UNLOCKING PRECISION AGRICULTURE'S CLIMATE POTENTIAL

C2ES CLIMATE INNOVATION 2050

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Achieving net-zero emissions will require large-scale change across all sectors of the economy, and efforts to drive this transition are intensifying. Over the past several years, through the Climate Innovation 2050 initiative, the Center for Climate and Energy Solutions (C2ES) has engaged closely with leading companies across diverse sectors to examine challenges and solutions to decarbonizing the U.S. economy by 2050. As we laid out in *Getting to Zero: A U.S. Climate Agenda*, reaching net-zero will require this large-scale change, but it will also require us to address a number of discrete and urgent challenges. To inform policymakers considering these near- and long-term questions, C2ES launched a series of *"Closer Look"* briefs to investigate important facets of the decarbonization challenge, focusing on key technologies, critical policy instruments, and cross-sectoral challenges. These briefs explore policy implications and outline key steps needed to reach net-zero by mid-century.

EXECUTIVE SUMMARY

For decades, a precision agriculture (PA) revolution has been 'just around the corner,' promising to transform American agriculture. While precision technologies—including variable rate applications, soil sensors, autosteering systems, and others—have significant potential to improve environmental outcomes, they have yet to be adopted at scale in the United States. As momentum grows to decarbonize every sector of the economy, PA is again gaining attention, due to its ability to both reduce emissions and enhance carbon sequestration in farmlands. PA technologies can address climate change in multiple ways, including by reducing fuel use, curbing the overapplication of nitrogen fertilizer, reducing product loss and waste, improving production efficiencies, and enabling conservation practices that grow farms' and ranches' carbon sink potential.

PA also faces numerous barriers, though, including high upfront costs, less applicability to small and diversified farming operations, lack of broadband connectivity, data privacy concerns, difficulty with interoperability between technologies, and producer skepticism. As a result, the promised PA 'revolution' may

never be fully realized, although expanding PA adoption even absent industry-wide transformation still offers tangible benefits.

To address barriers and maximize PA's potential, policymakers should take action in the following key areas:

- *Research, development, and demonstration*: To better characterize PA's climate benefits in various production systems, research needs to be ramped up to strengthen the climate case for PA investments and identify technologies with the highest potential. PA technologies also need to be developed that can be applied to a diversity of farming systems, beyond large-scale, monocultured row crops. In addition, demonstration efforts will be critical to scaling PA by allowing producers to see its impacts firsthand.
- *Enabling support for producers*: Multiple PA technologies have high barriers to entry (e.g., broadband requirements, upfront cost), and the abundance of information generated by PA equipment can make it challenging for producers to transform that data into climate-smart decisions. The U.S. Department of Agriculture (USDA) and its partners should address adoption barriers by investing in high-quality broadband and strengthening incentives for PA, while assisting producers to interpret PA data in ways that result in climate benefits.
- *Data considerations*: USDA, Congress, the private sector, and producers need to coordinate to address data challenges that can both limit PA adoption and dampen the utility of PA data. This includes addressing concerns with data privacy in the industry and enhancing the interoperability of PA equipment.

By taking action in these key areas, policymakers can help precision agriculture technologies play an important role in maintaining the productivity of American agriculture while delivering benefits for producers, improving environmental outcomes, and enhancing the sector's role in meeting economy-wide net-zero goals.

INTRODUCTION: THE POTENTIAL OF PRECISION AGRICULTURE

The U.S. agriculture sector occupies a unique space from a climate perspective: It acts both as an emissions source and as a carbon sink. In 2020, the sector was responsible for 11 percent of total U.S. greenhouse gas emissions.[1] Roughly half these emissions come from how agricultural soils are managed. For example, the overapplication of nitrogen-based fertilizer leaves excess nitrogen in the soil which turns into nitrous oxide (N_2O), a potent greenhouse gas. Emissions from enteric fermentation (i.e., methane released when ruminant animals such as cows digest feed) and manure management are the next largest sources, followed by fossil fuel combustion for tractors, combines, and other uses. At the same time, agricultural lands also sequester, or store, carbon in plant biomass (e.g., trees, shrubs, plants, and roots) and soils as part of the carbon cycle.

Efforts to enhance the sector's role in combatting climate change must therefore focus both on reducing emissions while enhancing agricultural lands' ability to sequester carbon. Making this dual task more challenging is the fact that U.S. agriculture must help meet growing global food demand (projected to increase 35–56 percent between 2010 and 2050) while both the number of farms and total farmland in the country have steadily decreased.[2]

In this context, precision agriculture (PA)—also sometimes referred to as digital agriculture, smart farming, agriculture 4.0, and other names—has emerged as an attractive tool to sustainably increase agricultural productivity while reducing the sector's resource needs. PA encompasses a broad set of practices that improve the accuracy, efficiency, productivity, and sustainability of agricultural production. The concept is not new: PA was conceived in the 1980s and grew in popularity with the advent of global positioning systems (GPS) and modern computing.[3] Multiple PA technologies have existed for decades, with the promise of revolutionizing the field.[4] Soil sensors, for instance, have been studied and applied in fields since the mid-1970s.[5] Still, a full-scale transformation in the sector has been elusive.

Recently, PA has gained attention for its potential role in addressing climate change in the agriculture sector by both reducing emissions and enhancing sequestration. Some PA technologies can also help agriculture better adapt to (and be more resilient in the face of) a changing climate. PA offers other direct benefits to producers as well, including saving money and time, reducing reliance on inputs like fertilizer, and bolstering competitiveness in agricultural markets that are increasingly guided by demand for sustainable products. To realize these outcomes, PA must overcome real barriers, though, and constraints in some technologies mean certain PA applications offer much greater potential than others.

To inform the use of PA to meet the climate challenge, this paper aims to characterize key PA technologies in the United States. It focuses in particular on seven technologies: soil mapping, yield mapping, guidance systems, variable rate application technologies (VRT), precision livestock farming applications, detect and treat technologies, and storage monitoring. The paper evaluates these seven technologies along the following criteria:

- **Climate impacts**: The technology's ability to enhance carbon sinks, reduce emissions, or bolster efficiency, relying on any data that quantifies its impact (see **Box 1**).
- **Co-benefits**: Non-emissions benefits that the technology creates (e.g., water quality improvements, reduced cost to producers, increased yield).
- **Status of use**: Whether the technology is established or nascent, including any data available on its adoption (see **Box 1**).
- **Constraints**: Factors that prevent the technology from scaling or that limit the technology's impact (e.g., cost, ease of use, lack of broad applicability).

The paper then discusses broader barriers to adoption of PA technologies in the United States. It concludes with recommendations for policies and other actions that can support PA's role in reducing emissions and sequestering carbon.

PRECISION AGRICULTURE TECHNOLOGIES

Precision agriculture technologies are relevant across the production cycle, from planning to post-harvest, and some technologies may cross boundaries (**Figure 1**). The seven sets of technologies evaluated below were chosen for their explicit climate impacts. While there are other PA technologies and applications (e.g., precision irrigation, robotic harvesting, robotic milking), some of which may offer ancillary climate benefits, they are not a focus of this research.

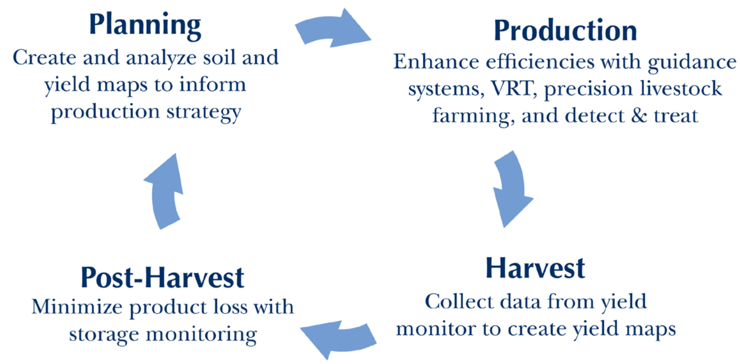
PLANNING STAGE

Using PA technologies such as soil and yield maps in the planning stage—when producers are deciding what to plant, where to plant it, and how to manage their crops

BOX 1: A note on data gaps

Research conducted for this paper revealed multiple data gaps on precision agriculture, including data on the adoption of PA technologies and on their emissions reduction potential in real-world applications. While USDA offers usage data for more established PA technologies from its Agricultural Resource Management Survey (ARMS) and Conservation Effects Assessment Project (CEAP), much of this data is outdated, inaccessible, or focused only on select crops (predominantly row crops). It is highly likely that adoption is greater today than these figures reflect. For more nascent technologies not included in ARMS or CEAP, no source was found to gauge industry-wide adoption. In some cases, nascent technologies also have little research quantifying their climate implications. USDA should undertake efforts to close these data gaps, but in the meantime, these shortcomings have been noted in the text and should be considered by readers when evaluating each technology.

FIGURE 1: Visualization of PA applications across production cycle



for the upcoming season—can equip producers with necessary information to help them make decisions that benefit both the climate and their bottom line.

Soil mapping

Soil maps display differences in soil characteristics across an area of land, including soil type, texture, nutrient levels, acidity, moisture, soil carbon, and other measurements. Maps have historically been created with data from core samples taken in-field that are then tested in labs, which is a time-consuming and costly process. Alternatives such as in-field electrical conductivity tests, spectroscopy, satellite imaging, and drone remote sensors all offer more efficient, and potentially less costly, mapping capabilities. Regardless of how data is collected, GPS coordinates are then used to plot the data on a map to allow producers to see in-field variability and tailor management approaches for their unique soil attributes (**Figure 2**).

Climate impacts

Soil maps are enabling technologies that equip producers with relevant information to make climate-smart decisions. They can inform management practices that maximize soil carbon sequestration while minimizing nitrogen loss. Soil nitrate sensors, for instance, can be used in combination with other data and mapped to help producers determine plants' nitrogen needs and tailor fertilizer applications to reduce N_2O emissions via variable rate application technology (VRT).[6] Producers can also use soil data to inform conservation approaches on their land. For instance, soil electrical conductivity tests can measure topsoil depth and help producers identify areas experiencing or prone to erosion; with that knowledge, producers can implement conservation measures such as planting cover crops or converting the area to prairie, which can increase soil carbon sequestration. In addition, producers can use in-field or remote soil sensing (via spectroscopy or drones) to estimate soil carbon fluxes on their land, which is critical to strengthening understanding of the soil carbon impacts of various management practices.

Co-benefits

Soil samples, sensors, and maps can detect and display a range of soil conditions. Understanding these variations in a field can help producers effectively manage water use and promote holistic soil health, which can enhance producers' resilience to drought, floods, and other extreme weather events.

Status of use

USDA's Economic Research Service (ERS) estimates, using data from ARMS, that soil mapping was used on more than 20 percent of corn and peanut planted acres (in 2016 and 2013, respectively), 20 percent of soy acres in 2012, 15 percent of rice acres in 2013, and under five percent of cotton and winter wheat planted acres (in 2015 and 2017, respectively).[7] The use of soil mapping lags behind the use of soil tests; from 2013–2016, 60 percent of all cultivated cropland

FIGURE 2: Soil type maps for field in Ontario, Canada

The left map displays a multitude of soil types present in a field near Guelph, Ontario, Canada, with dark green corresponding to a gravelly sandy loam type that the producer observed as particularly prone to erosion and degradation. Based on this detailed map, the producer created two distinct management zones (right image), deciding that the gravelly sandy loam soil (here in red) will be managed with no tillage to retain its health and prevent further erosion and degradation.

Photo source: Doug Aspinall, Nicole Rabe, and Ian McDonald, "Understanding precision agriculture," Ontario Grain Farmer Magazine, December 1, 2015, https://ontariograinfarmer.ca/2015/12/01/understanding-precision-agriculture-9/.

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acres had a soil test within the previous five years.[8] This suggests producers are collecting at least some soil data without transforming the data into maps. While these tests alone are useful, georeferencing and mapping the data, then using it in conjunction with other mapping applications (i.e., yield maps) to make geographically specific management decisions based on soil properties (e.g., through VRT), can amplify their utility. The lagging usage of soil maps compared to soil tests suggests producers may face constraints in the creation of maps (see below) but can also be taken as a positive sign since many producers already have at least some data from which they can create maps to gain additional insights. Given that the ARMS statistics are outdated, usage of soil mapping has likely increased moderately since the surveys were done, especially with recent growing interest in soil carbon sequestration and soil health.

Constraints

Soil mapping is an analytically intensive PA application, which may inhibit its use by some producers. Because soil maps can present a wide range of complex variables, producers may need experts to provide technical assistance to translate map data into management decisions (e.g., identifying an area prone to erosion and creating a plan to remedy it, understanding how soil nutrient levels should inform nitrogen fertilizer application). In addition, the various approaches to soil data collection have limitations: soil coring is a time-intensive and costly process and remote sensing applications often need to be calibrated or validated against in-field data to ensure accuracy.[9]

Yield mapping

Yield maps visualize variations in yield across a field, giving producers valuable insights into which areas of their field are consistently low- or high-producing (**Figure 3**). They are created using location-specific yield data gathered from GPS-enabled yield monitors, which are sensors mounted on combines and other harvesting equipment that gather data on the product flowing through the machine to calculate yield in each area of a field. Producers can use yield maps to make management decisions that minimize their use of inputs or enable them to convert consistently low-yielding areas of their field to conservation uses. Yield maps can also inform the use of variable rate application technologies.

Climate impacts

Like soil maps, yield maps are enabling technologies that can facilitate climate-smart management decisions based on yield data. The information displayed in yield maps can be used to both reduce emissions and enhance sinks. For instance, a yield map might reveal a consistently low-yield tract of marginal land in a field and lead the producer to convert that section of the field to prairie strip, increasing the field's carbon sequestration ability. Alternatively, a yield map might indicate that a field has highly variable yields throughout, pointing to a need for the producer to manage sections of it differently by using VRT. With VRT, the producer can apply the appropriate level of inputs (like nitrogen fertilizer) to each section of the field, potentially minimizing overapplication of fertilizer and reducing N_2O emissions.

Co-benefits

Yield maps allow producers to visualize the yield impacts of PA and other management interventions, giving them data required to make decisions that can sustainably enhance their yield. Yield maps can also inform the application of other inputs (such as pesticides or herbicides) and irrigation practices across a field, which can help producers responsibly manage water resources and minimize chemical spraying.

Status of use

Yield monitors are commonly used in row crop systems, but it is less common for monitoring data to be transformed into yield maps. In 2012, for instance, use of yield monitors on soy farms was double the use of yield maps.[10] Failing to transform yield data into maps leaves producers less able to gain insights from that information, such as seeing consistent variations in yield across a field that indicate a need for localized management approaches. Yield mapping is most widely used on corn farms (45 percent of planted acres in 2016), followed by soy farms (roughly 35 percent of acres in 2012).[11] Yield mapping for peanuts, cotton, rice, and winter wheat ranges from just over 5 to 15 percent of planted acres (based on data from 2013–2017).[12] Again, these statistics are out of date, and it is likely that usage has increased.

Constraints

Yield maps are most useful when created using multiple years of data, to minimize the risk of making decisions based on anomalies that might occur in any given year (e.g., extreme weather events). The value of yield data is thus limited for the first few years of collection. In addition, like with soil maps, it can be challenging for producers to make decisions using yield maps because of the expertise necessary to interpret them. Absent

FIGURE 3: Example of variation displayed in a yield map

Variation in yield for the 2015 winter wheat harvest in the same field near Guelph, Ontario, Canada. Red indicates lower yield (measured in bushels per acre), with dark green being highest yield. Note that much of the low yielding areas in this map correspond with the gravelly sandy loam soil type in **Figure 2** and pointed to a need for site-specific management (in this case, no tillage).

Photo source: Doug Aspinall, Nicole Rabe, and Ian McDonald, Understanding precision agriculture.

specialized expertise, producers could misinterpret the maps and make choices that may have negative climate consequences. For instance, a producer could interpret a consistently low-yielding portion of a field as requiring more nitrogen fertilizer (thus increasing N_2O emissions), when in fact that area would have been better put toward a conservation use. Yield monitoring and mapping are also most suited to row crop operations. Although yield monitoring is possible in specialty crop systems, the lack of mechanization, variety of crop types and harvesting methods, and delicacy of many specialty crops make yield monitoring and mapping applications for these crops a challenge.[13]

PRODUCTION STAGE

During the production stage, producers actively manage growing crops and maintain livestock herds and can make use of technologies (such as guidance systems, VRT, precision livestock farming, and detect and treat) that help make their operations more efficient and productive.

Guidance systems

Guidance systems use GPS capabilities to guide tractors and combines more precisely in a field. In this report, guidance systems encompass both systems that help guide a driver along lines in a field (akin to a navigation app highlighting your route while driving) and autosteering systems that automatically steer tractors and combines on set paths using GPS (akin to a self-driving car pre-programmed for a given route). Both of these systems minimize overlaps and gaps in field applications, allowing for more efficient seeding, spraying, fertilizing, and harvesting.

Climate impacts

The climate benefits of guidance systems include direct avoided emissions from less fuel use (as a result of minimized overlaps), as well as indirect avoided emissions from reductions in fertilizer and chemical inputs, both of which are emissions intensive to manufacture. One 2018 study that modeled tractor guidance's impact on three simulated farms found that it could reduce 31.4 kilograms of carbon dioxide equivalent per hectare (ha) in cotton farms and 19.2 kilograms of carbon dioxide equivalent/ha in a cotton/soy mix, when accounting for avoided fuel, fertilizer, and chemical emissions.[14]

Co-benefits

USDA's Natural Resources Conservation Service reports that using a guidance system on a 1,000-acre farm with a continuous corn crop would save approximately $13,000 per year (as of 2006) by reducing field overlaps, meaning the system could pay for itself within three years.[15] NRCS also estimates that using guidance systems on ten percent of planted acres in the United States would cut herbicide use by two million quarts and insecticide use by four million pounds per year.[16] Reductions in these chemical applications can improve water quality, ecosystem health, and the health of agricultural workers and others impacted by chemical exposure.

Status of use

Guidance systems do not require data collection or interpretation to generate value and can often be added to existing machinery via simple retrofits, making them easier to adopt compared to more data-intensive and specialized PA technologies. As a result, guidance systems are the most widely used PA technology. Guidance systems were used on roughly 60 percent of planted corn and winter wheat acres in 2016 and 2017, respectively, on roughly 50 percent of soy, peanut, and rice acres (as of surveys from 2012–2013), and on 30 percent of cotton acres in 2015.[17] Current adoption for these crops is likely higher than these outdated figures.

Constraints

Guidance systems are much more widely adopted on large farms than on smaller farms, suggesting barriers to entry for smaller-scale producers or limited perceived benefits compared to large operations.[18] For corn, for instance, only nine percent of farms under 250 acres used guidance systems in 2016, compared to 70 percent or more of farms over 1,000 acres.[19] These systems are also more established in and suited to row crop applications, although innovations are opening up guidance and autosteering applications for some specialty operations, including orchards and vineyards, and even wild blueberries.[20]

Variable rate application technologies

Variable rate application technology customizes various field applications to meet the needs of precise locations in a field using GPS controls in tractor cabs. A machine attachment with nozzles disperses the appropriate level of inputs, informed by a computer program using geo-referenced data points. VRT can be used for seeding, applying fertilizer, applying pesticide and other chemicals, or irrigation. Precise input levels are determined by field-level data to allow producers to effectively manage variability within their fields. As a result, VRT is most commonly used in combination with other PA technologies that provide this data, such as soil and yield maps.[21]

Climate impacts

VRT for nitrogen fertilizer offers the greatest climate impact by reducing overapplication of nitrogen and the resulting N_2O emissions, which are many times more potent than carbon dioxide. These reductions in N_2O emissions are particularly pronounced for low-yielding areas in a field, up to 34 percent in one 2003 study.[22] At a larger scale, variable nitrogen fertilizer applications could reduce nitrogen use in the Midwest by as much as 36 percent, thus cutting emissions from unused fertilizer by 890 kilograms of carbon dioxide equivalent/ha.[23]

Co-benefits

VRT can create savings for multiple input types due to more efficient applications. These savings can increase farm profits, as demonstrated by a 2010 USDA study of corn acres using VRT.[24] In addition, in specialty crop field tests, VRT sprayers reduced spray drift (whereby droplets move to unintended areas during or after spraying) by up to 87 percent and pesticide use between 30–85 percent.[25] These reductions positively impact worker, community, and ecosystem health and save producers money on inputs. When VRT is used for irrigation, it can also assist in water conservation, which is particularly valuable with worsening climate-caused drought conditions.[26]

Status of use

NRCS's second Conservation Effects Assessment Project report (CEAP II) indicates that 16 percent of total cultivated cropland acres in the United States used VRT for nutrient management between 2013 and 2016.[27] A May 2022 survey by McKinsey & Company of 1,300 row and specialty crop farmers indicates VRT usage for fertilizer may have increased significantly since then. The survey indicates VRT is currently being deployed on 45 percent of small farms (defined as under 2,000 acres), 63 percent of medium farms (2,000–5,000 acres), and 49 percent of large farms (over 5,000 acres), although differences in survey methodologies should be considered when comparing these figures to USDA data.[28] Broadly, VRT is used most widely for corn (roughly 40 percent of planted acres in 2016), with cotton, peanut, rice, and soy at roughly 15–22 percent of planted acres, according to USDA estimates between 2012–2015.[29] While VRT can be used for multiple applications, ARMS data show VRT is used most widely for fertilizer, with pesticide and seeding applications lagging behind in nearly every major row crop.[30] The higher usage for fertilizer is positive from a climate perspective given the direct benefit of reduced N_2O emissions when using VRT for nitrogen fertilizer.

Constraints

VRT has high upfront costs and may require specialized machinery, which can limit its application in smaller operations and diminish its profitability, even considering savings on inputs.[31] It is also best used on highly variable fields, where it offers the greatest benefits for sustainability and profitability. On fields with little to no variation, deploying VRT may create few benefits. For instance, in one study on non-variable corn fields, variable-rate nitrogen fertilizer application was found to create no benefit to profit.[32] In addition, because VRT is usually used in combination with other PA technologies, such as the soil and yield maps that inform VRT applications, producers adopting VRT must also overcome the barriers associated with those technologies.

Precision livestock farming

Precision livestock farming (PLF) includes multiple technologies that increase the efficiency of livestock production. In this research we consider wearable sensors and precision feeding. Wearable sensors (wearables) can include radio frequency identification (RFID) tags on ears, accelerometers akin to necklaces, or other technologies that sense changes in animal behavior (e.g., activity levels) to indicate disease or other health challenges. Producers can analyze data from these sensors to determine which animals need specific attention and intervene earlier than might otherwise be possible.

Precision feeding (PF) involves measuring animals' characteristics (e.g., weight, body composition), using models to estimate their nutrition requirements based on those characteristics, and implementing feeding systems that can recognize the individuals entering the feeder and blend feed to meet their unique needs (e.g., adjusting ratios of protein and nutrients). PF can improve the efficiency of livestock production, given that conventional feeding setups (which generally feed groups of animals the same blend of feed in stages across their lives) often oversupply protein and other nutrients to most animals. This conventional feeding approach is often inefficient (excess nutrients are just excreted) and environmentally harmful.[33]

Climate impacts

By tracking animal health with wearables, producers can reduce disease and mortality.[34] This can create an indirect climate benefit by allowing herds to increase production with fewer animal losses, and potentially fewer animals overall. More animals reaching finishing age also avoids waste of inputs like feed, thus avoiding emissions associated with producing those inputs. These productivity and climate implications warrant more study as they have yet to be well quantified in scientific literature.

Precision feeding reduces nitrogen excretion by livestock, which in turn reduces N_2O emissions. For pig operations, numerous studies (both modeled and on-farm) have found precision feeding reduces nitrogen excretion by anywhere from 18.5 to 40 percent.[35] The level of corresponding emissions reductions depends on the manure management system used; liquid management systems release less N_2O than dry systems, so reduced nitrogen excretion in these systems will offer fewer climate benefits than in dry management systems.[36] PF also has potential to reduce methane emissions—which are influenced by diet—from ruminant animals such as cows, which produce methane during digestion; however, this application of PF seems less explored than applications in pig operations. For example, precision feeders can adjust the proportions of forage and other ingredients in animals' feed to minimize methane emissions.[37] As feed additives to reduce methane emissions (such as seaweed) become more commercially available, PF may also distribute appropriate ratios of additives to individual animals. Lastly, by not oversupplying feed, PF can cut down on the quantity of feed animals require, thus avoiding emissions associated with growing that feed.

Co-benefits

By allowing for early detection of disease, wearables can improve animal health and welfare and reduce livestock losses due to mortality. They can also reduce time producers spend on animal monitoring, especially on rangelands where animals are spread over a larger area, thus freeing producers to spend more time on animals who need individualized care.[38] For PF, multiple studies have demonstrated reduced feed costs, in some cases by more than 10 percent.[39] Limiting excretion of both nitrogen and phosphorous via PF also creates multiple environmental benefits, such as reduced surface and groundwater pollution (which improves water quality both on-farm and downstream, where eutrophication is a concern) and reduced ammonia pollution in the air.[40]

Status of use

There is a gap in industry-wide data on the adoption of precision livestock technology. While these technologies have been tested in research settings for years, their commercial use is seemingly nascent.

Constraints

Due to costs and economies of scale, PLF technologies are best suited for large livestock operations. While wearables can be used in both ranching and confined livestock systems, PF is predominantly applicable in concentrated animal feeding operations (CAFOs). The innate suitability of PLF applications for CAFOs raises a concern that these technologies may promote further consolidation in the livestock industry by advantaging intensified and industrialized operations over smaller-scale and pasture-based operations.[41] While PLF technologies can provide environmental benefits in concentrated feeding systems relative to a baseline, enabling the expansion of CAFOs could create other climate impacts that could offset the advantages PLF offers (e.g., challenges managing manure and associated methane emissions).

In contrast to PA applications for crops, precision livestock applications also have to grapple with bioethics and concerns for animal welfare. Some experts have called for more research on animals' responses to PLF technologies to ensure the technologies allow animals to behave naturally and do not cause stress.[42] Consumers also call for these assurances; a study of European consumers found that while many recognized PLF's potential benefits, they were also concerned with potential increased industrialization and robotization of livestock farming and its impact on both animals and producers.[43]

Detect and treat technologies

Detect and treat refers to a category of technologies designed to recognize threats that can lead to crop loss (e.g., disease, weeds, pests) and make targeted interventions accordingly. These can include cameras mounted on field sprayers that recognize weeds and direct applications to them, drones that measure an array of variables and either alert users to problems or address problems independently (e.g., by spraying), or robots trained to scan fields for disease or pests and make treatments.[44] These technologies all require machine learning software to effectively identify field problems.

Climate impacts

Detect and treat technologies offer indirect climate benefits by reducing crop loss, which can potentially increase productivity on a given area and allow for less land to produce more food. According to USDA, machine learning to identify weeds, disease, and pests can reduce crop loss by 30 percent.[45] Precise interventions for disease, weeds, and pests can also reduce applications of pesticides, herbicides, fungicides, and other chemicals, thus reducing the emissions associated with producing those inputs. Lastly, when treatments are made by drones or robots instead of heavy agricultural equipment, producers may also be able to reduce fuel usage and associated emissions, although there is a research gap when it comes to quantifying this potential.

Co-benefits

Reduced spraying of pesticides, herbicides, fungicides, and other chemicals can positively impact water and air quality, minimize workers' chemical exposure, and save producers money on inputs. Using drones to monitor fields during production can also save producers time, particularly on large operations, by virtually eliminating the need to manually scout fields by foot or truck.[46]

Status of use

There is a lack of industry-wide data on the use of detect and treat technologies (including drones, robots, and those mounted on sprayers). While multiple technologies have been tested by researchers for more than a decade, and several are commercially available, their usage is seemingly low and limited to early adopters. Interviews with industry practitioners suggest sprayer-mounted detect and treat technologies are likely most established, followed by drone monitors. Additionally, more than 80 percent of precision equipment dealers had no near-term plans to offer robotic crop scouting or weeding services as of 2021, showing that robotic detect and treat applications are in their infancy and are unlikely to be widely scaled soon.[47]

Constraints

The machine learning necessary to enable detect and treat technologies requires training computers to accurately identify threats to crops, a process that involves capturing and processing thousands of images for each type of crop.[48] While these tasks would be done by technology manufacturers and not individual farmers, they are still a potential inhibitor to rolling out detect and treat applications for the multitude of U.S. crop types. In addition, even with training, accuracy of detection may not reach 90 percent in some cases, resulting either in unnecessary or missed treatment.[49] Machine detection also works best in monocropped fields where irregularities are more evident than in fields with multiple species, and in crops with distinct attributes where weeds and characteristics of plant disease are readily discernible from healthy plants.[50] In addition, to operate drones independently, producers require Federal Aviation Administration certification, which can be a barrier to adoption.[51] Lastly, automating tasks that would otherwise be performed by farm workers (i.e., spraying, weeding) may have labor market implications that should be considered.

POST-HARVEST STAGE

After crops are harvested, producers must store and maintain their product before it goes to market. Technologies such as storage monitors can limit waste during this stage and ensure producers get maximum value from selling a full, quality harvest.

Storage monitoring

Storage monitors are sensors placed in storage areas for harvested products (e.g., silos, bins) that measure multiple characteristics of the storage area and alert users to potential damage. Some sensors detect moisture and temperature changes, others monitor carbon dioxide levels (which can indicate the presence of molds or insects), and others go beyond monitoring to recommend interventions (e.g., suggest turning a fan on or off) or implement fully automated processes (e.g., independently drying, cooling, and rehydrating stored grain).[52] Similar monitoring technologies can be used not only on-farm, but elsewhere in supply chains (e.g., food storage warehouses, grocery stores, restaurants) to minimize waste.[53]

Climate impacts

More than one-third of food produced in the United States is wasted each year, representing roughly 170 million metric tons of carbon dioxide equivalent emitted from wasted agricultural production, food processing, distribution, and consumption—excluding emissions from landfills.[54] Storage monitors offer a straightforward solution to part of the food loss challenge by reducing product loss due to spoilage at multiple points along food supply chains. This avoided loss enhances the agricultural system's productivity and reduces emissions released when organic matter decomposes (notably methane, which is released when food rots in landfills). While there are clear climate benefits to storage monitors, data gaps exist in quantifying the avoided emissions they enable.

Co-benefits

By reducing product loss, storage monitors save producers money and allow them to sell a greater portion of their product. This is also true for food warehouses, grocery stores, and restaurants that use storage monitors. In addition, monitors can save time and increase safety by reducing the need for producers to climb silos and bins to perform visual inspections.

Status of use

Storage monitors are easy to adopt since they do not require much data interpretation or significant changes to existing practice. Numerous types of storage monitors are commercially available on the market with a range of functionalities, but there is a research gap on their usage industry wide. One industry expert estimated less than five percent of on-farm grain storage bins use monitoring technology as of 2018, although it is unclear whether this estimate refers only to automated monitoring systems or also to more basic applications.[55] Usage of storage monitors is therefore probably low, with high potential for growth.

Constraints

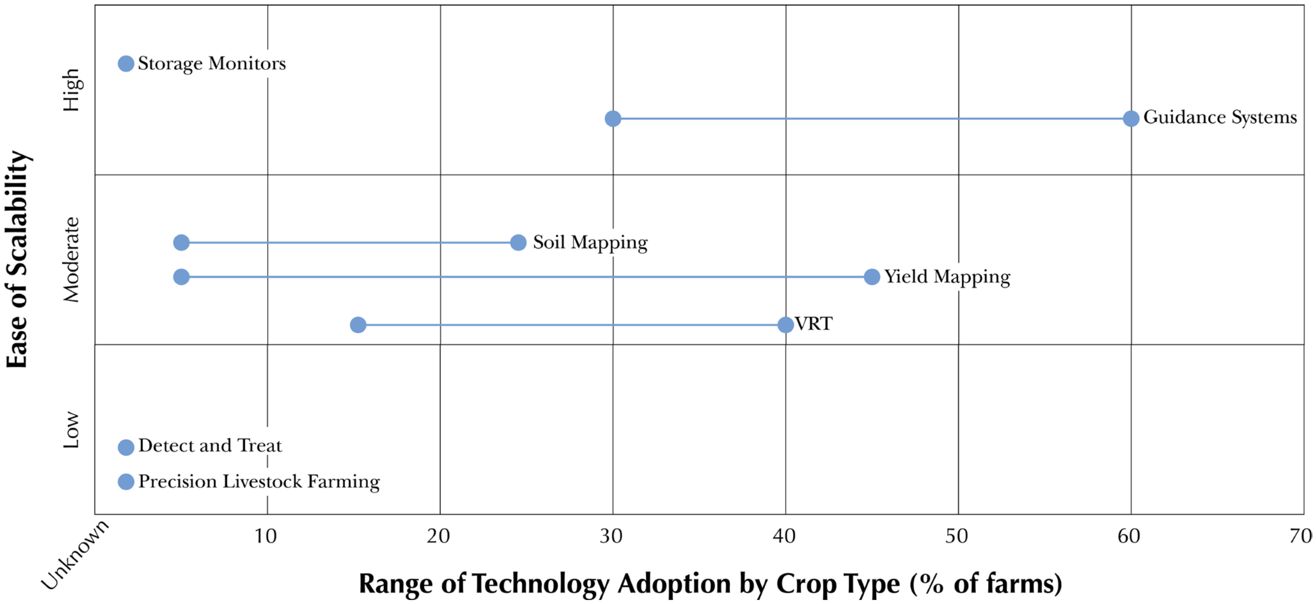
Addressing food loss at on-farm storage sites tackles only a small portion of food loss in the United States. By far most food loss in the country occurs at the consumption stage (roughly half), while losses during production are estimated at roughly one-quarter to one-third of total food loss.[56] Storage monitors would be able to prevent only some of the losses during production; other losses occur in the field and require their own approaches. Expanding storage monitoring to food distribution centers, restaurants, and grocery stores could increase the impact of storage monitoring technology, but additional interventions are needed outside PA to address the larger challenge of food waste at the household level. In the case of storage monitors that provide automation services or data analytics (which are optional features), the cost of an ongoing subscription can be a deterrent to adoption.[57] Beyond this challenge, though, storage monitors have low barriers to entry.

SYNTHESIS OF TECHNOLOGIES' ADOPTION LEVELS AND SCALABILITY

The technologies analyzed in this brief show that PA solutions are heterogeneous (see **Table 1** for summary). Some technologies are easy to adopt, while others have high costs or require significant data collection and analysis, posing barriers to entry for producers. These factors mean that, while the precision agriculture industry as a whole is likely to grow in the United States in coming years, certain technologies are more suited to scale than others (**Figure 4**).

Storage monitors are likely the most scalable technology; while they are currently estimated to have low levels of adoption, they are straightforward to use, are not capital intensive, and provide clear benefits to producers. Guidance systems follow as another easy-to-scale technology, aided by already high adoption rates and ease of use. The remaining technologies are more data-intensive, making them comparatively harder to scale due to the need for data collection, analysis, and interpretation. PLF technologies are least scalable due to high upfront costs, lack of applicability to small farms, industry consolidation concerns, and potential animal welfare issues unique to the livestock sector. Detect and treat also ranks low in scalability due to challenges with applying it widely in different cropping systems and crop types, although it is likely that certain detection applications (e.g., drones) will be scaled more readily than others (e.g., robots). Finally, VRT, soil mapping, and yield mapping are all moderately adopted at present and moderately scalable. The high upfront cost of VRT and the need to use it in combination with other PA technologies make it less scalable than both mapping applications. Soil maps are slightly easier to adopt than yield maps because many soil properties are relatively stable compared to changing yields, meaning they can be updated less frequently than yield maps while still retaining useful insights.

FIGURE 4: Synthesis of PA technologies' levels of adoption and ease of scalability



Note: Published literature and interviews with industry experts from USDA, academia, and companies have been used to inform technologies' ease of scalability. Adoption rates are based on most recently published data from USDA, with bars representing the variation in adoption rates among major row crops. Data on VRT fertilizer adoption from McKinsey & Company has been excluded for this figure, given it measured adoption by farm size, not commodity, and is much more recent than USDA data, making direct comparison with other technologies difficult.

BARRIERS TO PRECISION AGRICULTURE'S CLIMATE POTENTIAL

While the previous section described some of the constraints that apply to specific PA technologies, there remain broader barriers to the adoption of PA as a whole. These include ensuring access to reliable, high-speed broadband; making PA technologies applicable to a diverse range of farming systems; minimizing high capital costs and risk for producers; ensuring data privacy and security; developing systems so they are interoperable; and overcoming technology hesitancy.

ACCESS TO RELIABLE, HIGH-SPEED BROADBAND

Lagging broadband access in rural areas, and on farms specifically, is a central inhibitor to the adoption of PA technologies, many of which require connectivity to provide their maximum value.[58] Federal efforts to expand broadband in rural areas, like pandemic relief packages, the Infrastructure Investment and Jobs Act (IIJA), and USDA-led investments, have accelerated in recent years, but these efforts may not lead to the high-capacity networks needed to support the broad rollout of PA. For instance, the Federal Communications Commission (FCC) currently defines high-speed internet as 25 megabits per second for downloads and three megabits per second for uploads (25/3), with its Chairwoman proposing in July 2022 to increase that minimum speed to 100/20.[59] While this updated minimum speed is a positive development, it still places more emphasis on data flowing *to*—rather than *from*—the end user. With PA sensors gathering data across an operation, and real-time interpretation often necessary to make use of that data, higher speed uploads at multiple locations (beyond the farmhouse) can be vital to PA's utility. Federal efforts to expand broadband in rural areas should thus include support for higher speed, near-symmetrical networks with multiple points of connection across farmland to enable the adoption of PA technologies.

APPLICABILITY TO DIVERSE FARMING SYSTEMS

Precision agriculture is most widely used in row cropping systems, namely corn and soy, due to the mechanization of such systems.[60] PA is also mostly used on large farms,

TABLE 1: Summary of precision agriculture technologies

PLANNING				
TECHNOLOGY	**CLIMATE IMPACT**	**CO-BENEFITS**	**STATUS OF USE**	**CONSTRAINTS**
Soil mapping	Enabling technology—can inform emissions reductions or enhanced sinks and improve producers' resilience	Monitor overall soil health and inform other PA interventions	Low–moderate (estimated 5–25% usage for major row crops)	Successful map interpretation may require technical assistance. Data collection to create maps can be cumbersome.
Yield mapping	Enabling technology—can inform emissions reductions or enhanced sinks	Help enhance yields and inform other PA interventions	Moderate (estimated 5–45% usage for major row crops)	Successful map interpretation may require technical assistance. Most effective with multiple years of data.
PRODUCTION				
TECHNOLOGY	**CLIMATE IMPACT**	**CO-BENEFITS**	**STATUS OF USE**	**CONSTRAINTS**
Guidance systems	Reduced emissions	Cost savings, reduced chemical applications	Established (estimated 30–60% usage for major row crops)	Best suited for row crops and larger systems.
Variable rate application technologies (VRT)	Reduced emissions	Cost savings, increased yield in variable fields, reduced chemical applications, reduced water usage	Moderate (estimated 15–40% usage for major row crops, and up to 60% on medium sized farms)	High capital cost. Best results when used with other PA tech. Most suitable for highly variable fields.
Precision livestock farming (PLF)	Reduced emissions and improved productivity	Improved animal health, reduced air and water pollution, reduced feed costs	Unknown, but estimated nascent	High upfront costs. Best suited for large operations and, for precision feeding, confined feeding systems. May present animal welfare concerns or accelerate industry consolidation.
Detect and treat	Improved productivity	Reduced chemical applications and input cost savings	Unknown, but estimated nascent	Accuracy may not be high enough in certain applications. Best suited for monocropped fields and crops with distinct attributes.
POST-HARVEST				
TECHNOLOGY	**CLIMATE IMPACT**	**CO-BENEFITS**	**STATUS OF USE**	**CONSTRAINTS**
Storage monitoring	Reduced emissions	Saves money by avoiding product loss	Unknown, but estimated nascent	Addresses small portion of food waste issue.

given the high upfront costs and economies of scale that enable larger operations to benefit most from the technologies.[61] PA poses challenges for specialty crop operations, which have distinct processes for each crop that are often more difficult to automate, and for small farms, which may struggle to adopt costly new technologies.[62] Still, it is possible to open up access to PA in small, diverse farming systems, including by ramping up research and development of PA technologies suited to these operations. Between 2008 and 2018, for instance, USDA funded nearly $290 million in research to develop automation and mechanization applications for specialty crops, with PA research comprising nearly half that funding.[63]

COST AND RISK

Precision agriculture technologies will only be adopted at scale if it is economically viable for producers to do so. While several PA technologies can ultimately save producers money over the long run, the high upfront cost of certain technologies is an inhibiting factor for adoption.[64] As just noted, this is especially true for small and medium-sized farms which are less able to absorb large capital expenses. A lack of financial risk reduction mechanisms (e.g., cost share, grants) can also make producers hesitant to invest in PA. While some NRCS financial assistance programs (e.g., enhancements offered through the Conservation Stewardship Program) incentivize PA as a conservation approach, most programs are restricted from being used to purchase equipment that helps producers implement those conservation practices, such as autosteering systems.[65] More clearly incentivizing the use of PA in NRCS programs, while providing financial support through other avenues to purchase PA equipment (especially for small-scale and historically underserved producers), can help overcome this barrier.

DATA PRIVACY AND SECURITY

With PA technology capable of capturing thousands of distinct data points on numerous aspects of an agriculture operation, data privacy is a serious concern for producers, who may not want this data shared with equipment manufacturers, dealers, and other digital service providers.[66] The PA dealership survey conducted by CropLife Magazine and Purdue University indicates increasing producer concern with data privacy: In 2021, 30 percent of dealers perceived this as a barrier to adoption, up from only 11 percent in 2017.[67] Positively, though, data privacy statements and conditions are becoming increasingly common in the field.[68] Several initiatives have also created data privacy and security standards for farm data, such as the American Farm Bureau Federation's Privacy and Security Principles for Farm Data and the Open Ag Data Alliance, though these are all voluntary and have yet to be widely accepted across the industry.[69] To allay producers' concerns about data privacy, industry-wide minimum practice standards will likely be needed. In addition, PA may make the agriculture sector more prone to cyber-attacks, such as deliberate disruption of automated and digital equipment or the hacking of PA data to gain an unfair advantage.[70] Cybersecurity measures are necessary to mitigate the risk of such threats.

DATA INTEROPERABILITY

With a multitude of equipment companies each marketing their own PA technologies, producers may end up with various pieces of equipment that do not communicate with each other. They may be forced to re-enter data in various software, convert it into different formats, or become dependent on a single manufacturer for purchasing decisions.[71] A lack of interoperability between PA systems can lead to products working in isolation, preventing producers from reaping the full value of their data and attaining a systems-level view of their operation.[72] Advancing interoperability of PA will require coordination among the various actors in the industry, including producers, equipment manufacturers, input and service providers, government agencies, and others. Incentives or government standards may be required to overcome deterrents to collaboration, such as industry competition and the proprietary nature of some technology.[73] Addressing concerns about data privacy is also a prerequisite to effective interoperability.

TECHNOLOGY HESITANCY

Precision agriculture is an innately high-tech field, which can create barriers to entry for producers. With the average age of an American producer being 57.5 years, many may question the value of adopting new technology so close to retirement.[74] PA equipment may also face skepticism from the growing "right to repair" movement; equipment embedded with software and numerous sensors may be difficult for producers to repair independently or may even come with restrictions

BOX 2: Priorities for precision agriculture to 2030

Figure 4 shows precision agriculture technologies vary widely in both current adoption and ease of scalability, suggesting certain technologies will play a larger role in meeting the United States' 2030 climate target (i.e., reducing emissions 50–52 percent from a 2005 baseline). To unlock precision agriculture's potential to help meet the 2030 goal, significant effort will need to go toward rapidly scaling technologies that are field-ready. Producer education and outreach, financial assistance programs, and other efforts to limit barriers to entry will all be needed to promote near-term adoption. At the same time, research, development, and demonstrations are needed to mature and commercialize still nascent technologies to both bring down costs and prove their effectiveness on diverse farming systems. While these technologies may not all play as critical a role in meeting 2030 climate goals, it is possible they may have potential for impact in coming decades. Investments in PA today—from both the public and private sectors—can help PA technologies achieve the market penetration necessary to unlock their decarbonization potential, to 2030 and beyond.

on third-party repairs.[75] As a result, some producers may hesitate to buy PA equipment. One survey conducted by the U.S. PIRG Education Fund and National Farmers Union, for instance, found that 77 percent of surveyed farmers (74 farmers across 14 states) had bought older equipment to avoid software in new equipment.[76] Efforts are ongoing to enhance producers' right to repair, including through a July 2021 executive order by President Biden, a commitment from the Federal Trade Commission (FTC) to ramp up law enforcement on repair restrictions, right to repair bills introduced in dozens of states and at the federal level, and commitments by agriculture equipment manufacturers to increase access to diagnostic services.[77] Still, producers may need more concrete steps to lessen their hesitancy.

RECOMMENDATIONS

RESEARCH, DEVELOPMENT, AND DEMONSTRATION

USDA should undertake research to better understand the climate impact of various PA technologies in different production systems, with a focus on real-world adoption. While there is a body of research documenting the climate impact of technologies such as guidance systems and VRT, there is still a gap in understanding how less established technologies (e.g., storage and livestock monitoring, detect and treat) can create climate benefits in a variety of real-world farm systems. Existing research on PA's benefits also fails to capture the full diversity of farm production; data on precision livestock feeding, for instance, is most available for pig operations, while research into guidance systems focuses nearly exclusively on row crops. Strengthening understanding of how PA can improve efficiencies, reduce emissions, and enhance carbon sequestration in a diversity of operations will be critical to inform USDA's climate-smart agriculture and forestry strategy and to make the case to incentivize PA in federal programs and private sector operations.

USDA should facilitate research, development, and demonstration of PA in small-scale and diverse farming systems, including specialty crops and livestock. PA usage in specialty crop and livestock operations trails row crops, and small, diversified farms are often less suited for PA applications. USDA should support research and development to tailor PA technologies to the needs of these operations, then scale them through commercialization and on-farm demonstrations to producers. Quantifying the benefits associated with PA adoption on these systems will be necessary to give producers the confidence to adopt new technology.

USDA should work with its field offices, extension services, land grant universities, and the private sector to increase

producer knowledge of PA, including through in-field demonstrations and farmer-to-farmer exchanges. Demonstrations, exchanges, and other awareness-raising activities should highlight a variety of farm types and cropping systems (e.g., mid-size farms, orchards) so that producers can see PA work on an operation like theirs. USDA should also explore the creation of a PA ambassador program, with representatives in all regions, to facilitate farmer-to-farmer learning about PA. This type of outreach, using trusted messengers, is critical to make PA's benefits more concrete for prospective adopters and to build confidence in technologies.

USDA should conduct research on producers' adoption of PA across diverse farming systems and sizes, with an emphasis on identifying barriers to adoption. A lack of recent, industry-wide data on PA adoption makes it challenging to understand trends in the sector and gaps in usage. The most detailed data on PA adoption is from USDA's ARMS, which predominantly addresses row crops and more established technologies (e.g., guidance systems, VRT). Data on PA usage for nascent technologies and for specialty crop and livestock operations is comparatively lacking. USDA should undertake research to understand producers' current usage of various PA technologies, both new and established. This research could include synthesis of previous USDA data (e.g., from NRCS and ERS) and should include a new producer survey that represents different regions, farming systems, farm sizes, and other salient demographics. The research should also gauge producers' perceptions of barriers to PA adoption, with a focus on small, socially disadvantaged, beginning, and limited resource producers. Such research is critical to understanding how to remove obstacles for producers and scale their adoption of PA.

ENABLING SUPPORT FOR PRODUCERS

USDA and other federal agencies should invest heavily in symmetrical, high-speed broadband capabilities on farmland to enable PA investments. The IIJA, signed into law in November 2021, equipped federal agencies with $65 billion to invest in broadband in rural areas. For this funding to enable the rollout of PA, though, additional efforts will be needed. First, the FCC should revise its minimum broadband speed from 25/3 megabits per second to 100/20, as has been proposed. Federal programs should then meet or exceed these standards, such as by offering funding preferences to broadband providers that equip rural areas with faster, symmetrical connectivity that has less of a difference between upload and download speeds. USDA's ReConnect Program, for instance, requires speeds of 100 megabits/second for both uploads and downloads, which is more ambitious than other USDA broadband programs and better reflects the needs of PA adopters.[78] Lastly, Congress should increase funding to build out middle mile broadband infrastructure (which links major regional broadband 'backbones' with local connection points, like schools or community centers) by expanding the Department of Commerce's Enabling Middle Mile Broadband Infrastructure Program, authorized through IIJA and currently funded at $1 billion. Expanded middle mile infrastructure enables cheaper construction of the last mile infrastructure that links those local connection points to end users, helping producers get more affordable internet access.

Congress and USDA should more clearly incentivize and support PA in USDA conservation, technical assistance, and loan programs, with an emphasis on supporting investments with clear climate benefits. Multiple USDA programs can support producers in adopting PA, but PA is not a stated focus in most of these programs and should be more explicitly integrated to encourage adoption. To support PA in the Farm Service Agency's (FSA) loan and loan guarantee programs, Congress should either create a new FSA loan program with favorable terms specifically for precision agriculture equipment or, within existing programs, raise the portion of a loan that can be guaranteed for PA technology and give priority to loan applications for such technology. (The Precision Agriculture Loan Program Act, first introduced in the U.S. Senate in September 2021, takes the first approach, while the PRECISE Act and the Reducing Farm Input Costs and Barriers to Domestic Production Act, introduced in the U.S. House of Representatives in April 2021 and June 2022 respectively, take the latter.[79]) In NRCS, as conservation practice standards (CPSs), which form the basis of its conservation programs, are periodically updated, PA techniques should be considered and recommended, based on technology readiness. The field operations emissions reduction practice standard (NRCS Code 376) offers a good example of what this could look like; precision guidance and steering systems are prominently mentioned as one of five techniques that meet the standard.[80] In the nutrient management standard (NRCS Code 590), VRT, informed by yield mapping, is mentioned as an optional consideration that producers may choose to implement, above and beyond the minimum criteria.[81] As PA technologies become more established and accessible, NRCS should consider integrating them into the central criteria that meet the CPS, rather than as optional considerations. In implementing this recommendation, USDA agencies should cross-direct producers to complementary resources offered in other agencies. FSA, for instance, should refer producers purchasing PA equipment through FSA loan programs to NRCS for support with conservation planning and other needs, and vice versa. Such an approach would help USDA holistically address the technical, financial, and risk barriers to PA adoption.

Congress and USDA should increase support for historically underserved producers to access PA. While the above recommendations are a strong start to expanding PA adoption, tailored approaches are still needed to support historically underserved producers (i.e., beginning, socially disadvantaged, veteran, and limited resource producers) who may want to use PA but do not have access to equipment in the same way as large-scale producers. Many underserved producers, for instance, rent or borrow equipment instead of buying it outright. Congress should increase USDA funding available to local conservation districts and agricultural cooperatives, which offer technical assistance, equipment rental, and equipment sharing services that are often more accessible to small-scale and underserved producers. This increased funding would expand FSA and Rural Development loan programs for cooperatives and NRCS funding for conservation districts, with priority for applicants that will use funds to acquire PA equipment and provide technical assistance to underserved producers to address localized conservation challenges, such as nutrient management.

USDA and its partners should enhance their capacity to help producers implement PA practices and transform PA data into climate-friendly management decisions. NRCS has an extensive network of field staff and third-party technical service providers (TSPs) who work directly with producers in creating and implementing conservation plans, but, according to interviews with USDA staff, they often lack knowledge of PA as a conservation solution. USDA should create capacity building and training programs for NRCS staff and TSPs to enable them to guide producers to PA applications appropriate for their specific resource needs. USDA can also help producers make climate-smart decisions based on PA data, which can be a challenge without support from experts. Private equipment retailers and consultants are likely to play a central role in data interpretation, but USDA should also support NRCS field staff, land grant universities, extension services, TSPs, and other producer-serving organizations in understanding and applying PA data to be able to assist producers where necessary or use previously collected data in conservation activities. With this capacity building, these entities can then share their PA knowledge with producers via direct technical assistance, integration into conservation planning processes, workshops, and other means.

Food and agribusiness companies should encourage use of PA by engaging producers in trials or providing incentives for PA use, similar to existing corporate programs for regenerative agriculture and carbon credits. The private sector can be a powerful driver of practice change in the agriculture sector by incentivizing or requiring certain conservation practices by their suppliers, such as effective nutrient management. Many companies have launched producer engagement initiatives in other areas, pledging for instance to implement regenerative practices on a certain acreage or pay producers for additional carbon sequestered in soils.[82] Companies can replicate this approach by either incentivizing PA practices among their suppliers (e.g., by offering premium prices or paying for emissions reductions above a baseline) or implementing PA trials on supplying farms that can then be used to raise awareness among other potential adopters. Regardless of what approach the private sector takes, corporate engagement and demand will be essential to scaling PA.

DATA CONSIDERATIONS

Congress should explore the possibility of legislation to protect farm data, which could allow producers to confidently invest in digital tools in an increasingly data-driven society. Federal law already regulates data practices in the financial services and healthcare industries, and the FTC has authority to regulate data privacy and protection practices in all industries.[83] There are no federal regulations specifically tailored to agricultural data, though, and general FTC regulations lack minimum standards for data privacy and security.[84] As PA adoption increases and the value of farm data grows, Congress may need to explore new federal legislation designed for agricultural data security to allow producers to confidently share PA data with crop advisors, veterinarians, USDA staff, and others while knowing that data is protected. This legislation could draw on existing federal law such as the Gramm-Leach-Bliley Act, which pertains to financial data, or the Health Insurance Portability and Accountability Act (HIPAA), which pertains to health data, while finding a "happy medium" of stringency appropriate for agriculture.[85] Sector-wide consultation, including with producers, companies, and issue experts, will be essential to creating a law that provides effective protection without stifling the value that can come from appropriately sharing, aggregating, and analyzing farm data.

USDA should coordinate efforts to advance interoperability of PA systems, which can make it easier for producers to aggregate and use data they collect. This coordination must involve equipment manufacturers, academia, and producers and should aim to develop a series of both public and private sector actions to enhance interoperability. These actions could include the development of data storage and transfer tools, incentives to use open-source data architecture or facilitate use of application programming interfaces (APIs), or the creation of open data standards for PA. Since interoperability among many products and stakeholders can heighten producers' data privacy concerns, data confidentiality or aggregation measures need to be put in place to ensure integrity.

USDA should make its file management systems compatible with digital PA data so producers can report to USDA using data from PA practices without additional burdens. USDA must lead on data interoperability by ensuring its own file management systems can receive electronic data produced from PA (e.g., acreage records, yield data). This data can be useful for reporting for compliance with Farm Service Agency programs, crop insurance, and other purposes.[86] The seamless integration of these data layers with USDA systems can save producers time and showcase USDA's commitment to data interoperability.

CONCLUSION

The changing climate is already threatening agricultural production in the United States. While the sector is uniquely vulnerable to climate change, it is also uniquely poised to help address it by both reducing emissions and sequestering carbon. Precision agriculture offers one solution for the sector, enabling increased efficiencies, reduced waste, and climate-smart management decisions that can help producers both mitigate and adapt to climate change. A range of PA technologies—some established, some nascent—show promise, but more investment and policy support are needed to scale these technologies to meet climate goals. With these investments and policies, precision agriculture can be a critical piece of the climate solution in the agriculture sector.

Related C2ES Publications:

Getting to Zero: A U.S. Climate Agenda
https://www.c2es.org/document/getting-to-zero-a-u-s-climate-agenda/

A Building Block for Climate Action: Reporting on Embodied Emissions
https://www.c2es.org/document/a-building-block-for-climate-action-reporting-on-embodied-emissions/

Engineered Carbon Dioxide Removal: Scalability and Durability
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Catalyzing Investment with a National Climate Bank
https://www.c2es.org/document/catalyzing-investment-with-a-national-climate-bank-lessons-from-subnational-green-banks/

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https://www.c2es.org/document/carbon-dioxide-removal-pathways-and-policy-needs/

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