert meeting.

We conducted our work from April 2022 to January 2024 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for the findings and conclusions in this product.

[1]Pub. L. No. 117-167, div. B, tit. III, subt. E, § 10361(e), 136 Stat. 1366, 1567-68 (Aug. 2022). This section includes provisions for GAO to provide a technology assessment of precision agriculture technologies and a review of federal programs that provide support for precision agriculture, both of which are included in this technology assessment.

1 Background

In 2022, the U.S. Department of Agriculture (USDA) estimated there were 2 million farms[2] in the United States, covering approximately 893 million acres.[3] At that time, the average farm size was 446 acres. Smaller farms that produced up to $100,000 in goods accounted for approximately 81 percent of all farms in 2022 but only about 30 percent of all farmland. Large farms that produced $500,000 or more in goods in 2022 accounted for approximately 7 percent of all farms and 41 percent of total farmland.

Farms produce agricultural products, also known as commodities. These products fall within three categories: field crops, specialty crops, and animals/animal products, also referred to as livestock.[4]

To grow crops, farmers generally adhere to the following cycle of activities each growing season:

- **Pre-planting work**. Prior to planting, the soil needs to be prepared. This can include applying chemicals to kill weeds or to adjust the nutrients in the soil. Additionally, planning and decisions are conducted on what, when, where and which specific seeds to grow.
- **Planting**. Farm equipment including seed drills or planters are used to plant seeds for field crops. The application of inputs such as fertilizer can also take place during planting.
- **Input applications**. Inputs include seeds, water, pesticides, and fertilizer.[5] When applied in proper quantities and at appropriate times, inputs help crop yields. Improper application of inputs can create detrimental environmental impacts, particularly on water quality.
- **Harvest**. Field crops are harvested by machine, while many specialty crops are typically harvested by hand, although in certain cases, specialty crops may also be harvested by machine.
- **Post-season evaluation**. Assessing the results of the season to determine what changes are needed for the next growing season.

[2]Since 1974, the Census of Agriculture has defined a farm as any place that produced and sold, or normally would have been sold, at least $1,000 of agricultural products during a given year. U.S. Department of Agriculture, National Agricultural Statistics Service. *Farms and Land in Farms 2022 Summary* (Feb. 2023).

[3]The 893 million acres consists of agricultural land used for crops, pasture, or grazing. It also includes woodland and wasteland not actually under cultivation or used for pasture or grazing. U.S. Department of Agriculture, *Farms and Land in Farms 2022 Summary*.

[4]In this report, we focused on four agricultural products: corn and soybeans (field crops); grapes (specialty crops); and dairy (livestock). These products were selected based on economic impact; acres farmed (for field and specialty crops); pounds produced (for livestock); regional diversity; and existing precision agriculture use cases where benefits and challenges could be identified.

[5]Pesticides kill or control forms of animal and plant life considered to damage or be a nuisance in agriculture. The term pesticide includes herbicides (substances that destroy or control weeds and other unwanted vegetation) and insecticides (substances that kill or control insects). Fertilizers are used to increase soil's capacity to support plant growth.

1.1 Agricultural equipment

To produce commodities, farms use a variety of equipment, much of it specialized for specific farm activities.[6]

1.1.1 Field and specialty crop equipment

Tractors are largely used to pull farm equipment. Tractors can be designed for different crop types. For example, tractors used for field crops can be large, while tractors used for specialty crops such as at orchards are adapted to meet the narrower gaps between orchard rows.

Planters are farm machines typically attached behind a tractor, mainly used for sowing seeds. A *seeder* or *seed drill* can also be used to sow seeds. Both types of equipment plant seeds at an appropriate depth and distribution in the soil. The size of the seed can influence which machine is used by the farmer during planting field crops.

Sprayers apply liquid inputs such as herbicides or fertilizers to a crop and can come in many forms. Common sprayers found in commercial agriculture include self-propelled, large capacity, and tow-behind spraying equipment pulled by tractors.

When a crop has ripened and needs to be gathered, it is ready for harvest; the method of harvest is defined by the crop being grown. For field crops such as corn, soybeans, wheat, and oats, a *combine harvester*, also known as a *combine*, combines harvesting activities—cutting and separating grains—into a single process. In contrast, fruits such as strawberries and apples typically are handpicked to harvest the crop. Some fruits, including grapes, can be harvested using mechanical equipment.

1.1.2 Dairy livestock equipment

There are two primary designs for milking facilities. One involves moving milking equipment to cows, such as a tie stall or stanchion barn. The other involves moving cows to the equipment, such as a parlor.[7] As of 2014, the majority of dairy farms with fewer than 100 cows were milked in a tie stall or stanchion barn, while the majority of dairy farms with over 100 cows were milked in a parlor, according to USDA.[8]

Milking methods include hand milking and machine milking. In machine milking, a constant vacuum is applied to the end of a teat to extract the milk and carry it to a container. A milking cluster consists of four teat cup assemblies that attach to the cow. At the end of milking, the cluster can be removed by a human or automatically detach. Automatic takeoffs (or detachers) are designed to remove milking clusters from the teats once milk flow decreases to a specified level. Using properly adjusted and maintained takeoffs prevents over-milking and maintains

[6]We limited our scope of farm activities to those occurring in the field for field and specialty crops, and those occurring in the barn directly related to milk production.

[7]A stanchion is a housing in which a cow is restrained to a particular stall in a device with two rails that close around the cow's neck after she enters the stall. A tie stall is a housing in which a cow is restrained to a particular stall by a neck collar attached to the stall by a chain. Parlor layouts and types include rotary, herringbone, and parallel.

[8]U.S. Department of Agriculture, Animal and Plant Health Inspection Service. *Dairy 2014: Dairy Cattle Management Practices in the United States, 2014* (Fort Collins, CO: Feb. 2016).

optimum teat-end condition. Almost half of all dairy farms (49.1 percent) used automatic takeoffs, according to 2014 USDA data.[9] Almost all dairy farms with over 500 cows (93.5 percent) used automatic takeoffs, while only 19.9 percent of dairy farms under 100 cows used automatic takeoffs.

1.2 Precision agriculture technologies

There is no one common definition of precision agriculture. However, it is generally understood as collecting data that are specific in location or time and using the data to improve resource management through the precise application of inputs, such as water, fertilizer, and feed, leading to more efficient agricultural production. Terms such as digital agriculture and smart farming are also used to describe this process.[10] Precision agriculture is implemented through a suite of technologies, which can be used in isolation or in conjunction with other technologies.

[9]The most recent national study on the health and management of U.S. dairy operations was from 2014 data and issued in 2016. U.S. Department of Agriculture, Animal and Plant Health Inspection Service. *Dairy 2014: Milk Quality, Milking Procedures, and Mastitis on U.S. Dairies, 2014* (Fort Collins, CO: Sept. 2016).

[10]For the purpose of our work, we treat these phrases as interchangeable with precision agriculture.

1.2.1 Field and specialty crop technologies

Precision agriculture technologies used for both field and specialty crops are the same. Specific implementations of a technology and how it operates will vary between field and specialty crops, according to stakeholders. Figure 1 describes these technologies.

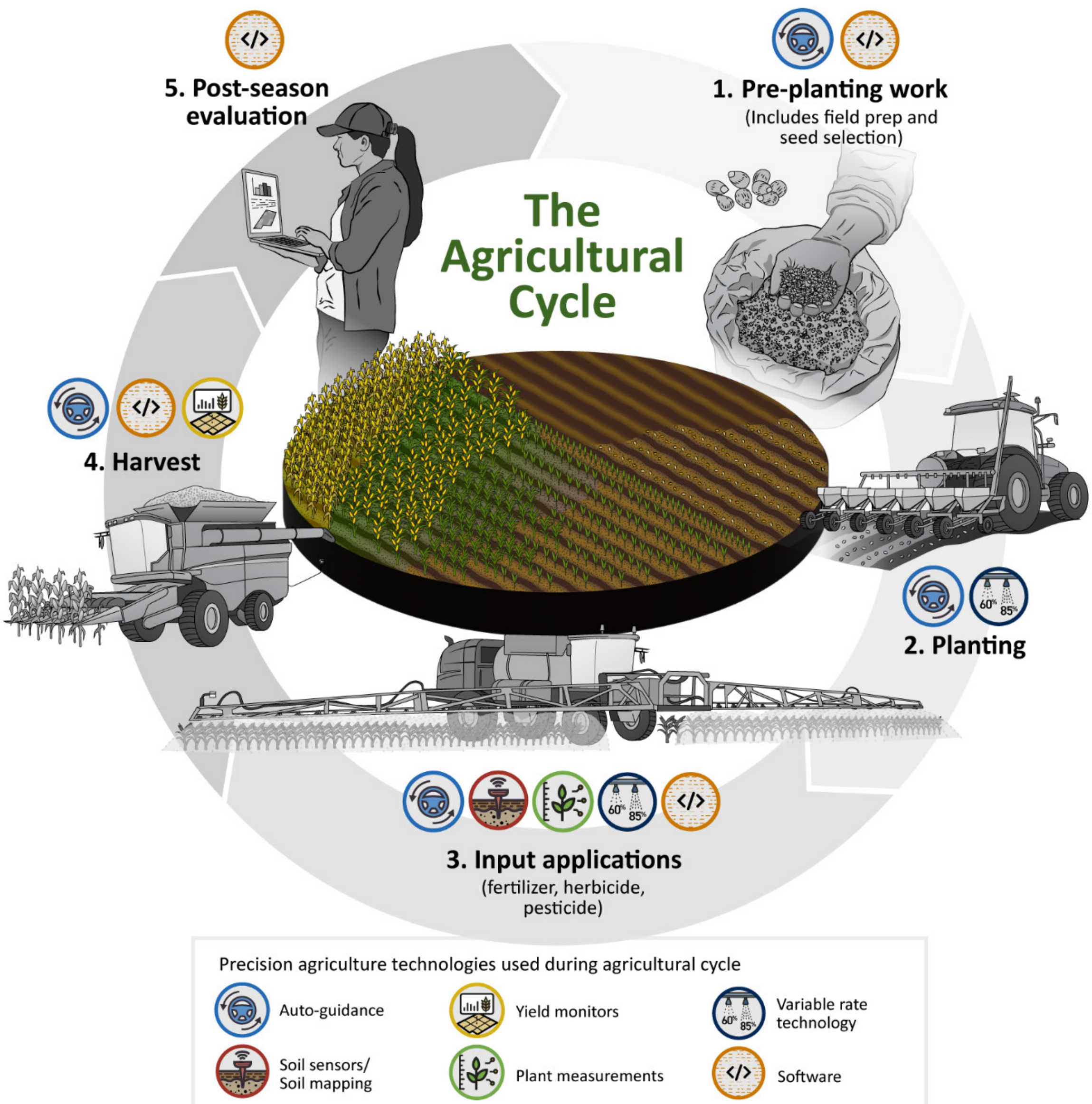
Figure 1: Precision agriculture technologies used in field and specialty crops

Technology	Description
Auto-guidance	A guidance system that steers agricultural equipment with accuracy within centimeters. Newer equipment has this technology embedded, and add-on systems can be retrofitted on older equipment. Auto-guidance can provide for near-total automated steering while in the field. With auto-guidance, equipment can repeatedly drive along designated paths. Sometimes referred to as auto-steer.
Soil mapping	Soil mapping is used to identify soil properties at different locations. With a soil map, a farmer can decide on actions to prepare soil for growing agricultural commodities or on alternative land use options. To create a soil map, different technologies exist, including: • Soil sampling: measures soil factors including composition and nutrients. Though accurate, soil sampling can be expensive for large fields given the large number of samples required to generate an accurate soil map. • Electromagnetic sensing: measures the electrical characteristics of the soil, which reflect the soil's composition. • In situ sensors: can measure soil moisture.
Yield monitors and yield mapping	Yield monitors measure the harvest of a crop and tag the yield with a latitude and longitude coordinate. Data from the yield monitor are used to create a yield map to quantify and characterize within-field production variability. Yield monitors are widely available for field crops, but they are not widely available for specialty crops. Other techniques such as overhead imagery can estimate crop yields for specialty crops.
Plant measurements	Plant characteristics can be measured by calculating vegetative indices using components of the electromagnetic spectrum. These indices provide estimates of characteristics, such as the amount of live green vegetation. Measurements are normally made remotely, with satellites, airplanes, or uncrewed aerial vehicles.
Variable rate technology	A system of sensors, controllers, and machinery that uses an application guidance map to direct the application of an input, such as herbicide or fertilizer, to a specific, identifiable location. Variable rate technology is dependent on measured farm data to build the application guidance map.
Farm management information systems (FMIS)	FMIS, a specific kind of software, is technology designed to assist farmers with performing data analysis from measured variability data, generate application guidance maps, and provide suggestions on specific farm operations, such as fertilization and irrigation scheduling to maximize yield and minimize costs. FMIS relies on data gathered by other precision agriculture technologies to make suggestions.

Source: GAO review of literature and agency documentation (text); GAO (icons). | GAO-24-105692

Precision agriculture technologies have a role throughout the entire agricultural cycle. See figure 2 for a depiction of the agricultural cycle, including illustration of where precision agriculture technologies are used with field crop production.

Figure 2: Agricultural cycle with precision agriculture technology applications



Source: GAO (analysis, icons, and illustrations). | GAO-24-105962

1.2.2 Dairy livestock technologies

Precision agriculture technologies for livestock perform different actions than those used for field and specialty crops.[11] However, the purpose of the technologies is the same—collection, analysis, and actions from data to improve outcomes. In the case of dairy, analyzing data gathered on the cows and the milk they produce enables farmers to take actions to optimize milk output and the health of the cow.

- **Activity monitors**. Wearable sensors that can be leg bands or collars (see fig. 3). The sensors monitor animal movement and collect other data such as body temperature, step counts, and eating habits that provide information about the health of the cow. Data are loaded into software for analysis.
- **Feeding technologies**. Autonomous robots can perform routine operations such as pushing feed closer to cows or delivering feed to cows without human oversight (see fig. 3). Feeding can also be supported by software that formulates cows' nutritional requirements while reducing diet costs and increasing milk production.

Figure 3: Autonomous feed delivery robot and activity monitor

Source: GAO. | GAO-24-105962

[11]Some dairy farms grow their own feed and may use precision agriculture technologies for field crops for their forage crops, according to stakeholders we interviewed. Forage crops are crops grown specifically for livestock consumption.

- **Automatic milking systems (AMS)**. AMS is a milk system where the cow voluntarily enters the milking unit (see fig. 4). Once in the unit, a robotic system of sensors, controllers, and machinery automates the milking process with little or no human oversight. The robotic system automatically cleans, sterilizes, and prepares the cow's teats for milking; automatically applies the teat cups; and analyzes the milk's characteristics. These data are recorded separately for each cow, allowing the farmer to make decisions on individual cows, rather than for an entire herd. A single automatic milking system unit can accommodate analyzes the milk's characteristics. These data are recorded separately for each cow, allowing the farmer to make decisions on individual cows, rather than for an entire herd. A single automatic milking system unit can accommodate approximately 60 cows in a 24-hour period.[12] A farm would need to purchase multiple AMS units for herds larger than 60 cows.

Figure 4: Automated milking system

Source: GAO. | GAO-24-105962

- **Farm management information systems (FMIS)**. Technology designed to assist with performing analysis of measured data from sources such as milk analysis or activity monitors and to generate individual alerts when a cow's condition deviates from what is considered normal. A computerized milking system that enables electronic data collection is one type of FMIS and can be attached to any machine milking system.

[12]As a voluntary milking system, the cow may choose to visit the AMS multiple times during the 24-hour period for milking.

1.2.3 Enabling technologies

Global Positioning System

Satellite navigation systems have become integral to many applications where mobility plays an important role. Within agriculture, satellite navigation began playing a major role when GPS equipment guidance was commercialized in the late 1990s. Since then, GPS has become an enabling technology for precision agriculture and is now used for field mapping, soil sampling, auto-guidance, crop scouting, variable rate applications, and yield mapping.

GPS-enabled smartphones can provide location accuracy to 5 meters. Greater location accuracy for agricultural equipment can be accomplished through differential correction systems enabling centimeter-level accuracy, in real-time, and while on the move.[13]

Broadband internet

Broadband internet has become critical for daily life.[14] The global internet reaches users—homes, businesses, and community institutions—via three primary components. The first component, referred to as the internet backbone, consists of high-capacity fiber-optic cables transmitting data between core networks. The second component, referred to as the "middle-mile" infrastructure, connects local networks to the global network. The third component or "last-mile" is where service providers connect end users to the internet. Discussions about broadband requirements in agriculture can reference the "last-acre" to indicate additional requirements beyond those in "last-mile" infrastructures.

Broadband internet plays an important role in operating a farm, but not all precision agriculture technologies rely on broadband. It is an enabler of precision agriculture technologies, facilitating the transfer of data collected in the field to software for data analysis. Data can be transferred through wireless technologies, such as Bluetooth or Wi-Fi, or through a physical connection, such as a universal serial bus (USB) drive. Some software technologies require uploading the data into their platforms in the cloud to conduct the data analysis.[15] Recommendations, such as application guidance maps using variable rate technology, are downloaded and transferred to equipment. According to USDA, peer-reviewed research on the required connection speeds for precision agriculture technologies is not yet available.[16]

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[13]Differential GPS uses a base station with a known location that compares the measured GPS position to the known location and provides corrections. These corrections enable other GPS equipment to improve their location accuracy.

[14]Broadband commonly refers to internet service with speeds generally faster than dial-up connections. The Federal Communications Commission's (FCC) current fixed speed benchmark for broadband used as part of determining whether advanced telecommunications capability is being deployed in a reasonable and timely fashion is 25 megabits per second (Mbps) download and 3 Mbps upload. See Federal Communications Commission, *Inquiry Concerning Deployment of Advanced Telecommunications Capability to all Americans in a Reasonable and Timely Fashion*, 36 FCC Rcd. 836, 841, para. 12 (2021) (Fourteenth Broadband Deployment Report).

[15]The National Institute of Standards and Technology defines cloud computing as a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.

[16]U.S. Department of Agriculture, *A Case for Rural Broadband: Insights on Rural Broadband Infrastructure and Next Generation Precision Agriculture Technologies* (Apr. 2019).

1.3 Commercial entities and government agencies support the agricultural sector

Commercial enterprises. Commercial entities provide a wide range of support to farmers. They can assist farmers in the efficient running of their farm, enabling the farmers to increase yields and profits. These entities can generally be classified into four groups:

- **Equipment manufacturers and dealers**. Equipment manufacturers design and build farm machinery, while dealers sell these products to farmers. The equipment includes tractors, planters, combines, and dairy machinery such as automated feeders or AMS.
- **Input manufacturers and retailers**. Input manufacturers research, design and produce agricultural inputs such as seed and fertilizer, while retailers sell these products to farmers. For livestock, inputs can include feed and animals. Retailers can provide knowledge and recommendations to farmers on best practices using specific inputs.
- **Agronomists and consultants**.[17] These specialists provide knowledge and advice to farmers on how to increase yield while being cost-effective. This advice can include recommendations on specific input types, application methods, and land use or land preparation. For livestock, this group includes veterinarians.
- **Service providers**. These are companies that provide specific services to farmers throughout the agricultural cycle. This could include machine maintenance, data acquisition, data analysis, and harvest operations. Equipment and input manufacturers may also provide their own service products, such as data analysis software.

Government agencies. Two federal agencies, USDA and the National Science Foundation (NSF), are largely responsible for current support to precision agriculture research, development, adoption, education, or training.

USDA carries out programs related to farming, rural economic development, and food. Within USDA, four agencies have a role in the research, development, adoption, and use of precision agriculture technologies:

- **Agricultural Research Service (ARS)**. ARS is USDA's principal research agency performing intramural research to deliver solutions, which include precision agriculture.[18]
- **Farm Service Agency (FSA)**. FSA administers loan programs that can assist with the adoption of precision agriculture technologies.
- **National Institute of Food and Agriculture (NIFA)**. NIFA is a USDA extramural research agency that provides funding to universities and other organizations to support the advancement of agriculture-related

[17]Agronomists advise farmers on soil health, disease prevention, and how to improve crop production and quality.

[18]Intramural research is conducted by employees of a federal agency in or through government-owned, government-operated facilities such as laboratories and clinics.

sciences, including precision agriculture technology research and development (R&D), education and Extension.[19]

- **Natural Resources Conservation Service (NRCS)**. As part of their mission of conservation, NRCS administers loan programs that can assist with the adoption of precision agriculture technology.

NSF funds research and education projects across all fields of fundamental science and engineering, including domains that may support precision agriculture.

The U.S. Cooperative Extension System (CES)—commonly referred to as Extension—is a mix of federal and state support. Established through the Smith-Lever Act of 1914, CES enables states to provide farmers with information from agricultural research and to encourage them to adopt improved farming methods. Extension is implemented through state and Tribal land-grant institutions, with federal funding and support provided through NIFA and nonfederal matching funds.[20]

[19]Extramural research is conducted by nonfederal scientists and personnel working at universities and academic or other institutions, who receive grants and other types of federal funding to conduct research.

[20]Act of May 8, 1914, ch. 79, 38 stat. 372 (codified as amended at 7 U.S.C. §§ 341-349).

2 Adoption of Currently Available Precision Agriculture Technologies Varies by Commodity and Technology and Emerging Technologies Focus on Automation

2.1 Precision agriculture technology adoption varies by commodity and technology

In 2023, 27 percent of U.S. farms or ranches used precision agriculture practices to manage crops or livestock according to USDA.[21] We identified four characteristics associated with the adoption of precision agriculture technologies:

- **Farm size**. Precision agriculture technologies are used on farms of all sizes. However, the likelihood a farm has adopted precision agriculture technologies increases as the farm size increases. This is due to both the physical size of a farm and economic factors associated with a farm's size. Technologies that apply an input to a specific location, such as variable rate technology, can adjust to the soil variability and only apply the quantity needed at that location. A small farm has less soil variability and therefore benefits less than a large farm does from these technologies.

  Stakeholders reported that larger farms with field crops are more likely to have the economic ability to invest in precision agriculture technologies. USDA reported other economic factors are related to larger farms being more likely to adopt precision agriculture technologies: lower per unit costs of inputs (made possible by spreading out high fixed-equipment costs over large areas); access to more favorable credit terms, which are often needed to finance the purchase of sophisticated, expensive equipment; and larger numbers of managers, permitting the kind of specialization of managerial labor that could lead to greater awareness of, and expertise in using precision agriculture technologies.[22]

  Dairy Extension officials stated larger dairy farms are better able to afford to outfit their cows with activity monitors, though small dairy farms could also benefit. However, the likelihood of adopting automatic milking systems (AMS—see fig. 4) is an exception to the larger farm adoption previously discussed. Each AMS unit is designed to accommodate approximately 60 cows according to stakeholders we spoke with. One industry trade group suggested that AMS are used on dairy farms with up to 300 cows. With larger cow herd sizes, it becomes cheaper to use labor and other parlor designs rather than to invest in enough AMS units, according to a dairy nonprofit organization we interviewed.[23]

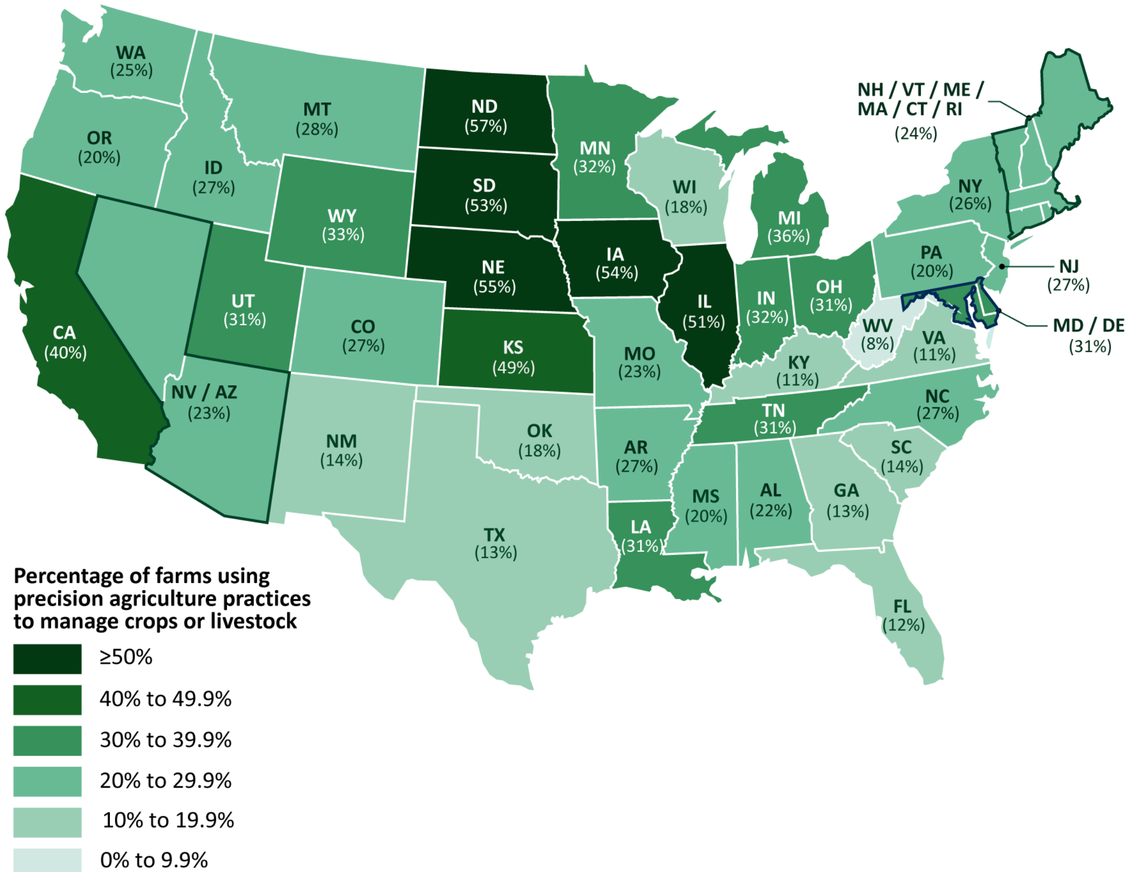
[21] This percentage excludes Alaska and Hawaii. U.S. Department of Agriculture, National Agricultural Statistics Service, *Technology Use (Farm Computer Usage and Ownership)* (Aug. 2023).

[22] U.S. Department of Agriculture, Economic Research Service, *Precision Agriculture in the Digital Era: Recent Adoption on U.S. Farms,* EIB-248 (Feb. 2023).

[23] With the ability to handle 500 cows each hour, a rotary parlor can milk many more cows per day than an AMS which can only handle about 60 cows per day. A rotary parlor uses labor to bring the cows to the parlor, attach the milking cluster and perform other sanitary actions to protect the cow.

- **Region.** In general, the Midwest has higher adoption rates of precision agriculture compared to other regions of the U.S., as seen in figure 5.

Figure 5: Use of precision agriculture practices by U.S. farms, June 2022–June 2023



Source: GAO summary of U.S. Department of Agriculture 2023 Technology Use (Farm Computer Usage and Ownership) data; Map Resources (map). | GAO-24-105962

Note: The 2023 Technology Use estimates are based on responses from approximately 14,000 agricultural operations and represent all sizes and types of farms. Estimates for some states were combined due to their low number of responses. Estimates in this figure have margins of error, at the 95 percent confidence level, ranging from plus or minus 4 percentage points to plus or minus 21 percentage points.

According to USDA data, the top five states using precision agriculture technologies—North Dakota, Nebraska, Iowa, South Dakota, and Illinois—account for approximately half of 2022 U.S. cash receipts for our field crops of interest corn (52.6 percent) and soybeans (45.7 percent).

While the field crops grown in the Midwest support the use of precision agriculture technologies, the technologies themselves may also be better suited for use in the Midwest. According to an Extension official from a northeastern state, soil sensing technologies, such as electrical conductivity sensors, tend to be calibrated for the Midwest, where there are more customers.

As seen in figure 5, most northeastern states have adoption rates below the U.S. average of 27 percent. Lower adoption in the Northeast may also be explained by smaller farm sizes in the region and diversified farming with multiple crop types in the region. These states have average farm sizes smaller than the national average and may have less benefit from precision agriculture technologies.

Lower adoption in the South may be due to the concentration of small, minority and under-resourced farmers lacking access to basic tools such as computers and continuing use of outdated technologies and practices from 40 years ago, according to academics from a southern state. Similar to the Northeast, many southern states have adoption rates below the U.S. average.

- **Farmer demographics**. Extension officials and other stakeholders told us they have observed younger farmers adopting precision agriculture technologies more often and more quickly compared to their older counterparts.[24] Academic studies also found that younger farmers are more likely to adopt precision agriculture technologies.[25]

- **Technology type**. According to stakeholders we spoke with, technologies that are relatively easy to use are, in general, adopted more quickly and widely than those that are more complex or require a large investment of farmers' time and resources. Stakeholders also indicated that data-intensive technologies that require farmers to collect, collate, analyze, and respond to data have a higher barrier to entry and are less widely adopted. As shown in table 1, technology adoption rates for corn and soybeans vary by crop type and the type of technology, according to the most recently available USDA data from 2016 and 2018, respectively.[26]

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[24]The 2017 Census of Agriculture reported the average age of U.S. farmers was 57.5 years old. The 2017 Census of Agriculture was the most current version available at the time of our work.

[25]Madhu Khanna, "Digital Transformers of the Agricultural Sector: Pathways, Drivers and Policy Implications," *Applied Economic Perspectives and Policy*, vol. 43, no. 4 (2021): pp.1221-1242; Nathan D. Delay, Nathanael M. Thompson, and James R. Mintert, "Precision agriculture technology adoption and technical efficiency," *Journal of Agricultural Economics*, vol. 73, no. 1 (2021): pp. 195-219; Terry W. Griffin, LaVona S. Traywick, and Elizabeth A. Yeager. "Interacting with the Next Wave of Farm Operators: Digital Agriculture and Potential Financial Implications" (paper presented at 2020 Agricultural Symposium: The Roots of Agricultural Productivity Growth).

[26]The USDA's Agricultural Resource Management Survey (ARMS) is an annual survey of U.S. farms and includes information on precision agriculture technology adoption. Major field crops (e.g., corn, soybeans, wheat, cotton, sorghum, rice) are surveyed on a rotating basis every 4 to 6 years. ARMS has included survey questions on precision agriculture adoption rates since 1996. ARMS is jointly administered by USDA's Economic Research Service and National Agricultural Statistics Service.

Table 1: Adoption rates of precision agriculture technologies by U.S. farmers for corn in 2016 and soybeans in 2018

	Crop (% of crop planted acres)	
Technology	Corn	Soybeans
Automated guidance	58	54
Yield mapping	44	44
Soil maps	22	14
Drone, aircraft and satellite imagery use[a]	7	10
Variable rate technology	37	25

Source: GAO summary of USDA *Precision Agriculture in the Digital Era: Recent Adoption on U.S. Farms* data. | GAO-24-105962

[a]Due to wording of USDA's survey questions, it is not possible to differentiate between the use of drones, aircraft, and satellites; adoption estimates are only available in aggregate.

Note: Estimates in this table were derived from the USDA, Economic Research Service (ERS) and National Agricultural Statistics Service (NASS), Agricultural Resource Management Survey (ARMS), years 2016–2019 and are subject to sampling errors. For example, the sampling error for estimates of corn acres, at the U.S. level, is about 1 percent.

- The adoption rates of auto-guidance technology are, at least in part, attributable to how easy it is to use, according to academic stakeholders. For example, stakeholders we interviewed explained that farm equipment receives and responds to GPS signals in real time with no need for farmer interaction. By comparison, variable-rate application technologies are more data-intensive, as they require farmers to create maps of in-field variability and respond to that variability while applying fertilizer, pesticides, and other inputs.
- Farmers can use data-gathering technologies to understand conditions on their farm, but not all farmers take the next step to analyze the data or act on the results of data analysis, according to stakeholders we spoke with.
- According to USDA, nationally representative estimates of precision agriculture technology adoption rates for specialty crops farming and livestock farming do not exist.[27] However, according to USDA data from 2016, computerized milking systems were used by almost half of dairy farms with 500 to 1,999 cows.[28]

[27]U.S. Department of Agriculture, *Precision Agriculture in the Digital Era: Recent Adoption on U.S. Farms*.

[28]U.S. Department of Agriculture, Economic Research Service, *Consolidation in U.S. Dairy Farming,* ERR-274 (July 2020).

2.2 Many emerging precision agriculture technologies focus on automation and measurement of agricultural conditions

2.2.1 Automation

Technologies automating agriculture operations discussed below rely on advances in machine learning, specifically computer vision.[29] Sensors gather data to be analyzed by onboard computers, resulting in real-time decisions without human involvement, automating specific tasks.

Targeted spray

Targeted spray systems rely on computer vision as part of a system to precisely spray herbicides only in a specific spot where weeds are present. Cameras are attached to farm spray equipment. As images are captured when the equipment rolls through a field, they are processed by an onboard computer on the farm spray equipment to determine the presence of a weed using machine learning algorithms. If a weed is identified, the computer activates a spray nozzle to spray a small amount of chemicals just at the spot where the weed was found. Targeted spray solutions exist for both field and specialty crops.

Automated mechanical weeding for specialty crops

Also relying on computer vision, automated mechanical weeding technologies use onboard sensors to identify the difference between weeds and crops. As equipment moves through a field, the onboard computer analyzes data captured from onboard sensors. As the onboard computer identifies weeds, it directs the mechanical weeding blades to start and stop to avoid damaging the growing plants while destroying weeds. Automated weeding systems provide an alternative to specialty crops' use of herbicides.

Autonomous vehicles

Autonomous farm vehicles can operate without human drivers. These systems incorporate sensors that "see" around the entire vehicle and use onboard computers to analyze data from the sensors. Autonomous vehicle solutions exist for both field and specialty crops.

Currently, some autonomous farm vehicles still retain a layout with a cab for a human operator to provide an option for a human driver. Though they received much publicity in 2022, autonomous tractors are not widely available to purchase. Some companies are developing kits to retrofit equipment, into autonomous vehicles.

Autonomous vehicles may require improved broadband connectivity at the farm. For example, one autonomous tractor requires connectivity so the farmer can remotely control the tractor operation via a cellphone or tablet. If the autonomous tractor encounters an obstacle, the tractor will stop until restarted by the farmer.

[29]Machine learning systems are a central focus in present-day artificial intelligence (AI) innovation. Machine learning underpins applications of AI including computer vision. Computer vision includes algorithms and techniques to classify or understand the content of scenes.

Automated rotary milking parlor

Rotary parlors are mostly used on large dairy farms, including herds that have thousands of cows according to a dairy trade organization. Parlors can milk 100 to 120 cows simultaneously in a consolidated area, with about 500 cows being brought in for milking each hour. Robotics can replace human operators with specific tasks, such as sanitation after the cow has been milked. Because rotary parlors have a higher capacity than automatic milking systems (AMS), emerging technology solutions include a completely automated rotary milking parlor.

These automated rotary milking parlors are similar to AMS, in that the automatic robotic system automatically cleans, sterilizes, and prepares the cow's teats for milking, automatically applies the teat cups, collects the milk and analyzes the milk's characteristics. With the ability to handle 500 cows each hour, an automated rotary parlor can milk many more cows per day than an AMS which can only handle about 60 cows per day. Unlike AMS, rotary parlors are not designed for voluntary milking, in which the cow may choose when to be milked.

2.2.2 Agricultural conditions measurement

Historically, sensors and sensing technologies have been used in food and agriculture to measure certain characteristics of interest (e.g., temperature, soil moisture).[30] New sensor capabilities and platforms can provide different measurements allowing farmers to proactively take actions accounting for changing field conditions, offering additional optimization opportunities.

New sensors to monitor plant stress and nutrients

To take advantage of precision agriculture technologies, including variable rate technologies, there is a growing need to measure multiple soil and plant properties such as temperature, moisture, and nutrients at a very high frequency and data density. Advances in materials science, microelectronics, and nanotechnology are poised to enable the creation of novel sensors.[31] These new sensors will be able to provide farmers near-real-time information to aid in decision-making.

For example, one novel sensor being researched by those in academia is a small, biodegradable, inexpensive, energy-efficient disposable soil sensor.[32] Currently, soil nitrate analysis requires taking samples to

[30]Sensors are devices that detect or measure physical, chemical, or biological properties and then record, indicate, or respond to those results. National Academies of Sciences, Engineering, and Medicine, *Science Breakthroughs to Advance Food and Agricultural Research by 2030* (Washington, D.C.: 2019), 91.

[31]National Academies of Sciences, Engineering, and Medicine, *Science Breakthroughs to Advance Food and Agricultural Research by 2030.*

[32]Carol Baumbauer, Payton Goodrich, Ana Arias, "Printed Nitrate Sensors for In-Soil Measurements." *Proceedings of the 15th International Conference on Precision Agriculture* (June 2022), https://www.ispag.org/proceedings/?action=abstract&id=8770&title=Printed+Nitrate+Sensors+for+In-soil+Measurements+&search=types.

laboratories for chemical or spectrographic analysis. With this new type of sensor, real-time nitrate information from throughout the field could be provided to a farmer. With this information, a farmer can optimize in-season nitrogen inputs.

Other sensor technologies being researched include nanoparticles that change color to indicate plant moisture levels.[33] The Center for Research on Programmable Plant Systems, a NSF Science and Technology Center, has demonstrated the ability to measure a plant's moisture levels, and create an observed change in the fluorescence spectrum[34] in a research setting.[35] Another similar nanoparticle sensor creating an observable change in the fluorescence spectrum is being researched to detect and monitor levels of arsenic.[36]

Digital twins in agriculture

Digital twins are virtual representations of people or physical objects, processes, or systems, ranging from vehicles to industrial plants to clinical trial patients. These "living" computational models integrate with data from a physical twin, such that any changes made to the physical twin can automatically lead to changes in the digital twin. Digital twins can be used to remotely maintain or monitor the physical twin, or to predict how it will perform.[a]

Digital twins may have a role in agriculture. Digital twins can integrate machine learning algorithms to predict how a farm action, such as irrigation or fertilization, would affect the growth and yield of the crop. After the crop is harvested, post-season evaluation of the digital twin's predictions compared to what physically happened in the field can lead to algorithmic improvements for the next season.

Currently, digital twins in agriculture are not deployed outside of research. However, one company we interviewed is actively using data gathered from the field to create digital twins to analyze the real-world responses from their in-field experiments.

[a]For additional information on digital twins, see GAO-23-106453.

Source: GAO analysis of literature and industry interview. | GAO-24-105962

New platforms for remote sensing

Historically, agriculture has used remote sensing to measure the electromagnetic properties of soil or plants.[37] The platforms for making these measurements have historically been satellites or aircraft. New platforms such as uncrewed aircraft systems (UAS), also known as drones, or uncrewed ground vehicles (UGV) can also provide measurements on crop conditions. While UAS sensors look down from the air on a crop, UGV sensors look up from the ground. According to academic and Extension stakeholders from a midwestern state, interest in the use of UAS in agriculture is increasing.

[33]Nanoparticles are particles at the scale of a nanometer: 1 billionth of 1 meter.

[34]Fluorescence is the property of some atoms to absorb light and then reemit light that can be measured.

[35]Piyush Jain, et al, "A minimally disruptive method for measuring water potential in planta using hydrogel nanoreporters." *Proceedings of the National Academy of Sciences*, vol. 118, no. 23 (2021).

[36]Tedrick Thomas Salim Lew, Minkyung Park, Jianqiao Cui, and Michael S. Strano, "Plant Nanobionic Sensors for Arsenic Detection." *Advanced Materials*, vol 33. no. 1 (2020).

[37]Remote sensing refers to non-contact measurements from agricultural fields. Measurements made with ground equipment or hand-held sensors are also known as proximal sensing.

3 Several Federal Agencies Support Precision Agriculture Technology Adoption, R&D, Education, and Training

Several federal agencies support precision agriculture adoption, research and development (R&D), and education and training.[38] USDA provides financial assistance and loan programs that can indirectly assist with precision agriculture technology adoption. In addition, some USDA agencies and NSF perform or provide funding for R&D related to precision agriculture and provide support for education and training related to precision agriculture. For a list of federal efforts that support precision agriculture, please see appendix II where we identified 43 efforts from 11 agencies.

3.1 USDA supports precision agriculture technology adoption with financial assistance and loan programs

3.1.1 Natural Resources Conservation Service (NRCS) indirectly supports precision agriculture technology adoption through financial assistance programs

NRCS's Conservation Stewardship Program (CSP) and Environmental Quality Incentives Program (EQIP) provide payments to farmers for implementing practices that provide a conservation benefit. These NRCS financial assistance programs can help increase precision agriculture technology adoption, but NRCS officials said that CSP and EQIP are not intended to help farmers directly purchase equipment. Instead, officials said program financial assistance supports adoption and implementation of certain conservation practices—be that with equipment, technology, or other farm management decisions. Nonetheless, officials told us farmers may use financial assistance for implementing conservation practices to offset the cost of purchasing new equipment.

For both CSP and EQIP, NRCS works with farmers to implement conservation practices to help solve on-farm resource and conservation issues and increase their level of conservation. Farmers implement practices and activities that can lead to cleaner water and air, healthier soil, and better wildlife habitat, while improving their agricultural operations. NRCS officials said conservation activities, such as NRCS's nutrient management conservation practice, are how NRCS supports precision agriculture technology adoption.[39] NRCS officials said precision agriculture technologies can be used to implement nutrient management by, for example, using a technology that applies planting inputs to achieve a more precise placement of nutrients. Officials also told us the most common precision agriculture

[38]For this report we define "support" to broadly encompass any federal support of precision agriculture technologies, which includes applicable federal programs. Federal support can take many forms, including, but not limited to, financial assistance, grant, or loan programs; research funding; technical assistance; collaboration with other federal and nonfederal entities; regulations; ordinances; policies; or guidance.

[39]Nutrient Management Practice Standard 590 is used to manage the rate, source, placement, and timing of plant nutrients and soil amendments while reducing environmental impacts. Farmers can develop site-specific yield maps using yield monitoring systems, imagery, or other methods, and then use the data to further delineate high and low yield areas to make management changes. Farmers can also use variable rate nutrient application based on site-specific factors.

technologies used to implement nutrient management practices include variable rate and yield monitor technologies. Officials said additional soil sampling technologies are becoming more common and help nutrient management practices by increasing the accuracy of soil maps.

Additionally, NRCS officials characterized farmer implementation of the agency's pest management conservation practice as another practice that can be achieved using precision agriculture technologies. For example, pesticide application using smart sprayer technology, such as sensors, and GPS-based variable rate application and computer-controlled spray nozzles, can substantially reduce the amount of pesticide applied. NRCS officials also said that additional NRCS conservation practices for planting crops, perennial plantings, and amending soil properties could be implemented with precision agriculture technologies.[40] For example, GPS and auto-guidance technologies could be used to implement conservation practices related to planting spacing or population control.

NRCS estimated it provided $253.6 million in financial assistance through CSP and EQIP for fiscal years 2017 through 2021 for conservation practices that may use precision agriculture technologies.

3.1.2 USDA's Farm Service Agency loan programs support precision agriculture technology adoption

USDA's Farm Service Agency (FSA) administers loan programs that can support precision agriculture technology adoption, through its Farm Operating Loan Program and Farm Ownership Loan Program as direct or guaranteed loans, according to FSA officials.[41]

- **Farm Operating Loan Program**. Loans to purchase farm items such as livestock, seed, and equipment, including technologies for agricultural operations, according to USDA. FSA officials told us this loan program is the most common FSA loan that would support the adoption of precision agriculture technologies.
- **Farm Ownership Loan Program**. Loans to purchase or expand a farm and capital improvements to the farm. FSA officials said improvements could be installing solar panels or more efficient heating and lighting for a barn.

FSA officials said that, while these loan programs can be used to purchase precision agriculture technologies, their primary purpose is not specific to precision agriculture. Nonetheless, FSA officials said they expect these loan programs to be used more to finance precision agriculture technologies as the use of such technologies becomes more common among farmers.

According to data provided by FSA, the agency provided $19.5 billion in Farm

[40]Perennial plantings persist for many growing seasons. Once planted, perennials grow from the previous year's growth.

[41]Direct loans are made directly from FSA to the farmer, while guaranteed loans are made by a USDA-approved lender and backed by FSA.

Ownership Loans and $10.8 billion in Farm Operating Loans from fiscal years 2017 through 2021.[42] FSA officials said that the agency does not track whether FSA loans were used to finance precision agriculture technologies, and therefore the expenditures are program totals and not specific to precision agriculture technologies.[43] Nonetheless, FSA officials said the agency plans to track expenditure data in the future, including whether a loan was used for precision agriculture technologies (such as new solar tractors), the number of estimated acres for a technology's use, and estimates of carbon savings.

FSA officials told us that its Conservation Loan Program can also be used for precision agriculture technologies, but that the program has not gained much interest from farmers. In particular, officials said that this type of loan has a 1.5 percent fee added to the loan amount, which may have served to limit participation in this program in comparison to other FSA loan programs.[44] FSA officials said the agency has not disbursed a loan under the Conservation Loan Program since 2016 or 2017.

3.2 USDA and NSF support precision agriculture R&D

USDA and NSF provided $98.9 million and $93.2 million, respectively, in funding for precision agriculture R&D from fiscal years 2017 through 2021 (see table 2). USDA provides R&D funding primarily through its Agricultural Research Service (ARS), the Economic Research Service (ERS) and the National Institute of Food and Agriculture (NIFA). In addition, NSF provides grants in support of R&D that advances precision agriculture.

Table 2: Funding provided by USDA and NSF for precision agriculture research and development, fiscal years 2017—2021

In dollars

Agency	2017	2018	2019	2020	2021	Total
U.S. Department of Agriculture (USDA) Economic Research Service	0	0	0	25,000	0	**25,000**
USDA Agricultural Research Service	4,312,600	7,338,900	7,338,900	7,751,500	10,395,400	**37,137,300**
USDA National Institute of Food and Agriculture	1,236,745	4,628,588	9,687,008	22,973,993	23,202,103	**61,728,437**
National Science Foundation (NSF)	6,807,701	13,628,244	41,192,472	24,358,321	7,188,941	**93,175,679**
Total	**12,357,046**	**25,595,732**	**58,218,380**	**55,108,814**	**40,786,444**	**192,066,416**

Source: GAO analysis of USDA and NSF data. | GAO-24-105962.

[42]Agency totals include amounts provided under both direct and guaranteed loans.

[43]According to FSA officials, the current loan tracking system tracks the purpose of a loan at a high level (e.g., a loan given in a specific fiscal year to purchase equipment). However, FSA databases do not record what type of equipment the loan was used to finance. As such, they cannot provide data on the extent to which their loan programs were used to finance precision agriculture technologies.

[44]FSA officials told us the Conservation Loan Program is similar to the Farm Operating Loan Program, but does not have a requirement for assessing an applicant's credit, which helps farmers that are unable to obtain a loan from another lender.

3.2.1 USDA's Agricultural Research Service

As an intramural research agency within USDA, ARS scientists conduct agriculture research, often in collaboration with researchers at universities and land-grant colleges. ARS operates 90 different sites, more than one-third of which are colocated with a university. ARS officials said many of these sites are working on some aspect of precision agriculture technologies or processes, including irrigation management, livestock tracking, automated feeding and milking systems, rangeland management (e.g., virtual fencing, auto-steer machinery), and planting. ARS officials said some of their main precision agriculture research areas are tillage management, agronomics, and decision support tools. Additionally, ARS has conducted research on precision irrigation and the benefits and costs of auto-guidance systems to farmers and the environment, as well as research to determine the economic and environmental sustainability of precision agriculture practices. ARS provided about $37.1 million in funding to precision agriculture research projects from fiscal years 2017 through 2021.

ARS officials said that, while precision agriculture is not a specific ARS research goal, the number of precision agriculture-related projects has increased over time.[45] Some ARS research has resulted in environmentally friendly precision agriculture technologies that enable farmers to participate in environmental markets, including those managed by NRCS.[46] Specifically, farmers participating in such markets are eligible to receive additional income when they implement conservation practices on their lands. For example, one technology borne out of ARS-funded research is a targeted weed sprayer with on board cameras that use artificial intelligence to detect weeds and apply herbicide only where it is necessary. In addition to earnings from environmental markets, farmers who use this technology can save time and money, as they do not have to refill their sprayers as often. Another example is ARS research in Nebraska and Missouri to develop a system to optically sense corn nitrogen needs and apply the needed amount variably across fields.

Other ARS research has led to an improved management strategy related to rangeland grazing. For example, ARS officials told us ARS researchers are working on a project in Idaho using cattle to graze flammable plants. They said virtual fences direct cattle to graze highly flammable and invasive plants, such as cheat grass, and the reduction in cheat grass creates a natural fire break. ARS officials also said ARS researchers use jaw sensors to determine

[45]ARS Goal 2.2 – Improve Management of Soil Resources, Reduce Impact on Air Resources, Efficiently Use Inputs, and Contribute to Ecosystem Services, National Program 212 – Soil and Air: 2021-2025 states the agency will "use innovative precision agriculture, remote sensing, and/or modeling strategies for farming systems development and assessment" as a strategy and means for Goal 2.2.

[46]When farmers and ranchers implement conservation practices on their lands, they generate ecosystem services—environmental benefits that healthy ecosystems provide, such as clean water and healthy soils. Producers who generate ecosystem services credits can voluntarily participate in environmental markets, providing an additional source of income. When ecosystem services can be measured and quantified—for example, the amount of carbon stored in soil—they can be sold and purchased through emerging markets. These markets are called ecosystem or environmental markets. Water Quality Trading and Greenhouse Gas Markets are examples of NRCS environmental markets activities.

what cattle are grazing at what times of year and use virtual fencing to direct the cattle to areas of need. Officials said that three or four fires have died on the firebreaks from using this technology.

3.2.2 USDA's Economic Research Service

USDA's Economic Research Service's (ERS) mission is to anticipate trends and emerging issues in agriculture, food, the environment, and rural America and to conduct high-quality, objective economic research to inform and enhance public and private decision making. ERS provided funding of approximately $25,000 for precision agriculture research in fiscal years 2017—2021.

ERS has produced many reports on various agricultural economics topics, as well as reports on precision agriculture. ERS, in collaboration with the USDA National Agricultural Statistics Service, produces the Agricultural Resources Management Survey (ARMS), which is a multiphase series of interviews with farm operators about their cropping practices, farm businesses, and households.[47] In particular, USDA officials said ARMS primarily collects data on the adoption of precision agriculture related to yield monitor use, variable rate technology use, GPS-enabled technologies, and mapping. According to USDA officials, in 2015, ARMS started collecting data on drone use as part of an inquiry into satellite and aircraft imagery. The survey also started to collect information on public data that farmers downloaded and the use of smart technologies, including cab control displays for tractors. Officials also said that in 2018, ARMS began including questions about computer tablet and smartphone use, automatic section control in equipment, and precision agriculture technology costs and prices.[48] ERS officials stated that ARMS has been tracking use of yield and soil maps since the mid-1990s. ERS officials are hopeful that ARMS questions in the future will focus on certain precision agriculture applications used with livestock and specialty crops.

3.2.3 USDA's National Institute of Food and Agriculture

NIFA is an extramural funding agency that offers grants and cooperative agreements to support research, education, and Extension activities, as well as for precision agriculture.[49] Examples of NIFA-funded projects range from monitoring pasture quality and quantity using field robotics to variable and site-specific precision planting to enhance weed suppression in row crop systems. Officials also told us NIFA funds precision livestock farming projects that range from measuring methane emissions on grazing beef cattle to the deployment of high-definition cameras to improve poultry welfare and productivity. NIFA provided $61.7 million in funding for precision agriculture research from fiscal years 2017 through 2021.

[47]A survey of U.S. farms, ARMS is USDA's primary source of information about the resource use, production practices, and economic well-being of the U.S. agricultural sector.

[48]Automatic section control, associated with planters and sprayers, automatically shuts off sections or rows of the implement for areas it previously covered, and turns it back on for areas it did not previously cover.

[49]NIFA officials said grants are either capacity grants or competitive grants. Capacity grants are noncompetitive and mostly awarded to land grant universities based on Congressional authorizations. Most of NIFA's grants related to precision agriculture, where NIFA can set priorities, are competitive grants.

NIFA also manages the Agriculture and Food Research Initiative (AFRI) that officials said supports precision agriculture R&D. AFRI is the nation's leading competitive grant program for agricultural sciences, with $455 million in funding awarded in fiscal year 2023, some of which officials said supported precision agriculture projects.[50] USDA officials said examples of AFRI-funded projects involving precision agriculture range from the use of wearable sensors for disease detection in livestock to the use of sensors and modeling to help farmers better respond to issues that arise during the farming season.

3.2.4 USDA and NSF's Artificial Intelligence (AI) institutes

USDA and NSF partner on several artificial intelligence (AI) research institutes that NSF officials identified as providing support for precision agriculture R&D. A 2018 memorandum of understanding between USDA's NIFA and NSF outlines the agencies' cooperation in, for example, AI and machine learning, automation, digital agriculture, and information and communication technology in agriculture. As shown in table 3, there are currently five AI institutes that are solely funded by NIFA and comanaged by USDA and NSF.

Table 3: USDA and NSF artificial intelligence institutes that support precision agriculture

Name	Established	Lead university	Description
AI Institute for Next Generation Food Systems (AIFS)	2020	University of California, Davis	Aims to meet growing demands in the food supply by increasing efficiencies using artificial intelligence (AI) and data spanning the food supply system from crop growth through consumption. AIFS research addresses autonomous farming, labor optimization, environmental resilience, soil monitoring and health, technology adoption, and public policy.
AI for Future Agricultural Resilience, Management, and Sustainability Institute (AIFARMS)	2020	University of Illinois	Advances AI to address challenges facing world agriculture, with an emphasis on researching technologies that affect production practices, developing a diverse and technically skilled workforce in digital agriculture, and supporting women and minority farmers. AIFARMS research includes autonomous farming, efficiency for livestock operations, environmental resilience, soil health, and technology adoption.

[50]AFRI was established by Congress in the 2008 Farm Bill, Pub. L. No. 110-246, § 7406, 122 Stat. 1651, 2009 (codified as amended at 7 U.S.C. § 3157(b)), and re-authorized in the 2018 Farm Bill, Pub. L. No. 115-334, § 7504(3), 132 Stat. 4490, 4822. NIFA provides AFRI grants to support research, education, and Extension activities in six areas: Plant Health and Production and Plant Products; Animal Health and Production and Animal Products; Food Safety, Nutrition, and Health; Bioenergy, Natural Resources, and Environment; Agriculture Systems and Technology; and Agriculture Economics and Rural Communities.

Name	Established	Lead university	Description
AI Institute for Transforming Workforce and Decision Support (AgAID)	2021	Washington State University	Integrates AI methods into agricultural operations for prediction, decision support, and robotics-enabled agriculture to address agricultural challenges. AgAID uses an approach called “adopt-adapt-amplify” to develop and deliver AI solutions that address pressing challenges related to labor, water, weather, and climate change.
AI Institute for Resilient Agriculture (AIIRA)	2021	Iowa State University	Focuses on an AI-driven digital twins and a supporting framework for modeling plants at various agronomically relevant scales. Models can be deployed across several agricultural applications in crop improvement and production. These include streamlining and revolutionizing plant breeding, assisting farmers and their advisors in adopting improved farming techniques and technologies, and driving economic development across the rural landscape through AI-inspired ventures.
AI Institute for Climate-Land Interactions, Mitigation, Adaptation, Tradeoffs and Economy (AI-CLIMATE)	2023	University of Minnesota	Pursues AI advances by incorporating knowledge from agriculture and forestry sciences and leveraging unique, new AI methods to curb the effects of climate change while supporting rural economies. AI-powered knowledge and solutions include AI-enhanced estimation methods of greenhouse gases and specialized field-to-market decision support tools.

Source: GAO analysis and summary of agency websites and interviews with agency officials. | GAO-24-105962

Note: USDA = U.S. Department of Agriculture; NSF = National Science Foundation.

3.2.5 NSF directorates

NSF supports precision agriculture R&D through research funding across its directorates. NSF provided $93.2 million in funding for such projects from fiscal years 2017 through 2021. Of the $93.2 million in funding, the Engineering (ENG), Computer and Information Science and Engineering (CISE), and Technology, Innovation and Partnerships (TIP) directorates provided $85.3 million.

- Engineering Directorate. Funding provided by this directorate has addressed such topics as sensors and sensing systems, robots, and the recovery of manure nutrients for use in sustainable fertilizers while reducing pollution. For example, one project examined the risks and benefits of precision agriculture technologies to the farm or operation-level workforce in the near future (i.e., 10-15 years). The directorate has funded approximately 40 awards related to precision agriculture over the last 10 years, according to NSF, and provided $47.5 million in funding for precision agriculture research and development from fiscal years 2017 through 2021.

- Computer and Information Science and Engineering (CISE) Directorate. This directorate led a multi-directorate Cyber-Innovation for Sustainability Science and Engineering (CyberSEES) program that supported precision agriculture education and outreach. The program aimed to advance interdisciplinary research in which the science and engineering of sustainability are enabled by new advances in computing. The CyberSEES program funded one collaborative project in precision agriculture that investigated a comprehensive research, educational, and outreach program called SmartFarm, which combines new scientific research in computer science, agronomics, and precision agriculture with outreach and educational pathways that enable youth and communities to participate in agriculture sustainability. Another CISE-funded project supports precision agriculture via cyberinfrastructure for analyzing drone and satellite data. The CISE Directorate provided $22.6 million in funding for precision agriculture R&D from fiscal years 2017 through 2021.

- Technology, Innovation and Partnerships (TIP) Directorate. TIP was established in March 2022. Several existing programs were moved into TIP upon its establishment, such as the NSF Innovation Corps, Partnerships for Innovation, Small Business Innovation Research/Small Business Technology Transfer, and Convergence Accelerator programs. In addition, the directorate has launched several new programs to accelerate technology development and translation as well as workforce development. TIP has provided funding for projects that intersect with precision agriculture topics. For example, NSF officials said one division funded 133 awards with a focus on precision agriculture topics such as soil nutrient sensors, unmanned aerial vehicles, weed and parasite control, mesh networks to facilitate wireless connectivity, and drone use for fire suppression. One project used remote sensing via unmanned aerial systems to help with disease models, harvest timing, and yield predictions. TIP and its predecessor provided $15.2 million in funding for precision agriculture research, development, and commercialization from fiscal years 2017 through 2021, according to NSF.

3.3 USDA and NSF provide precision agriculture education and training through Extension, service centers, and educational programs

USDA and NSF support precision agriculture technology education and training through USDA Extension, USDA service centers and technical assistance providers, and educational initiatives. USDA and NSF provided $26.6 million and $3.9 million, respectively, in funding for precision agriculture education and training from fiscal years 2017 through 2021.

3.3.1 Cooperative Extension efforts provide agricultural information to farmers

The Cooperative Extension System — commonly referred to as Extension—was established by the Smith-Lever Act of 1914, enabling states to provide farmers with information from agricultural research and encourage them to adopt improved farming methods. Extension is implemented through state and Tribal land-grant universities with support through Smith-Lever, 1890 Extension funds, and other capacity funds provided through NIFA and through nonfederal matching funds.[51]

Through Extension programs, land-grant universities offer their resources to address public needs by educating farmers on business operations and modern agricultural sciences and technologies. Extension works to translate science for practical application, identify new research questions, and connect people to information and assistance. An Extension agent we interviewed said Extension can offer workshops and demonstrations to help educate farmers, including by allowing them to observe the use of precision agriculture technologies. Additionally, the agent said some Extension agents create podcasts to help spread more information about new precision agriculture technologies to farmers. One Extension office also collaborates with the National Aeronautics and Space Administration (NASA). Specifically, the University of Illinois Extension office serves as a conduit to integrate NASA technology at the farm level, according to NASA officials. USDA provided $13 million in funding to cooperative Extension from fiscal years 2017 through 2021 for precision agriculture.

3.3.2 USDA service centers and technical assistance promote communication between farmers and USDA staff

USDA service centers offer locations where farmers can meet face-to-face with staff from FSA, NRCS, and Rural Development to discuss the farmers' visions and goals and hear how USDA can provide agricultural assistance. According to USDA, it employs FSA and NRCS staff members in approximately 2,300 service center offices nationwide. However, both USDA officials and participants at our expert meetings told us that not all staff members have experience in precision agriculture technologies.

NRCS also provides free technical assistance to farmers, even if they do not participate in NRCS programs. According to NRCS officials, this can help farmers become aware of NRCS programs and share knowledge about how to assess and treat agricultural effects on natural resources, enhance conservation achievements, and meet regulatory requirements. Farmers can also take advantage of technical service providers to help them understand precision agriculture technologies.[52] Given the wide range of precision agriculture technologies, technical service providers can provide knowledge on a range of topics, such as variable rate technology, enhanced efficiency fertilizers, and in-season testing that help farmers refine nutrient applications through the year, according to NRCS officials.

NRCS officials told us that the agency is developing a precision agriculture curriculum for state staff because state and local staff have varying degrees of knowledge and skill sets. Officials said that precision agriculture technologies are evolving and changing, and

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[51]The Smith-Lever Act of 1914 formalized Cooperative Extension in the United States between USDA and land grant universities. Act of May 8, 1914, ch. 79, 38 stat. 372 (codified as amended at 7 U.S.C. §§ 341-349)).

[52]Technical service providers (TSPs) offer planning, design, and implementation services on behalf of NRCS to agricultural producers such as farmers, ranchers, and private forest landowners. TSPs include individuals, private businesses, American Indian tribes, nonprofit organizations, and public agencies.

NRCS staff need to be aware of what is available. Officials also said that NRCS does not intend for state staff to become experts on precision agriculture technologies, but rather to have the awareness needed to promote precision agriculture technologies.

3.3.3 NSF Directorate for STEM Education

NSF officials told us that while many NSF research awards include some aspect of education and training outreach, specific precision agriculture education and training support has been funded through NSF's Directorate for Science, Technology, Engineering, and Mathematics (STEM) Education. According to NSF, this directorate funds education efforts in precision agriculture primarily through the Advanced Technological Education program. This program's portfolio includes approximately 29 awards focused on training the precision agriculture technical workforce in precision agriculture, aerial systems technology, geographical information systems, GPS, robotics, electronics, and other emerging technologies relevant to precision agriculture. NSF provided $3.9 million in funding for precision agriculture education and training from fiscal years 2017 through 2021.

3.4 Other federal precision agriculture efforts

The Federal Communications Commission (FCC), NASA and the Environmental Protection Agency (EPA) support precision agriculture indirectly. For example, the FCC uses its existing broadband expansion programs, the Connect America Fund and Rural Digital Opportunity Fund, to help bring internet access to farms and farm fields throughout the country, according to FCC officials. NASA collects satellite imagery for farmers to use to make better informed decisions about their agricultural operations. In addition, EPA officials told us the agency is exploring its pesticide management regulations due to the emergence of newer precision agriculture technologies.

3.4.1 Federal broadband programs indirectly support precision agriculture technology adoption by expanding rural connectivity

As mandated by the 2018 Farm Bill, the FCC created The Task Force for Reviewing the Connectivity and Technology Needs of Precision Agriculture in the United States (Task Force) to, among other things, promote rural connectivity for farmers.[53,54] The Commission set up four working groups for the Task Force that examine (1) mapping and analyzing connectivity on agricultural lands, (2) accelerating broadband deployment on unserved agricultural lands, (3) examining current and future connectivity demand for precision agriculture, and (4) encouraging the adoption of precision agriculture and availability of high-quality jobs on connected farms. On November 6, 2023, the Task Force adopted a final report that made

[53]The Task Force for Reviewing the Connectivity and Technology Needs of Precision Agriculture in the United States is a federal advisory committee that consults with USDA and collaborates with public and private stakeholders in the agriculture and technology fields to promote precision agriculture. Since 2019, FCC officials said the Task Force has provided advice and recommendations to the FCC concerning assessing and advancing deployment of broadband internet access service on unserved agriculture land to promote precision agriculture.

[54]Agricultural Improvement Act of 2018 (2018 Farm Bill), Pub L. No. 115-334, § 12511(b)(3), 132 Stat. 4490, 4993.

recommendations on how to assess and advance the deployment of broadband internet access service on unserved and underserved agricultural land and promote precision agriculture for both cropping and husbandry.

According to FCC officials, the High-Cost Program, which includes the Connect America Fund, Rural Digital Opportunity Fund, and the 5G Fund for Rural America (5G Fund) could be used to bring connectivity to the "last mile." FCC's High Cost Program provided $28.3 billion in funding for broadband projects from fiscal years 2015 through 2020.[55] FCC officials said that the Connect America Fund and Rural Digital Opportunity Fund are designed to ensure that consumers in rural, insular, and high-cost areas have access to modern communications networks capable of providing voice and broadband service, both fixed and mobile, at rates that are reasonably comparable to those in urban areas. Specifically, officials said funding supports deploying, operating, and maintaining networks to residential and small business locations. As such, FCC officials said these programs provide opportunities for rural farms to be served. They said a small farm, or a location with attached farmland, could be considered a home or a small business. Additionally, they said that the fiber used to build out broadband systems using Connect America Fund and Rural Digital Opportunity Fund funds will help with the expansion of broadband to farmland.

The 5G Fund could help with additional rural connectivity, including the "last mile" and "last acre." FCC officials also told us it could be a mechanism for addressing precision agriculture broadband needs. The 2020 FCC Report and Order on Establishing a 5G Fund for Rural America says that FCC will target support nationwide to all eligible rural areas in Phase I, and the deployment of technologically innovative 5G networks that facilitate precision agriculture in Phase II.[56] The FCC concluded that a budget of at least $1 billion would be necessary for Phase II of the 5G Fund for carriers to commit to the deployment of technologically innovative 5G networks that facilitate precision agriculture and would help close the remaining digital divide in vast areas of agricultural lands that currently remain unserved. We previously reported that FCC has taken steps to address the digital divide, including making up to $9 billion in funding available to carriers to deploy 5G in rural areas of the United States.[57]

USDA's Rural Development agency indirectly assists with precision agriculture technology adoption with its broadband programs. Rural Development officials said their ReConnect, Community Connect, Farm Bill Broadband, and Telecommunications Infrastructure programs provide indirect support by funding construction, improvement, or acquisition of facilities and equipment needed to provide broadband service in eligible rural areas, including to farms.[58] Officials also said that these programs fund "last-mile" connectivity

[55]GAO, *Broadband: National Strategy Needed to Guide Federal Efforts to Reduce Digital Divide*, GAO-22-104611 (Washington, D.C.: May 31, 2022).

[56]Federal Communications Commission, *Establishing a 5G Fund for Rural America*, GN Docket No. 20-32, Report and Order (Oct. 29, 2020).

[57]GAO, *5G Deployment: FCC Needs Comprehensive Strategic Planning to Guide Its Efforts,* GAO-20-468 (Washington, D.C.: June 12, 2020).

[58]USDA's ReConnect Program, Telecommunications Infrastructure Program, Community Connect Grant Program, and Rural Broadband Programs awarded $1.4 billion, $1.3 billion, $132 million, and $95.8 million from fiscal years 2015 through 2020, respectively.

to all potential customers located within an approved project, including farmers.

3.4.2 NASA's agriculture portfolio facilitates improved farming decisions by augmenting ground information with satellite data

According to NASA officials, NASA's agriculture portfolio provides foundational observations and applied research that directly affect irrigation management, baselines and scaling capabilities for snow water runoff and drought forecasts, applied research to improve weather forecasting, and food security and the efficient use of data and information to promote agriculture, both on the domestic and international scale. NASA achieves these activities via the Harvest, Acres, OpenET, and the Short-term Prediction Research and Transition efforts. Officials said that these efforts use data from Earth observing satellites to improve both domestic and worldwide agriculture, with the primary goal related to precision agriculture of helping farmers more effectively manage their inputs and decisions. To do so, the programs are intended to help farmers tie satellite data to ground information with the goal of leveraging satellite information at farms for better decision making. Satellite imagery is calibrated in space and time, and can provide information to scale, validate measurements, compare and support standards, and provide best practices to the agriculture industry. For example, officials said NASA partnered with a soil moisture technology firm that has developed ground sensors. The data provided by ground sensors is linked with satellite data, which, when combined, can be used to predict how crop yields might be impacted by adjusting water inputs. Another example officials provided is when a winery used satellite data to create applications to identify clusters of vines that had died in a vineyard, track land temperatures and vegetation water stress, and identify blocked nozzles.

Additionally, officials said NASA satellite data are used in combination with ground-based data and crop models that relate to water and fertilizer use. They said by analyzing the combined data, it is possible to better track how crop outputs might change from changes in irrigation and nitrogen fertilizer applications. They also said it is possible to provide recommendations to increase irrigation efficiency and reduce the amount of fertilizer that needs to be applied by providing guidance on water and fertilizer requirements that account for the current weather conditions and the crop growth stage. For instance, if water is not managed precisely, there is increased risk of fertilizer applications being washed through roots more quickly, before the fertilizer can be taken up and used by the crop, according to NASA officials.

3.4.3 EPA pesticide regulation related to precision agriculture

As an EPA advisory committee, the Pesticide Program Dialogue Committee's Emerging Agricultural Technologies Working Group advised the EPA Office of Pesticide Programs on incorporation of advances in precision agriculture in future pesticide risk assessments and pesticide labels.[59] The Working Group reported that precision agriculture technologies should lead to changes in the regulatory approach used by the EPA Office of Pesticide Programs. The Working Group recommended that, in particular, EPA should adopt more realistic exposure and risk assessments—moving from assessments that use multiple "worst-case" assumptions to ones that incorporate localized, and ultimately more precise, exposure estimates. The Working Group also reported that the EPA Office of Pesticide Programs policy and practice should be adapted for the adoption of autonomous machine application of crop protection products. For example, EPA officials said that when the agency develops a pesticide label, it is developed with the assumption that a human is applying the pesticide. They told us that in the case of an automated system, such as the smart spraying system, the machine could make decisions about the application of pesticide without any or limited human input. Officials said the machine is unable to read and understand a pesticide label; as a result, new technologies may not be aligned with EPA's pesticide labeling system and how a given pesticide was approved for use. EPA officials said a new label could contain metadata or a QR code so the tractor can digitally receive the information from the label on the rules for applying the pesticide, which could potentially reduce the use of pesticides applied by these newer technologies.

[59]The Pesticide Program Dialogue Committee is an advisory committee that provides feedback to EPA on various pesticide regulatory, policy, and program implementation issues.

4 Precision Agriculture Technologies Can Provide Benefits to Farmers and Society, but Challenges Limit Broader Adoption and Use

Precision agriculture technologies can provide multiple benefits to farmers, society, and the environment, but various challenges, such as high up-front acquisition costs, and concerns about ownership and control of farm data may limit further adoption and use.[60]

4.1 Precision agriculture technologies can benefit farmers, society, and the environment

We identified three primary benefits from adopting and using precision agriculture technologies: (1) reduced costs and increased farm profits, (2) improved workplace safety conditions and an enhanced quality of life, and (3) reduced negative environmental impacts. By adopting precision agriculture technologies and the use of data-driven decision-making and automation, farmers could more efficiently use inputs, such as fertilizers, pesticides, and water, to enhance productivity.

4.1.1 Reducing costs and increasing farm profits

The potential for increased profits is the most important factor for farmers to adopt and use precision agriculture technologies. Precision agriculture technologies can enhance farmer profitability by increasing crop yield through more efficient use of nutrients and other inputs while reducing costs. Similarly, precision dairy farming can enable producers to replace manual labor with automation, cutting costs, enhancing efficiency, and facilitating timely, informed decisions for increased profitability. However, contributions of many precision agriculture technologies to farm profitability are not always clear, and estimates have varied, in part due to differences across farms. For example, profitability can differ from farm to farm due to differences in soils, climate, and farm size. Furthermore, larger farms may be more profitable because of the economies of scale associated with larger operations, rather than precision agriculture adoption. These site-specific differences can make it difficult to compare profits between adopters and non-adopters of precision agriculture technologies. According to a USDA report, farmers' use of GPS for navigation and mapping increased operating profits by almost 3 percent, while using variable rate technologies raised both operating profits and net returns by about 1 percent on corn farms.[61] Similarly, data collected during a field trial of a tractor with an auto-guidance system, conducted jointly by USDA and academia on pasture crops (vegetation planted to provide forage for grazing livestock), found the use of auto-guidance improved production gains by between 2.7

[60]Some of the benefits and challenges discussed here are from controlled studies. The actual benefits and challenges experienced by farmers on their commercial operations could vary from those found in industry, government, or academic studies.

[61]USDA research suggests that the increased profitability is likely the result of increased yield, though it is challenging to separate the effects of these technologies on total revenues from total costs. See U.S. Department of Agriculture, Economic Research Service, *Farm Profits and Adoption of Precision Agriculture*, ERR-217 (Oct. 2016).

and 6.5 percent.[62] Other research points to the role of technology costs in determining whether and at what point adoption of technologies becomes profitable.[63]

While nationwide estimates of economic benefits from the use of precision agriculture technologies vary and are limited, these technologies can potentially increase an individual farmer's profits in the following ways.

- **Increased crop yield**. Crop yields in the U.S. have risen, but it is not clear how much is attributable to the use of precision agriculture technologies.[64] According to literature sources and stakeholders we interviewed, precision agriculture technologies allow farmers to increase crop yields with the same amount of inputs or achieve an equivalent yield with fewer inputs, or a combination thereof. A USDA study shows that annual corn yields increased from 130 bushels per acre in 1996 to 183 bushels per acre in 2016, averaging an annual growth rate of 1.7 percent. While such yield increases have not been directly attributed to precision agriculture technologies, their adoption increased from 1996 to 2017 and may have contributed to these yield increases. For example, from 2001 to 2016, the adoption of self-propelled machinery with guidance systems increased from 3 to 39 percent for U.S. corn-planted acres, and variable-rate fertilizer application increased from 6 to 19 percent for U.S. corn-planted acres.[65] Additionally, USDA's Economic Research Service estimated that yield maps and soil maps increased efficiency in U.S. corn production by 7-8 percent.[66] Furthermore, USDA crop yield data provides evidence that average crop yields are higher for technology adopters than non-adopters.[67] In addition, precision dairy farming technologies such as activity monitors, feed quality monitors, automated feeders designed to provide the correct levels of nutrition to dairy cows, and robotic milking can increase milk yield per cow. One industry association noted that precision dairy technologies have contributed to a 6 percent increase in milk yield per cow in North America since 2007.[68]

- **Reduced application of crop inputs**. Precision agriculture technologies can reduce the application of crop inputs such

[62]Amanda J. Ashworth et al., "Environmental Impact Assessment of Tractor Guidance Systems Based on Pasture Management Scenarios," *Journal of the American Society of Agricultural and Biological Engineers*, vol. 65(3), (2022), 645-653.

[63]Sunil P. Dhoubhadel, "Precision Agriculture Technologies and Farm Profitability*", Journal of Agricultural and Resource Economics,* vol. 46, no. 2 (2020): 256–268.

[64]Other factors can also influence the increase in crop yields. For example, farmers' use of genetically engineered corn seeds increases yields by mitigating yield losses from insects. They tend to result in higher yield than conventional seeds. See U.S. Department of Agriculture, Economic Research Service, *Genetically Engineered Crops in the United States*, ERR-162, (Feb. 2014).

[65]U.S. Department of Agriculture, Economic Research Service*, Trends in Production Practices and Costs of the U.S. Corn Sector*, Economic Research Report-294, (July 2021).

[66]Jonathan McFadden, Alicia Rosburg, and Eric Njuki, "Information Inputs and Technical Efficiency in Midwest Corn Production: Evidence from Farmers' Use of Yield and Soil Maps," *American Journal of Agricultural Economics*, vol. 104, no. 2 (2021).

[67]U.S. Department of Agriculture, *Precision Agriculture in the Digital Era*.

[68]Factors other than the rise in the adoption and use of precision dairy farming may also have influenced the increase in milk yields. Association of Equipment Manufacturers, Environmental Benefits of Modern Dairy, Hay, and Forage Production Technologies, 2022.

as fertilizer, herbicide, fuel and water. The efficiencies gained by reduced input application can help lower operating costs and increase profits. For example, farmers can outfit seeders and sprayers with GPS-enabled automatic "shut-off" technologies that stop seeding, fertilization, and pesticide application when driving over already treated areas. Similarly, making more efficient use of water can be particularly beneficial in areas with water shortages, such as during droughts or in regions where the demand for water exceeds the local supply. For example, we previously reported that the use of precision agriculture technologies, such as soil moisture sensors and variable rate technology, could help optimize irrigation schedules and conserve the amount of water used on a farm.[69] In addition, multiple technologies can be used simultaneously to help reduce input use. For example, various literature sources report that drone-based imaging can enable weed and crop yield mapping. Such a capability can help map the nutrient conditions in a crop field so that the application of fertilizer could be optimized and directly deployed to the low-nutrient areas. However, precision agriculture technologies may not reduce inputs in all situations. For example, while stakeholders said auto-guidance reduces fuel use, one field study measured an increase in fuel use when auto-guidance was used.[70] Additionally, in some cases precision management helps farmers redistribute, rather than reduce, overall inputs. For example, precision agriculture technology use could result in a redistribution of fertilizer across a field, rather than a reduction in total fertilizer use. While the extent of crop input reductions from precision agriculture technologies is not always clear, precision dairy technologies are generally observed to allow farmers to reduce inputs through more efficient feeding, monitoring, and raising of their animals. For example, one industry association study found that the use of dairy technologies over the last 15 years, such as advanced feeder systems, activity monitors, and radio frequency identification, contributed to a 4 percent reduction in feed use per cow.[71] Cattle feed is the single greatest farming production expenditure for livestock farms in the U.S., with farms spending on average $41,917 per farm on cattle feed in 2022 (out of an average total farm expenditure of $200,359 per farm for livestock farms), according to USDA.[72] The savings gained by these efficiencies help lower total operating costs for farmers.

- **Enhanced operational efficiency through reducing labor costs and mitigating shortages**. Precision agriculture

[69]GAO, *Irrigated Agriculture: Technologies, Practices, and Implications for Water Scarcity*, GAO-20-128SP (Washington, D.C.: Nov. 12, 2019).

[70]A USDA field trial study on pasture crops reported an increase in fuel use per hectare when tractor auto-guidance was 'on', due to the longer travel distances required for more uniform coverage of herbicides and fertilizer, sloped terrain in these pasture systems, and automated speed, all culminating in reducing fuel efficiency. Ashworth et al., "Environmental Impact Assessment of Tractor Guidance," 645-653.

[71]Association of Equipment Manufacturers, "Environmental Benefits". Factors other than the increased use of precision agriculture may also have influenced the reduction in feed use per cow.

[72]U.S. Department of Agriculture, National Agricultural Statistics Service, *Farm Production Expenditures 2022 Summary* (July 2023).

technologies such as robotic systems can partially or fully automate farm tasks, which can reduce labor and harvesting costs for the grower and mitigate the effects of labor shortages across all agricultural sectors. For example, tractors using GPS-supported auto-guidance can operate across large tracts of land without constant operator attention while ensuring precise and accurate field management. Harvesters and offloading systems equipped with sensors and machine-to-machine communication can work in tandem by communicating how much is being harvested and what the capacity of the offloading system is, requiring less real-time involvement from farm owners. Similarly, drone-based imaging can help address labor shortages. Drones can cover a significantly greater area in a shorter amount of time and detect crop diseases with a high degree of accuracy, reducing the need for workers to check vegetable crops individually. By improving operational efficiency, drones can help avoid shortages of forage (edible part of a plant that can provide feed for grazing animals or can be harvested for feeding). For instance, some dairy farmers can utilize drones equipped with surveying applications to estimate feed inventories and usage rates effectively. Partnering with their nutritionists, they can then plan feeding programs while managing inventories to prevent shortages. Furthermore, automated milking systems—a system of sensors, controllers, and machinery that automate the milking process with little or no human oversight—and barn automation systems can reduce the time and extent of work associated with milking and can help address the labor shortage in the U.S. dairy industry.[73] A USDA official told us that precision agriculture technologies can have a redistributive effect on labor demand by driving the need for workers with different skills. For example, individuals with a greater ability to use precision agriculture management apps or those possessing basic engineering or programming skills, such as the ability to operate variable rate chemical input applicators, may be in greater demand.

- **Improved plant and livestock health detection**. Several technologies can help farmers monitor plant and livestock health and improve the detection of disease. According to USDA, plant diseases reduce yields, lower product quality or shelf-life, and decrease nutritional value, among others. These diseases result in billions of dollars in economic losses each year to crops, land, and forests in the United States.[74] Early detection of disease is critical in protecting yield, minimizing crop loss, and reducing pesticide use. For example, optical or infrared sensors and hyperspectral imaging can help farmers monitor crop health and better detect the early onset of disease or pests. Citrus farm managers may better detect the early onset of disease and reduce the use of pesticides by spraying affected areas

[73]Barn automation system refers to a fully integrated barn operating system that optimizes animal well-being while driving operational efficiency. It allows dairy operations to control the barn's ventilation, lighting and cooling to create an automated, consistent, animal-centered environment.

[74]U.S. Department of Agriculture, Agricultural Research Service, *National Program 303: Plant Diseases*, *Action Plan 2022 – 2026* (2021).

instead of an entire field, according to USDA officials. Similarly, technologies such as activity monitors, sensors, artificial intelligence, and machine learning algorithms enable farmers to react to diseases in livestock. Constant monitoring of key animal health parameters such as movement, air quality, or consumption of feed and water may more quickly identify diseased animals. The collection and analysis of data generated by these technologies help farmers identify any detrimental health conditions earlier, which can prevent financial loss by treating sick animals sooner.

4.1.2 Improving workplace safety conditions and enhancing quality of life

Farmers who adopt and use precision agriculture technologies may create safer workplace conditions and an enhanced quality of life.

- **Safer workplace conditions**. Precision agriculture technologies can improve farm safety and health by automating chemical applications, such as pesticides, which significantly reduces the need for farmers to perform such tasks, thereby reducing exposure risks. For example, the use of uncrewed aerial vehicles to spray orchards can result in a reduction of chemical exposure risk to farmers who may otherwise be exposed to herbicides or pesticides. Other technologies can selectively target the application of chemicals when and where needed, which can help reduce the total amount of chemicals that are sprayed on farms.

- **Improving quality of life for farmers**. Farmers' quality of life can be improved by increases in efficiency through certain automation technologies which save time spent on the field and reduces a farmer's fatigue. For example, auto-guidance systems can provide multiple potential benefits to farmers, including a reduction in the use of crop inputs and ensuring that none of the farm field is skipped. They can also provide quality of life improvements because of reduced operator fatigue and the ability to complete other tasks while in an auto-guided cab. Efficiencies gained through using auto-guidance reduce the overall amount of time farmers spend working in the field. For example, a 2010 ARMS survey reported that the total amount of labor-hours per bushel of corn for adopters of yield and georeferenced soil maps was 35 percent lower than that of non-adopters. [75] These quality-of-life benefits might help encourage more people to start farming, according to an industry association representing farmers. For example, dairy farmers said that their adoption of precision dairy farming technologies, such as automated milking systems and barn automation systems has reduced their workload and improved their quality of life.

4.1.3 Reducing environmental impacts

Precision agriculture technologies can mitigate negative environmental impacts

[75] U.S. Department of Agriculture, *Farm Profits and Adoption of Precision Agriculture*.

from agriculture processes by enabling the efficient use of land, water, fertilizers, herbicides, and fossil fuels.

- **Improved water and soil quality**. Farmers can use precision agriculture to better align the application of crop inputs such as fertilizer with the site-specific needs of the field, ultimately reducing the amounts of chemicals and nutrients that are applied and run off into the soil and local waterways, avoiding harmful effects associated with it. Furthermore, soil compaction and erosion can be reduced by precisely controlling where equipment travels in a field to limit compaction to defined wheel tracks, thereby improving overall soil quality. For example, with GPS auto-guidance for all equipment used in the field, the same wheel tracks are used year after year. Over time, this will result in less compaction and improved soil quality in the areas outside the wheel tracks where crops are planted, according to USDA.[76]

- **Reduced greenhouse gas emissions per unit of production**. Precision agriculture technologies have the potential to reduce crop input (e.g., fertilizers, pesticides, fuel, and water) that contribute to greenhouse gas emissions. However, studies on the technology's impact on greenhouse gas emissions is limited in literature. Using precision agriculture techniques, farmers can reduce the amount of fertilizer applied. Because production of fertilizers generates significant greenhouse gas emissions (carbon dioxide), reducing fertilizer use could result in a reduction in fertilizer production which would result in a carbon dioxide benefit. Furthermore, officials from an industry association state that efficiencies gained through using auto-guidance systems can reduce fuel consumption and, thereby, emissions.

- **Enhanced biodiversity**. Farmers can help enhance biodiversity through precision agriculture technologies and practices. Without these technologies, farmers may decide to spray their entire fields with pesticides or herbicides to eliminate existing threats. However, this approach can harm animals and insects that do not pose a threat to their crops and that benefit the local ecosystem. Applying pesticides more precisely can help mitigate potential harm to nonthreatening animals and insects, thus preventing loss of biodiversity. Furthermore, greater biodiversity in turn may benefit agriculture through effects such as an increase in pollinators, the presence of species that reduce pests, and better soil quality, according to a joint publication by the National Academy of Sciences and the Royal Society.[77]

4.2 Various challenges limit broader adoption and use of precision agriculture technology

There are several challenges that limit broader adoption and use of precision agriculture technologies including: (1) high up-front acquisition costs, (2) limited access

[76]U.S. Department of Agriculture, Natural Resources Conservation Service Research Service, *Precision Agriculture: NRCS Support for Emerging Technologies* (June 2007).

[77]National Academy of Sciences, *The Challenge of Feeding the World, Sustainably: Summary of the US-UK Scientific Forum on Sustainable Agriculture* (Washington, D.C.: 2021).

to farm data and lack of analytical tools to determine cost-effectiveness of precision agriculture technologies, (3) limited precision agriculture-focused education and training opportunities, (4) difficulties with data analysis and interpretation, (5) farm data ownership and control issues, (6) lack of standards and interoperability, and (7) lack of ubiquitous and reliable rural broadband services.

4.2.1 High up-front acquisition costs discourage broader adoption by small farms

High up-front acquisition costs are a key factor in discouraging the broader adoption of precision agriculture technology. These costs can be especially prohibitive for small and mid-sized farms with limited resources or access to capital. Large and advanced farm equipment, such as combines or tractors equipped with the latest technologies, can cost hundreds of thousands of dollars. Many smaller farms are unable to afford such equipment. Moreover, such equipment can have significant repair or replacement costs. According to USDA, the average premium paid by U.S. soybean farmers for variable rate technology applicators was approximately $5,600, and the equipment replacement costs for yield monitors was $8,000 in 2018.[78] In addition, some precision agriculture tools have annual user fees (i.e., subscription to cloud-based farm management information systems). Consequently, those managing smaller farms are less likely to adopt new precision agriculture-enabled equipment and technologies.

In contrast, adoption rates are generally higher among larger farms. For example, according to USDA, from 2016 through 2019, only 7 percent of the smallest corn farms (less than 200 acres) had an operator who adopted yield maps. In contrast, 50 percent of larger corn farms (more than 1,725 acres) had an operator who adopted yield maps. More broadly, adoption rates tend to increase with farm size, regardless of technology or crop. Large commercial farming operations are likely better positioned to routinely upgrade or buy new equipment, as they can spread out the costs over a large enough cropland base while earning sufficiently high revenues.

4.2.2 Limited access to farm data and lack of analytical tools to determine costs and benefits of precision agriculture technologies

Because precision agriculture relies on accurate and timely farm data, limited access to such data may be a barrier to widespread adoption of precision agriculture technologies. While precision agriculture equipment manufacturers are collecting large amounts of data directly from farm fields, such as soil moisture levels, weather patterns, crop yield, and crop health information, such data may not be readily accessible to farmers via farm equipment or smart applications, according to USDA.[79] In addition, equipment manufacturers are not likely to share data with policymakers and researchers. Furthermore, farm data from equipment manufacturers or service providers may not be accurate or comprehensive. Consequently, absent data and a means of analyzing the

[78]U.S. Department of Agriculture, *Precision Agriculture in the Digital Era*.

[79]U.S. Department of Agriculture, *Precision Agriculture in the Digital Era*.

data, farmers are reluctant to adopt new technologies if the return on investment cannot be determined or estimated with confidence.

While farmers must determine whether technologies would be cost beneficial for their own farming operations, few analytical tools exist to help them make such determinations. Furthermore, production environments are unique, and specific to each farm, which can limit a farmer's ability to make decisions about whether to adopt a technology for cost-effectiveness when comparing with other farms.

4.2.3 Additional education and training opportunities may be needed for the successful use of precision agriculture technologies

Additional education and training opportunities may be needed to help farmers successfully use precision agriculture technologies. Increasingly, precision agriculture technologies involve data-intensive software. They have also become more complex over time and costly to learn. Therefore, as farmers adopt precision agriculture technologies, they will require workers with different skills. For instance, individuals proficient in using precision agriculture software apps and cloud-based tools can empower farmers to better track, manage, and maximize crop yields and revenues while preserving resources. While larger farms typically possess the resources and workforce necessary for learning the proper installation, operation, and maintenance of these technologies, some farmers lack the necessary skills and knowledge about their availability and benefits, which may limit adoption. According to USDA, a gap exists between farm operators who are technologically savvy and those who are not.[80] The latter group may increasingly miss opportunities for productivity improvements from precision agriculture technologies. Relatedly, some farmers lack trust in digital technologies, according to a recent paper.[81]

4.2.4 Difficulties with data analysis and interpretation limits adoption

Farmers can face challenges with analysis and interpretation of farm-generated data and need assistance translating data into actionable information. Farmers must analyze increasingly larger quantities of data generated by precision agriculture technologies to obtain insights for informed decision-making. However, there are relatively few software programs that translate data into actionable decisions, though these have been increasing in recent years. Furthermore, difficulties interpreting data and carrying out analysis have negatively affected adoption rates of some technologies. Additionally, for early adopters, these problems are complicated by a relative lack of educational resources about new technologies. For example, data imaging technologies have not been widely adopted despite their availability because farmers are either unable to readily analyze data

[80] U.S. Department of Agriculture, *Precision Agriculture in the Digital Era*.

[81] Jonathan McFadden, Francesca Casalini, and Jesus Antón, *Policies to Bolster Trust in Agricultural Digitalisation: Issues Note*, OECD Organisation for Economic Co-operation and Development Food, Agriculture and Fisheries Paper No. 175 (Apr. 13, 2022).

produced by these technologies, or they are not sure how to make decisions and act based on imagery and related data, according to agency officials.

4.2.5 Farm data ownership and control issues

Increased precision agriculture technology use has raised concerns about ownership and control of farm data. More farmers are adopting precision agriculture technologies, and new devices are collecting increasingly larger amounts of real-time data on more farms. However, some farmers are concerned about losing ownership or control of their farm data if they decide to share that data with others. Their concerns include:

- **Concerns about loss of competitive advantage**. According to stakeholders we interviewed, some farmers are reluctant to share their data with third-party entities because of concerns about disclosures that may result in a loss of a competitive advantage. For example, agency officials have observed farmers protecting their data from other farmers in their local area, who they may see as their competitors.

- **Farm data sharing and ownership issues**. According to stakeholders we interviewed, some farmers are concerned about losing ownership or control of their farm data if they decide to share that data with others, which may limit their willingness to adopt technologies altogether. Because farm-level data is needed to train the AI models, concerns regarding farm data sharing and ownership can also pose obstacles to the widespread use of AI in agriculture.

  Farmers are also concerned about the security of their farm data in terms of cyber security and the potential for misuse. If they believe a company or third party may use their farm data in ways of which they are not aware, they may not adopt certain technologies. In addition, farmers may be hesitant to try a technology that provides data to a third party for repair or maintenance purposes, according to an academic professor. However, the extent to which farmers are concerned about the ownership and control of their data varies. While some farmers may worry about competitors having access to and using their data for a competitive advantage, some farmers are ambivalent or may not be concerned about sharing data if the technology is benefiting their operation.

- **Regulatory concerns**. Some farmers are reluctant to share their data with the federal government or third-party entities due to concerns about potential disclosures that may result in additional regulatory scrutiny. For example, an industry association representing farmers told us that farmers are concerned about the prospect of their pesticide or fertilizer usage data becoming available to the public, including regulators, which might result in more regulation. This concern could hinder further technology adoption.

4.2.7 Lack of standards affects the interoperability of precision agriculture technologies

A lack of standardization among different devices and platforms can hamper interoperability between different precision agriculture technologies. The value of many connected technologies comes from interoperability, but the industry lacks standards to drive compatibility between precision agriculture technologies, according to USDA. For example, farmers often do not have a homogeneous set of equipment from a single manufacturer and instead tend to own equipment from a variety of manufacturers. Without interoperability standards, farmers have to evaluate if new technologies can work with the equipment they already own. Without interoperable software, farmers may have a difficult time assessing the effectiveness of their farming operations, which may limit their ability to use devices to their full potential.[82] Additionally, a lack of interoperability could also create compatibility and data quality issues and impede broader adoption of precision agriculture technologies. Representatives from an industry association we interviewed stated that all equipment should be able to "talk to each other." While manufacturers may be trying to make technologies more interoperable with one another, farmers currently experience challenges with equipment interoperability.

4.2.8 Lack of ubiquitous and reliable rural broadband services

A lack of reliable rural broadband connectivity limits the ability of farmers to aggregate, analyze, and act on data. A reliable broadband connection to the internet is an enabling technology of precision agriculture that can further maximize efficiencies, but it is not widely available across rural America. While some "next generation" precision agriculture technologies function with basic internet connections, many require a more reliable and high-speed internet connection. For example, although cloud-based data sharing and aggregation services are emerging, such services are not readily available. This especially affects farmers in the specialty crops and livestock and dairy industry—those who might benefit more than those using row crop applications. According to USDA, the benefits derived from precision agriculture technologies are substantially diminished when the internet is not reliable enough to support connected devices used in such technologies.

We have previously reported that the gap—or differences in levels of internet access—is persistent and affected by gaps in broadband availability and in adoption. Although progress has been made in expanding broadband deployment in the United States, a significant gap in fixed broadband availability remains between urban and rural populations.[83] At least 17 percent of rural Americans lack access to fixed broadband at speeds of 25 megabits per second when downloading and 3 megabits per second

[82]For this report, we refer to farming operations as any operation involved in the growing or harvesting of crops, the raising of livestock or poultry, or related activities conducted by a farmer on sites such as farms, ranches, orchards, and dairy farms or similar farming operations.

[83]GAO-22-104611.

when uploading, compared to only 1 percent of Americans in urban areas, according to FCC data from the end of 2019.[84] According to FCC and USDA, broadband programs may assist rural farms with obtaining broadband connectivity to the "last mile" or "last acre."[85].

[84]Federal Communications Commission, *Fourteenth Broadband Deployment Report,* para. 33. FCC uses the Census Bureau definitions of urban and rural. Urban areas represent densely developed territory, and encompass residential, commercial, and other non-residential urban land uses. The term "rural" encompasses all other areas.

[85]For the purposes of this report, we focus on broadband connectivity in rural areas from the community to the farm and field, or the "last mile" or "last acre" which we define as the link between internet service provider and the farmhouse or farm field, respectively.

5 Policy Options to Enhance Benefits and Address Challenges Associated with Precision Agriculture Technology Adoption and Use

We examined policy options that could help address the challenges or enhance the benefits of precision agriculture and structured them to support three policy goals. Specifically, we examined (1) three policy options to encourage greater adoption and use of precision agriculture technologies, (2) two policy options to encourage further innovation in precision agriculture technologies, and (3) two policy options to manage greater amounts of data generated by precision agriculture technologies. These policy options identify possible actions by policymakers, which include Congress, federal agencies, state and local governments, academic and research institutions, and industry. In addition, for each of these three policy goals, we discuss an option in which policymakers may choose no additional policy interventions—that is, maintaining the status quo by continuing existing activities. It is also important to note that policymakers face a range of important and competing priorities for funding investments across programs and areas of the economy.

5.1 Encourage greater adoption and use of precision agriculture technologies

We examined three policy options in support of the goal of encouraging greater adoption and use of precision agriculture technologies: provide additional incentives or other financial support to facilitate the purchase and use of such technologies; support efforts to better quantify benefits of their use; and encourage further promotion and outreach to users. In addition, policymakers may choose an option representing no additional policy intervention, or status quo.

5.1.1 Maintain the status quo

Policymakers may choose not to take any new actions to encourage greater adoption and use of precision agriculture technologies.

Actions taken

- The federal government has supported technology adoption through financial assistance programs. For example, USDA financial assistance programs support the implementation of certain conservation practices, which can be used to offset the cost of purchasing equipment. According to USDA officials, government loan programs also indirectly support adoption by providing financing for technology acquisition, although such programs are not explicitly designed for precision agriculture equipment.

- Some federal agencies provide precision agriculture education and training through Extension, service centers, and educational programs. Private sector companies, often through dealerships and equipment retailers, provide some support services to farmers on using precision agriculture technologies.

Opportunities and considerations

According to USDA, 27 percent of U.S. farms and ranches used precision agriculture technologies in 2023. Prior USDA data showed that, while over half of the soybean crops used auto-guidance in 2018, less than a quarter of them used soil mapping. As policymakers consider whether additional actions may be unnecessary, several factors could be considered, including:

- Variety in technology adoption by the size of the farm. Farms with more acreage have led in the adoption and use of precision agriculture technologies, with smaller farms lagging.
- Type of agricultural product. For example, most federal government support for precision agriculture technology adoption and use has been used by farms producing field crops, rather than specialty crop or dairy, production.
- Potentially slower adoption and use of precision agriculture technologies.

5.1.2 Additional incentives or other financial support

Policymakers could consider providing additional or revised incentives, or other types of financial support, to facilitate the purchase and use of precision agriculture technologies.

High up-front acquisition costs for precision agriculture technologies have discouraged broader adoption by farmers. In particular, smaller farms have more limited resources to invest, which limits their available capital for acquisition or maintenance of equipment.

Implementation approaches

- Consider modifying eligibility criteria for existing federal government financial assistance programs to explicitly cover the acquisition and use of precision agriculture technologies.
- Consider expanding the level of financial assistance through new or existing federal government programs for the acquisition and use of precision agriculture technologies.
- Develop tools such as apps or websites to make it easier for farmers to identify available funding and financial assistance programs related to precision agriculture.

Opportunities and considerations

This option could help encourage the acquisition and use of precision agriculture technologies by mitigating the financial barrier that limits their use by farmers.

Farmers may not be aware that current USDA programs could provide financial assistance in adopting and using precision agriculture technologies, in part because the programs are not specifically designed to support precision agriculture. Providing information to farmers about existing financial assistance programs could increase the use of existing financial assistance programs.

As policymakers consider modifying or creating financial assistance programs, several factors could be considered, including:

- The type of program to make available to farmers, including through loan guarantees, and grants;
- Eligibility requirements, including the size or income of the farm, crop type, and which technologies or conservation practices would merit eligibility;

- How the use of precision agriculture technologies could be tied to the achievement of broader goals, such as environmental conservation;
- The extent to which a program may cover the purchase or rental and operating costs of precision agriculture equipment; and
- The overall cost of the program.

One expert told us that loan programs would likely support lower-income and smaller farming operations the most because, historically, most large commercial farmers have access to credit and would not want to accept the extensive terms and conditions typically associated with government funding programs. Further, loan programs may be designed to have a low cost to the government relative to the amounts loaned, and some loan programs have resulted in estimated budgetary savings to the government. In addition, a stakeholder told us that equipment rental programs could allow farmers to gain experience with new technologies with a relatively low financial commitment.

Another expert told us that existing tax law provides certain benefits through how agricultural equipment depreciation is handled. As such, according to this expert, policy options for increasing precision agriculture technology adoption may need to be achieved through alternative financial assistance programs rather than tax benefits.

Experts also told us that policies could be devised that also realize goals such as environmental protection, which could be a justification for financial assistance supporting farmers. However, it is difficult to measure and quantify environmental benefits from technology adoption and use. Other goals that could be considered include addressing food insecurity and enhancing U.S. agricultural competitiveness.

5.1.3 Quantify benefits and costs of precision agriculture technologies

Policymakers could consider supporting efforts to better understand and quantify the benefits and costs of using precision agriculture technologies.

Data and studies on benefits to farmers, as well as to society and the environment, from the use of precision agriculture technologies are limited. Some available studies indicate that adoption and use of precision agriculture technologies can help farmers increase profits and have the potential to increase societal benefits, such as improved environmental quality. However, the variability of farm conditions, such as soil type, makes it challenging to develop comparisons between farms and presents difficulties estimating benefits.

Despite the promise of increased benefits, farmers can be reluctant to adopt and use precision agriculture technologies unless they have a high degree of confidence in the potential for increased profits and yields. Developing better return on investment estimates can help farmers visualize and understand the long-term financial implications of adopting precision agriculture technologies.

Implementation approaches

- Support the development of analytical tools, models, and research to calculate costs and benefits associated with adopting precision agriculture technologies.
- Incentivize farmers to better assess or measure the effects of adoption and use of precision agriculture technologies on yield.

Opportunities and considerations

Because changing on-farm practices through technology use costs money and can create risks, obtaining good information to estimate the return on investment could help farmers visualize and understand longer-term financial implications. Improved analytical tools could help farmers better estimate potential costs and benefits for more informed decision-making.

As policymakers consider supporting efforts to better quantify costs and benefits from precision agriculture technology adoption and use, several factors could be considered, including:

- The development of tools that can be configured to be specific to a farm, factoring in geography, soil type(s), weather, technologies, and crop production systems;
- Tools that are easy to use and can be adapted to pre-existing methods for calculating or estimating yield, given different farming operations and conditions;
- Demonstration that estimates of benefits are based on data-driven models and real-world experiences, which can help increase farmers' confidence in what potential benefits could be for them; and
- The extent to which environmental benefits can be quantified in conjunction with financial benefits estimates, such as changes in nutrient runoff or greenhouse gas reductions stemming from technology use.

Experts told us that precision agriculture technologies need to be proven as beneficial. For example, a specific type of in-ground sensor to measure agricultural conditions has seen little adoption in part because it has not been demonstrated to increase the efficiency of farming operations.

5.1.4 Promotion and outreach to users

Policymakers could consider encouraging further promotion and outreach activities to farmers to increase awareness of precision agriculture technologies and their use.

As precision agriculture functionality is added to farm equipment, some farmers will need training to learn how to fully use the functionality. Further, data-intensive technologies require certain skill sets to analyze and interpret the data. In some cases, farmers are unaware of the availability of certain precision agriculture technologies and how they could benefit farm operations. Finally, some farmers are reluctant to adopt precision agriculture technologies as they need to see technology working for one or more growing seasons before deciding to purchase their own equipment.

Implementation approaches

- Consider expanding Extension services to enable development of more expertise and technical support to farmers.
- Increase on-farm field demonstrations and experimentation.
- Create education and training opportunities for farmers and the agricultural workforce to improve skills to be able to fully use current or emerging precision agriculture technologies and interpret complex farm data generated by the technologies.

Opportunities and considerations

Providing farmers with objective information on different technologies and how they can benefit a farmer's operations are critical steps to greater adoption. Extension service providers are perceived as honest brokers of information and can help farmers build trust with precision agriculture technologies while decreasing the time and effort needed to learn them. However, according to Extension officials and others, Extension practitioners themselves may need additional training, and it can take years for them to fully understand and assess the efficacy of new technologies.

As policymakers consider education and training opportunities for farmers on the use of precision agriculture technologies, a variety of factors could be considered, including:

- The extent to which federal agencies could provide training, such as through USDA service centers;
- Courses that could be offered by local community colleges and 4-year universities; and
- The potential for technology companies and dealerships to take on more of a role, as they are often the first to be informed about the latest technology innovations.

Experts told us that Extension services have diminished over the years and more technical and other support has shifted to states and private consultants. Extension specialists who provide information to farmers now work more with consultants, dealers, retailers, and crop advisors than they have in the past. In addition, training and education efforts provided by government could help build trust and foster greater communication between farmers and companies.

Experts told us that land-grant universities have historically hired some faculty members to dedicate nearly all of their time to Extension work. More recently, however, faculty are being hired with much less of their time dedicated to Extension work, where universities are prioritizing teaching needs.

Some stakeholders told us that on-site demonstrations provide opportunities for farmers to learn about precision agriculture technologies and get instruction on how to use new machinery and calibrate and work the controls.

Another expert told us that it is important that Extension specialists work in collaboration with private consultants or retailers who provide agriculture services.

5.2 Encouraging further innovation in precision agriculture technologies

We examined two policy options in support of the goal of encouraging further innovation of precision agriculture technologies: supporting further research, development, and deployment of technologies for improved data gathering and analysis of agricultural conditions; and promoting the development and use of standards. We also describe a status quo option representing no additional policy intervention.

5.2.1 Maintain the status quo

Policymakers may choose not to take any new actions to encourage further innovation of precision agriculture technologies.

Actions taken

- Federal agencies have directly and indirectly supported innovation in precision agriculture technologies through various R&D activities. USDA and NSF together provided almost $200 million from fiscal years 2017 through 2021. Other examples:
    - USDA conducts or funds research on topics such as automated feeding and milking systems, livestock tracking, rangeland management, and irrigation management.
    - USDA also conducts research on agricultural economics and manages a survey that includes questions on precision agriculture adoption.
    - NSF funds topics relevant to precision agriculture R&D, including on sensors, robotics, and unmanned aerial systems.
    - USDA and NSF jointly support emerging technology research on automation and AI to help solve challenges in the agricultural sector.
    - NASA manages programs focused on helping farmers manage inputs and make decisions more effectively using satellite and ground-based data.
- Some stakeholder groups, including standards development organizations, industry organizations, and private sector companies, are working on data integration and interoperability.

Opportunities and considerations

Federal investments in R&D have resulted in the development of some precision agriculture technologies. For example, according to USDA, one technology that resulted from its funded research is a weed sprayer that uses AI to identify weeds for herbicide spraying.

As policymakers consider whether an expansion of precision agriculture R&D activities is needed, the following could be considered:

- Roles of the government and private sector in conducting R&D. Private R&D investment in precision agriculture is expected as long as there is the potential for profit. However, according to the National Academies of Sciences, Engineering, and Medicine, left to itself, the private sector will generally underinvest in socially desirable research.

More fundamental basic research tends to need the support of governments or foundations.

- Whether current R&D programs are addressing the current and future needs for growth of precision agriculture in the United States.

- How to get the results of R&D programs commercialized and adopted by farmers.

In addition, precision agriculture technology standards could be developed by government, nonprofit associations, or the private sector without further intervention. However, existing organizations involved in standard setting may not include all stakeholders, with some hesitant to accept standards created without their input. Moreover, according to some academics, technologies may not work as intended due to lack of standardization.

5.2.2 Research, development, and deployment of technologies

Policymakers could consider supporting further research and development, and deployment, of technologies to improve on-farm data gathering and improved analysis of on-farm conditions.

The ability to gather information relating to on-farm conditions is one way to monitor soil conditions and crop growth on a more regular basis. Better sensor capabilities can provide farmers with more detailed and near-real-time measurements, allowing for more proactive decision-making accounting for changing field conditions. In addition, improved on-farm data collection can help train and test models that could help predict farm outcomes.

Implementation approaches

- Increase research for in-ground sensors to provide more detailed information on soil conditions such as nutrient and moisture levels.

- Examine ways in which remote imagery, such as from drones or robots operating under or within crops, can be analyzed and more fully used to improve on-farm data gathering.

- Explore ways to expand broadband internet access to the fields.

Opportunities and considerations

Increases in funding may be able to fill gaps where current incentives are lacking for research. However, it is not always clear how government-supported R&D can avoid duplicating private efforts while still driving material changes in technology innovation.

While R&D can help support the greater adoption of precision agriculture technology, much of the research currently focuses on large agriculture production environments rather than the needs of smaller-scale farming operations.

As policymakers consider supporting further R&D to improve on-farm data gathering and analysis of farm conditions, a variety of factors could be considered, including:

- How in-ground sensors can provide more detailed information on soil conditions which can enable farmers to further optimize the application of inputs to increase yields while minimizing costs and to identify and solve problems sooner; and

- The ability of new remote imagery sensors on drones or ground robots to provide greater image resolution, more frequent data, and quicker data delivery than traditional satellite remote imagery sources.

One expert told us, and others have reported, that investments in broadband infrastructure are needed since connectivity in the farm field will be important for use of these technologies.

In terms of technology deployment to farm fields, an expert told us there is interest in robotic cultivation and weeding, given a lack of reregistration of some herbicides.[86] Robotic cultivation could change the cost-benefit ratio for some farmers. In addition, according to two stakeholders we interviewed, the deployment of some unmanned aerial vehicle technologies on farm fields has been limited due to relevant Federal Aviation Administration regulations. Pesticide labeling and use requirements typically assume a uniform spread of a pesticide over a farm field, but this does not align with newer technology application methods.

5.2.3 Standards for precision agriculture technologies

Policymakers could consider promoting the development and use of standards for precision agriculture technologies.

This policy option could help facilitate interoperability among different farm manufacturers' technologies, particularly in moving data from one proprietary software package to another. Relatively few standards exist for precision agriculture technologies across different hardware and software platforms. Improved interoperability of different technologies could help farmers by limiting the amount of work required to determine whether certain technologies can work with equipment they already own or are considering for acquisition. It could also help address difficulties farmers and other agricultural stakeholders experience when comparing and evaluating equipment with precision agriculture technologies.

Standards are rules, conditions, guidelines, or agreed-upon practices that are adopted within an industry.[87] Created to provide

[86]According to EPA officials, EPA periodically reviews existing registered pesticides to ensure they can be used safely, without unreasonable risks to human health and the environment. According to these officials, the registration review program is intended to make sure that, as the ability to assess risk evolves and as policies and practices change, all registered pesticides continue to meet the statutory standard of no unreasonable adverse effects. In addition, in 2008, EPA completed a review of older pesticides—those initially registered before November 1, 1984—to ensure that they met current scientific and regulatory standards, according to EPA. The results of EPA's reviews were summarized in Reregistration Eligibility Decisions. See Environmental Protection Agency, "Reregistration and Other Review Programs Predating Pesticide Registration Review," Pesticide Reevaluation (Jan. 25, 2023). https://www.epa.gov/pesticide-reevaluation/reregistration-and-other-review-programs-predating-pesticide-registration.

[87]Standards include documentary standards, reference materials, and reference data. Documentary standards are written documents that describe protocols, experimental methods, technical specifications, or terminologies. Reference materials are highly characterized substances with known properties, used to ensure consistency and quality of a product, calibrate equipment, serve as experimental controls, or aid in describing and evaluating qualitative and quantitative data. Reference data are critically evaluated quantitative data related to a measurable physical or chemical property of a substance. See GAO, Regenerative Medicine*: Therapeutic Applications, Challenges, and Policy Options*, GAO-23-105430 (Washington, D.C.: Jul. 13, 2023).

researchers and developers with a common framework, standards promote consistency across product development, manufacturing, and other processes. Standards are often developed outside of the federal government by independent organizations and are therefore distinct from federal statutory or regulatory requirements.

Implementation approaches

- Promote the development of performance standards for precision agriculture technologies.

- Promote the development of data standards that could improve equipment interoperability.

- Financial assistance programs could consider specifying that precision agriculture equipment purchased through such programs comply with any applicable standards.

Opportunities and considerations

Through support of the development of performance standards for precision agriculture technologies, the government and industry may be able to set conditions allowing for rigorous, unbiased evaluation of precision agriculture technologies. For example, an accreditation program with third-party evaluation of technologies could be established to provide farmers with greater assurances of what technologies can deliver.[88] However, some precision agriculture technologies may be unsuitable for performance standards.

Since farmers may use equipment from multiple manufacturers, affecting interoperability and ease of use, data standards could lower the costs of switching between technologies and promote greater competition amongst manufacturers. Standards must be clear to ensure consistency for farm-collected data, and standard-setting entities should consider types of content, format, and data storage protocols.

Private-sector stakeholders may hesitate to adopt standards if they perceive that doing so will cost them a controlling market position. Because standards are usually developed by consensus-based organizations, the length of time between initiation of a standards working group to the publication of the standard is often long.

Experts told us that standards are important but disagreed on which aspect of standardization was most important and on the specific role for government. For example:

- One expert said that, while innovation may be hampered by standardization in the short term, it could help more entities participate in innovation.

- With respect to dairy farmers, one expert told us that developing industry standards for metrics and data aggregation are important to establish benchmarks. It also

[88]The National Institute of Standards and Technology's (NIST) National Voluntary Laboratory Accreditation Program, for example, provides third-party accreditation to testing and calibration laboratories in response to legislative actions or requests from government agencies or private sector organizations. See National Voluntary Laboratory Accreditation Program, https://www.nist.gov/nvlap.

provides a method for producers to share their data with outside consultants. Often, the raw data from sensors cannot be standardized across manufacturers of those sensors if the raw data are even available to a producer directly. Establishing methods to transform these data and enable comparisons among farms will improve competition and reduce costs to improve access and adoption of precision technologies.

- Another expert said that consolidations and monopolies may arise in the agriculture sector and that standards could help level the playing field.
- Another expert said that standards are increasingly important and that, without them, it can be hard to assess the quality of data derived from farm measurements and limit the use of data for research or other purposes.
- One expert said that some farm data, such as those on soil fertility, are largely useless without good metadata, such as information extracted directly from a soil sample. The expert said that metadata are especially important when making comparisons across geographic regions.
- One expert said that professional societies have played an important role with respect to standardization issues on farms.

5.3 Managing greater amounts of data generated by precision agriculture technologies

We examined two policy options in support of the goal of managing greater amounts of data generated by precision agriculture technologies, along with a status quo option that represents no additional policy intervention. The two policy options are to enhance data analysis to provide more useful information to farmers and to encourage precision agriculture data sharing.

5.3.1 Maintain the status quo

Policymakers may choose not to take any new actions to manage greater amounts of data generated by precision agriculture technologies.

Actions taken

- Limited tools are available to help farmers manage and analyze large amounts of data.
- Large farms have invested time and money with private-sector companies, paying a fee for data curation and analysis services. However, many small farms may not have the resources to pay for such services or to hire crop consultants or agronomists.

Opportunities and considerations

Many farming operations will continue to collect data, increasingly so with certain precision agriculture technologies. However, farmers typically do not use the data or perform analysis of data beyond yield maps. Further, agronomists and Extension officials rarely receive farm-specific data that could be used to better innovate and improve services to the farm. Precision agriculture equipment manufacturers collect large amounts of data directly from their equipment deployed at farms, including information on soil moisture levels, crop yield, and crop health.

5.3.2 Enhance data analysis

Policymakers could consider enhancing data analytic tools to provide useful information to farmers.

Enhancing and improving analysis of data generated on farms is becoming more important as precision agriculture technologies increasingly collect more data on farm conditions. Data analysis techniques leveraging advanced computing power can serve multiple purposes, such as generating valuable information from a large amount of data, forecasting, increasing crop production, reducing production cost and food loss, and automating the farming process.

Some farmers can find the task of interpreting data collected on their fields to be difficult. Farmers who are new to precision agriculture might not know how to use the information collected from their farm and stored in spreadsheets and maps for decision-making. In addition, universal algorithms or software programs that could easily translate data collected on farms into actionable decisions do not exist. This gap leaves farmers with the responsibility of analyzing data on their own or seeking the help of third-party experts.

Implementation approaches

- Support the development of software that could help farmers better manage their farms.
- Examine how AI and machine learning could help facilitate the analysis and interpretation of increasingly complex agriculture data.
- Ensure the accessibility, interoperability, and use of publicly available farm data for data analysis and improved management of farm operations.

Opportunities and considerations

With additional data analysis, farmers could improve decision-making, such as better identifying underperforming portions of farms and determining what land to augment or remove from production. It could also help farmers make decisions that simultaneously help the environment, for example, by reducing the use of fertilizer on poorly performing land that would result in less nutrient run off into waterways.

Data analytics and high-performance computing approaches hold the promise of generating valuable information that can be used by farmers and other agricultural stakeholders to maximize crop production and help minimize costs. However, these approaches require large amounts of data. Software applications could help farmers make better on-farm decisions, but the development and use of such software is often contingent on the availability of datasets and other information, which can be unique to geographic regions, crop type, and different stages of growth.

One expert told us that precision agriculture technologies can give farmers tools, such as yield monitors, to help identify outcomes of various decisions. However, farmers generally do not have the tools or ability needed to analyze the data appropriately. While some software has been developed to streamline the planning of farming operations and help with data analysis, such software is not commonly used. Another expert said that decision support tools are needed to implement better on-farm practices. For example, variable rate irrigation and scheduling technologies exist, but decision support tools on how to apply the technologies are lacking. As a result, farmers may continue to rely on agronomists, Extension officials, and consultants to help them use the data to improve their farm operations.

While AI and machine learning can be used to develop predictive models to help many farmers, one expert told us that AI systems and models need large agricultural datasets for developing such models. The expert added that there are many benefits of using data from multiple farmers, over many farm fields and growing seasons. For example, AI can help farmers leverage data from multiple farms from prior growing seasons and combine it with in-season satellite imagery to learn how a crop may respond to different applications of nitrogen.

One expert told us that profitability maps can be a useful tool for farmers, many of whom tend to optimize yield rather than minimize cost. For example, some farmers do not know the production costs on their farms, or they prioritize saving time over cost. Profitability maps can help increase a farmer's awareness of trade-offs and how to better optimize decision-making.

5.3.3 Data sharing

Policymakers could consider encouraging farmers to share precision agriculture data.

Optimizing farm operations requires the aggregation and analysis of data from many farms. With less or potentially biased data, the ability to conduct meaningful analyses and the quality of any findings declines. However, the quality of analysis increases as the number of users providing data increases. Increased data sharing could help encourage broader collection of information on farm conditions, thereby helping develop programs to improve societal and environmental benefits or allowing others to provide analysis and help make farm-specific management decisions.

Implementation approaches

- Use incentives to encourage data sharing by farmers.
- Develop a governance framework to manage, access, and store agricultural data.
- Establish easy-to-understand private data license agreements and codes of conduct that enable the free flow of data, making it easier for farmers to switch to other solutions and services.
- Increase awareness within the agricultural stakeholder community of the value of data sharing to help all farmers make data-driven decisions.

Opportunities and considerations

A key consideration for farmers is the ownership and sharing of data stemming, in part, from a general lack of trust in the way farm data are being collected and managed, for example, through the onboard computers of some farm machinery. If data are to be shared, terms and conditions of data licenses must be easy to understand and transparent.

Farmers are often best positioned to collect specific and detailed data on farm conditions and can do so more efficiently than federal agencies or third parties. Such data collection could be incentivized with federal funding. With further data sharing, according to experts, data could be made available to researchers resulting in publicly available analyses that could in turn help farmers and other agricultural stakeholders.

A governance framework for storing, sharing, and managing agricultural data could include a recourse for farmers in the event of a loss of control over data, such as the unintentional release of data, according to stakeholders we interviewed. Such a framework could also include protections against data misuse or breaches and enhanced cybersecurity control requirements.

Experts told us that an important distinction is between data that require collection across multiple farms and data that are used within a given farm. According to the experts, the former poses the greatest potential for issues such as farmer mistrust to arise. Farm-specific data such as input use or cost typically varies from farm to farm and is considered by farmers as sensitive. Other data can be anonymous and linked to a general location but not a specific farm field. Experts said there is an opportunity to think about analysis of such data over a broader region, which can help all farmers in that region make better decisions based on the shared data.

With respect to dairy farms, an expert described how producers at large operations rarely gain access to raw data, which are retained by the owner or company. While a dairy farmer may not need access to such data, outside consultants are unable to make comparisons across farming operations, for example to establish benchmarks.

Experts described a broader opportunity for sharing data on a national level to enable more access that could result in greater benefits to society. Research institutions, for example, could use the data to provide new insights that could benefit farmers and society. Similar to how weather data are collected through a series of meteorological stations, farm data could be collected and analyzed to help farmers make better decisions.

6 Agency and Expert Comments

We provided a draft of this report to the Departments of Agriculture, Commerce, and Health and Human Services; the Environmental Protection Agency; the Federal Communications Commission; the National Aeronautics and Space Administration; and the National Science Foundation for their review and comments. The Department of Agriculture, Environmental Protection Agency, Federal Communications Commission, National Aeronautics and Space Administration, and National Science Foundation provided technical comments, which we incorporated as appropriate. The Departments of Commerce and Health and Human Services responded that they did not have any comments.

We also provided a draft of this report to 13 experts for their technical review. Seven of the experts responded, five of which provided technical comments, which we incorporated as appropriate. The other two experts that responded indicated that they did not have any comments. Six of the experts did not respond.

We are sending copies of this report to the appropriate congressional committees, relevant federal agencies, and other interested parties. In addition, the report is available at no charge on the GAO website at https://www.gao.gov.

If you or your staff members have any questions about this report, please contact Brian Bothwell at (202) 512-6888 or BothwellB@gao.gov or Steve D. Morris at (202)-512-3841 or MorrisS@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made contributions to this report are listed in Appendix IV.

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Appendix I: Objectives, Scope, and Methodology

We prepared this report in response to section 10361 in the Advancing IoT for Precision Agriculture Act of 2021, contained in what is commonly referred to as the CHIPS and Science Act of 2022.[89] It includes a provision for GAO to provide a technology assessment of precision agriculture technologies. In addition, the statute includes a provision for GAO to perform a review of federal programs that provide support for precision agriculture research, development, adoption, education, or training, in existence on the date of enactment. This technology assessment responds to both of these provisions. We examined (1) precision agriculture technology adoption and emerging precision agriculture technologies, (2) federal programs providing support for precision agriculture, (3) benefits and challenges of adopting and using precision agriculture technologies, and (4) policy options that could help enhance benefits or address challenges related to adopting and using precision agriculture technologies.

For the purposes of this review, we defined “precision agriculture” as the collection of data that are specific in location or time that is used to improve resource management through the precise application of inputs, such as water, fertilizer, and feed, leading to more efficient agricultural production. Literature and stakeholders used additional and complementary terms such as smart farming and digital agriculture. For our work, we treated the phrases as interchangeable with precision agriculture.

Using a criteria-based approach, we selected four agriculture commodities as a judgmental sample: corn, soybeans, grapes, and dairy. Our criteria included: economic impact; acres farmed (for field and specialty crops); pounds produced (for livestock); regional diversity; and existing precision agriculture use cases where benefits and challenges could be identified.

We further scoped our work to focus on farm activities that occur on the field or in the dairy barn. These activities include planting of row and specialty crops; nutrient management for plants and animals; data collection on the condition of the farm, commodity, or animal(s); data analysis on collected data; actions conducted by the farmer based on recommendations from data analysis; harvest of a commodity; and equipment and technology supporting the above activities.

To conduct our work across all four objectives, we:

- Interviewed officials from the Federal Communications Commission, Environmental Protection Agency, Food and Drug Administration, National Aeronautics and Space Administration, the Department of Commerce (National Institute of Standards and Technology, National Oceanic and Atmospheric Administration, and National

[89]Pub. L. No. 117-167, div. B, tit. III, subt. E, § 10361(e), 136 Stat. 1366, 1567-68 (Aug. 2022).

Telecommunications and Information Administration), National Science Foundation (NSF), and the U.S. Department of Agriculture (USDA). Within USDA we interviewed officials from the Agricultural Research Service, Economic Research Service, Farm Service Agency, National Agricultural Statistics Service, National Institute of Food and Agriculture, and Natural Resources Conservation Service. We also interviewed a non-generalizable sample of stakeholders from academia, cooperative Extension, industry, and trade groups.

- Conducted two site visits in Illinois and Pennsylvania where we visited industry, two dairy farms, and an academic institution. The information gathered on site visits does not represent a generalizable sample of technologies or stakeholder views.

- Attended the International Society of Precision Agriculture conference in Minneapolis, Minnesota, from June 26-29, 2022, to learn about emerging precision agriculture topics.

- Attended the Alabama Extension Precision Agriculture Workshop on February 8, 2023, to gather information on the use and implementation of precision agriculture technologies.

- Reviewed agency documents and reports, peer-reviewed literature, and other literature, such as white papers and industry reports. We identified literature based on online searches and at the recommendation of agency officials, experts, and other stakeholders. We also conducted a literature search on precision agriculture technologies, adoption, benefits, and challenges. A GAO librarian searched databases using keywords such as "precision agriculture", "digital agriculture," "digital farming," and "smart farming" to identify relevant articles.

For our first objective, we used USDA's Agricultural Resource Management Survey (ARMS) as a primary source to discuss precision agriculture technology adoption. Through our review of related ARMS documentation, an interview with Economic Research Service (ERS) and National Agricultural Statistics Service (NASS) officials, and because NASS is a federal statistical center, we determined that the ARMS data was sufficiently reliable for our work. The list of agriculture equipment and precision agriculture technologies discussed in this report is not intended to be exhaustive.

For our second objective, we also reviewed and analyzed USDA and NSF financial data related to precision agriculture expenditures. We assessed the reliability of those data by asking agency officials to explain the data systems, including how data are entered, recorded, tracked, maintained, and any uncertainty in the data. We determined the data to be sufficiently reliable for our work. We also created a database or inventory of federal programs that support precision agriculture research, development, adoption, education, or training from agency websites, agency documentation, and interviews with agency officials.

For our third objective, we conducted an analysis of USDA's ARMS data and relevant studies by industrial organizations to gain insights into the benefits and challenges of adopting and using precision agriculture technologies. We then summarized these benefits and challenges. We selected specific benefits and challenges that were well supported in the literature or corroborated by testimonial evidence from agency officials and industry representatives whom we interviewed. While some of the benefits and challenges we discuss are derived from experimental studies and surveys reported in the literature, the findings from these studies are non-generalizable. They serve as illustrative examples, providing insights into potential benefits and challenges related to the adoption of precision agriculture technology. The real benefits and challenges experienced by farmers using precision agriculture technologies may differ from those observed in these studies or proposed by industry associations.

For our fourth objective, we conducted a virtual 3-day meeting of 13 experts to gather evidence and viewpoints on potential policy options to enhance benefits or address identified precision agriculture adoption challenges. With the assistance of the National Academies of Sciences, Engineering, and Medicine, we selected experts based on their expertise of precision agriculture, including expertise with row and specialty crops, livestock dairy farming, agricultural economics, technology adoption, agronomy, and environmental and conservation issues in agriculture. We also sought to obtain a balance of perspectives across the industrial and academic sectors. Top candidates were identified and prioritized according to their level of expertise. National Academies staff followed up with experts to ask questions regarding conflicts of interest using a GAO-provided form, and GAO screened the experts regarding any conflicts of interest that were disclosed. One expert did not provide a completed conflict of interest form, despite our efforts to obtain it. Although this expert had minor participation during our meeting, the contributions from the expert were limited and nothing this expert said at the meeting contributed to, or was relied on, for this report. We did not ask experts to speak on behalf of the organizations they represent but rather on the basis of their personal professional views. The complete expert list is shown in appendix III. While the experts were identified with the assistance of the National Academies to better ensure that a breadth of expertise was brought to bear in its preparation, all final decisions regarding expert selections were the responsibility of GAO. Prior to the meetings, we asked experts to review a list of policy goals and options we developed from reviews of scholarly peer-reviewed material, conference papers, government reports, trade or industry articles, and association and nonprofit publications. This was done through SCOPUS and ProQuest search engines. We searched information sources using a variety of terms, including but not limited to “precision agriculture,” “digital agriculture,” “precision livestock farming,” and “smart farming,” and our searches returned a total of 607 documents. We also obtained information through 13 federal agency and 25 stakeholder group interviews. The policy goals and options, along with implementation approaches, were identified based on whether the term “policy” or “policy goal” appeared or if the source(s) discussed options that could be taken that could achieve a policy aim, such as increasing technology adoption, enhancing benefits from technology use, or addressing a challenge to increased adoption. The initial policy goals and options were categorized into themes, depending on if they frequently arose during our reviews of these materials. Those that did not appear as frequently across these sources were not included in the final policy goal and options categories. More specifically, the policy options categories were developed if the topics arose three or more times and were clearly distinct from other categories. In addition, opportunities and considerations for each of the identified policy options may have been identified in one or more of the information sources we reviewed. We further refined and assessed these policy goals and options after the initial categorization to ensure they were adequately supported by the evidence we collected, could be feasibly implemented, and fit into the overall scope of our work.

During the expert meetings, we discussed each policy goal, associated policy options, and which implementation approaches or actions may or may not work to implement them. We had experts elaborate on opportunities and considerations for each. We also asked which policy options, if any, would be counterproductive to increase precision agriculture technology adoption and to achieve the other policy goals we identified. We also asked experts whether the policy goals and each policy option were appropriate, and solicited input on their structure and whether additional policy options should be considered. To finalize our list of policy options, policy goals, implementation approaches, and opportunities and considerations, we analyzed the information obtained through the expert meetings, along with information derived from our analysis of literature, government and nongovernmental reports, and stakeholders we interviewed. In reporting the policy themes that were identified and discussed most frequently, we highlight multiple perspectives on a topic to ensure a holistic and representative presentation of the information. This means, at times, the views of one or two experts are highlighted in order to reflect the full range of expert views.

Our methodology allowed for open responses from experts to identify which policies from our list of options stood out to them. Therefore, we did not receive comments from every expert on each of the policies. The total number of experts who agreed or disagreed with a particular policy option reflects only those experts who identified the option as either particularly beneficial or particularly unhelpful.

All final decisions regarding meeting substance and expert participation are the responsibility of and were made by GAO. The expert meeting was not designed to produce a consensus on policy options or other topics among the experts who participated. Rather, it was designed to generate a range of experts' perspectives on each of the policy options discussed. As a result, experts may have agreed with each other on some points but disagreed with each other on other points. We offered our meeting experts the opportunity to review and provide technical comments on a draft of our report. We received comments from 7 of the 13 experts. We incorporated expert comments into the report, as appropriate.

We conducted our work from April 2022 to January 2024 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

Appendix II: Federal Support Related to Precision Agriculture

The table below displays federal agency efforts to support precision agriculture technology adoption, research and development, education, and training. The following descriptions consist of information from agency websites, documentation, and interviews with agency officials.

Table 4: Federal support related to precision agriculture

Agency	Effort	Description
Federal Communications Commission (FCC)	Task Force for Reviewing the Connectivity and Technology Needs of Precision Agriculture in the United States	Provides advice and recommendations to the FCC on how to assess and advance deployment of broadband internet access service on unserved agriculture land to promote precision agriculture.
FCC	High-Cost Program	Designed to support the construction, operation, and maintenance of infrastructure for broadband and voice service in rural, insular, and high-cost areas. FCC officials said the High-Cost Program includes rural broadband efforts within the Connect America Fund, Rural Digital Opportunity Fund, and 5G Fund for Rural America.
National Aeronautics and Space Administration (NASA)	Acres	Established by NASA in 2023, Acres focuses on applying Earth observation information to the most pressing agricultural and food security challenges facing U.S. farmers, ranchers, and agrifood system stakeholders.
NASA	Harvest	Enables and advances adoption of satellite Earth observations by public and private organizations to benefit food security, agriculture, and human and environmental resiliency in the U.S. and worldwide.
NASA	OpenET	Uses best available science to provide easily accessible satellite-based estimates of evapotranspiration (ET) for improved water management across the western United States. The OpenET collaborative includes leading national and international experts in remote sensing of ET, cloud computing, and water policy, partnered with nationally recognized web development teams and leaders in the western agriculture and water management communities.
NASA	Short-term Prediction Research and Transition	Focuses on applied research and applications in focus areas that span weather, atmospheric, and land surface topics with partnerships across government, academia, and the private sector.
National Science Foundation (NSF)	Directorate for Engineering (ENG)	Leads initiatives or funds projects in precision agriculture. Major efforts include the ENG Core programs, and Signals in the Soil in partnership with USDA/NIFA. ENG funded 40 awards in precision agriculture over the last 10 years.

Agency	Effort	Description
NSF	Directorate for Technology, Innovation and Partnerships (TIP)	TIP was established in March 2022. Several existing programs were moved into TIP upon its establishment, such as the NSF Innovation Corps, Partnerships for Innovation, Small Business Innovation Research/Small Business Technology Transfer, and Convergence Accelerator programs. In addition, the directorate has launched several new programs to accelerate technology development and translation as well as workforce development. TIP aims to advance critical and emerging technologies, address pressing societal and economic challenges, and accelerate the translation of research results from lab to market and society. TIP has provided funding for projects that intersect with precision agriculture topics
NSF	Directorate for Biological Sciences (BIO)	BIO supports a broad range of projects that are aimed at developing new tools for precision agriculture. BIO uses standard grants from various BIO directorates, as well as instrumentation awards, postdoctoral fellowships to train the next generation of precision agriculture innovators, and workshops to bring together researchers from diverse disciplines. BIO has funded 24 projects in precision agriculture in the last decade.
NSF	Directorate for STEM Education (EDU)	EDU funds education efforts in precision agriculture primarily through the Advanced Technological Education program. This program awarded approximately 29 projects focused on training the precision agriculture technical workforce. Awards in this portfolio include curriculum development and technician education efforts in precision agriculture, aerial systems technology, geographical information systems, GPS, robotics, electronics, and other emerging technologies relevant to precision agriculture.
NSF	Artificial Intelligence Research Institute for Advances in Optimization (AI4OPT)	According to NSF, AI4OPT focuses on automated decision-making at scale in several use-inspired domains, including optimizing the resilience and sustainability of food systems through the fusion of artificial intelligence (AI) and mathematical optimization.
NSF	AI Institute for Intelligent Cyberinfrastructure with Computational Learning in the Environment	Building a next-generation "plug-and-play" AI-enabled cyberinfrastructure to make development of AI-driven innovation more accessible and to propel the further democratization of AI in society. The use-inspired research of this institute is significantly focused on agriculture and food systems, including research on smart foodsheds, digital agriculture, and animal ecology. This institute was established in late 2021.
NSF	Computer and Information Science and Engineering (CISE) Directorate	CISE supports research in science that advances precision agriculture through various efforts, including solicitations, the core CISE programs and the Office of Advanced Infrastructure. Projects ranged from optimizing health surveillance in the swine production pipeline to an effort that couples new scientific research in computer science, agronomics, and precision agriculture with novel outreach and educational pathways that enable youth and communities to transform and ensure agriculture sustainability.
United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS)	Conservation Stewardship Program (CSP)	CSP is designed to compensate agricultural and forest producers who agree to increase their level of conservation by adopting additional conservation activities and maintaining their baseline level of conservation. NRCS officials cited nutrient management, pest management, and irrigation management as being used with precision agriculture technologies.

Agency	Effort	Description
USDA NRCS	Environmental Quality Incentives Program (EQIP)	EQIP helps farmers implement practices and activities in their conservation plan that can lead to cleaner water and air, healthier soil and better wildlife habitat, all while improving their agricultural operations. NRCS officials cited Nutrient Management, Pest Management, and Irrigation management as being used with precision agriculture technologies.
USDA NRCS	Conservation Effects Assessment Project (CEAP)	According to NRCS, CEAP findings are used to guide conservation program development and support conservationists, agricultural producers, and partners in choosing the most effective conservation actions and making informed management decisions backed by data and science. NRCS officials said there has been an increase in precision agriculture usage since beginning these assessments.
USDA Agricultural Marketing Service	Specialty Crop Block Grant Program	The Agricultural Marketing Service awarded a total of $72.9 million in fiscal year 2022 for the Specialty Crop Block Grant Program to support farmers growing specialty crops, including fruits, vegetables, tree nuts, and nursery crops.
USDA Agricultural Research Service (ARS)	National Program 305 Crop Production	The mission is to enhance U.S. agricultural crop productivity, efficiency, and sustainability, and ensure a high quality and safe supply of food, fiber, feed, ornamental, and industrial crops for the nation.
USDA ARS	National Program 216 Sustainable Agricultural Systems Research	The mission is to build the science-based foundations for farming systems of the future using a systems approach without bias for a particular science discipline. Producers will be equipped with management options offering multiple routes to achieving sustainable agriculture.
USDA ARS	National Program 211 Water Availability and Watershed Management	Conducts fundamental and applied research on the processes that control water availability and quality to promote public health and economic growth and develops new and improved technologies for managing U.S. agricultural water resources. These advances in knowledge and technologies will help improve water conservation and water use efficiency in agriculture.
USDA ARS	National Program 215 Grass, Forage, and Rangeland Agroecosystems	Develop and integrate improved management practices, germplasm, and land-use strategies to optimize economic viability and environmental enhancement in managing vegetation, livestock, and natural resources on private and public lands. Research activities can include: enhancing conservation and restoration of agroecosystems; improving management of fire, invasive weeds, and grazing; and developing grazing-based livestock systems.
USDA ARS	National Program 212 Soil and Air	Improve the quality of atmosphere and soil resources affected by and influencing agriculture and to understand the effects of and prepare agriculture for adaptation to climate change. Program priorities for research include improving air quality via management and mitigation of emissions from agricultural operations, reducing atmospheric greenhouse gas concentrations through management of agricultural emissions and carbon sequestration, adapting agriculture to climate change, and maintaining and enhancing soil resources.
USDA Animal and Plant Health Inspection Service	Plant Protection and Quarantine	Safeguards U.S. agriculture and natural resources against the entry, establishment, and spread of economically and environmentally significant pests, and facilitates the safe trade of agricultural products.

Agency	Effort	Description
USDA Economic Research Service	Agricultural Resource Management Survey (ARMS)	ARMS is the USDA's primary source of information on the production practices, resource use, and economic well-being of America's farms and ranches. The results of this survey give farmers, ranchers, and many others factual insights into many aspects of farming, ranching, and conditions in agricultural communities.
USDA Farm Service Agency (FSA)	Farm Ownership Loan	Helps farmers and ranchers purchase or enlarge family farms, improve and expand current operations, increase agricultural productivity, and assist with land tenure to save farmland for future generations. FSA officials said an example of a precision agriculture-related improvement would be constructing a new building such as a concentrated animal feeding operation that can later be outfitted with internet connectivity.
USDA FSA	Operating Loan	Provides new farmers a gateway into agricultural production by financing the cost of operating a farm. FSA officials said this loan program can help farmers acquire precision agriculture equipment such as targeted sprayers or variable rate applicators.
USDA National Institute of Food and Agriculture (NIFA)	Sustainable Agriculture Programs	Sustainable agriculture seeks to provide more profitable farm income, promote environmental stewardship, and enhance quality of life for farm families and communities. NIFA promotes sustainable agriculture through national program leadership and funding for research and Extension. It offers competitive grants programs and a professional development program, and it collaborates with other federal agencies through the USDA Sustainable Development Council.
USDA NIFA	Inter-Disciplinary Engagement in Animal Systems (A1261)	Seeks to bridge traditional disciplinary divides and address complex issues in animal agriculture. Precision animal management is a priority area, with a focus in developing technologies such as resource-smart feeding and monitoring to enhance animal production while maintaining environmental integrity.
USDA NIFA	Engineering for Agricultural Production and Processing (A1521)	Focuses on engineered devices, technologies, and tools to improve plant, animal, and forestry systems. Emphasis areas include technologies for nutrient recovery from manure; water, nutrient, pest, or disease management; and development technology for sensing and mechanization of labor-intensive tasks in crop and animal production.
USDA NIFA	Engineering for Precision Crop and Water Management (A1551)	Focuses on engineered devices, technologies, sensors, and tools to provide precision crop and orchard management, technologies for targeted application of crop protection materials, and improve efficiency of irrigation and nutrient use in agricultural systems.
USDA NIFA	Specialty Crops Research Initiative	Promotes collaboration, open communication, the exchange of information, and the development of resources that accelerate application of scientific discovery and technology to solving needs of the various specialty crop industries.
USDA NIFA	Agriculture and Food Research Initiative (AFRI)	AFRI is the nation's leading competitive grants program, according to NIFA, for agricultural sciences. AFRI awards research, education, and Extension grants to improve rural economies, increase food production, stimulate the bioeconomy, mitigate impacts of climate variability, address water availability issues, ensure food safety and security, enhance human nutrition, and train the next generation of the agricultural workforce.

Agency	Effort	Description
USDA NIFA	Farm of the Future	Competitive grant program to establish an agricultural test bed and demonstration site for precision agriculture, smart automation, data connectivity, and transfer and to demonstrate best practices in climate-smart agriculture, forestry, and animal production systems that enhance sustainability and farm profitability.
USDA NIFA	Digital Infrastructure for Research and Extension on Crops and Technology for Agriculture	Demonstrate on farms how sensors, novel genetics, and data analytics can provide rich datasets, which will better inform decision support tools for enhancing the efficiency of maize production. This will enable innovative approaches to delivering digital agriculture to both large-scale farms and to limited-resource, small-scale, and socially disadvantaged farms.
USDA Rural Development	Community Connect Grants	Provides financial assistance to eligible applicants that will provide broadband service in rural, economically challenged communities where service does not exist.
USDA Rural Development	Rural Broadband Loans, Loan/Grant Combinations, and Loan Guarantees	Furnishes loans and loan guarantees to provide funds for the costs of construction, improvement, or acquisition of facilities and equipment needed to provide broadband service in eligible rural areas.
USDA Rural Development	ReConnect	The ReConnect Program offers loans, grants, and loan-grant combinations to facilitate broadband deployment in areas of rural America.
USDA and NSF	AI Institute for Next Generation Food Systems (AIFS)	Aims to meet growing demands in the food supply by increasing efficiencies using AI and data spanning the food supply system from crop growth through consumption. AIFS research addresses autonomous farming, labor optimization, environmental resilience, soil monitoring and health, technology adoption, and public policy.
USDA and NSF	AI for Future Agricultural Resilience, Management, and Sustainability Institute (AIFARMS)	Advances AI to address challenges facing world agriculture, with an emphasis on researching technologies that affect production practices, developing a diverse and technically skilled workforce in digital agriculture, and supporting women and minority farmers. AIFARMS research includes autonomous farming, efficiency for livestock operations, environmental resilience, soil health, and technology adoption.
USDA and NSF	AI Institute for Transforming Workforce and Decision Support (AgAID)	Integrates AI methods into agricultural operations for prediction, decision support, and robotics-enabled agriculture to address agricultural challenges. AgAID uses an approach called “adopt-adapt-amplify” to develop and deliver AI solutions that address pressing challenges related to labor, water, weather and climate change.
USDA and NSF	AI Institute for Resilient Agriculture	Focuses on an AI-driven digital twins and supporting framework for modeling plants at various agronomically relevant scales. Models can be deployed across several agricultural applications in crop improvement and production. These include streamlining and revolutionizing plant breeding, assisting farmers and their advisors in adopting improved farming techniques and technologies, and driving economic development across the rural landscape through AI-inspired ventures.
USDA and NSF	AI Institute for Climate-Land Interactions, Mitigation, Adaptation, Tradeoffs and Economy	Pursues AI advances by incorporating knowledge from agriculture and forestry sciences and leveraging unique, new AI methods to curb the effects of climate change while supporting rural economies. AI-powered knowledge and solutions include AI-enhanced estimation methods of greenhouse gases and specialized field-to-market decision support tools.

Agency	Effort	Description
USDA and NSF	COntext Aware LEarning for Sustainable CybEr-agriculture systems	Develops a novel, context-aware cyber-agricultural system that encompasses sensing, modeling, and actuation to enable farmers to respond to crop stressors with lower cost, greater agility, and significantly lower environmental impact than current practices allow.

Source: GAO analysis/summary of agency and AI institute websites, agency documentation, and interviews with agency officials. | GAO-24-105962

Note: Precision agriculture is generally understood as collecting data that are specific in location or time and using the data to improve resource management through the precise application of inputs, such as water, fertilizer, and feed, leading to more efficient agricultural production. Terms such as "digital agriculture" and "smart farming" are also used to describe this collection, analysis, and actions in response to farm data.

Appendix III: Expert Participation

We collaborated with the National Academies of Science, Engineering, and Medicine to identify experts to inform our work on precision agriculture technologies. We convened meetings with these experts over 3 days. The meetings were held virtually from May 2 to 4, 2023. Experts who participated in this meeting are listed below. We provided our draft report to the experts for their technical review.

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