AGRICULTURAL TECHNOLOGY DISCOVERY REPORT

March 2023

Environmental Defense Fund

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EXECUTIVE SUMMARY

Emergent agricultural technology is often defined by market opportunities that focus on maximizing output (i.e., yield). This narrow, extractive view fails to recognize and harness the multitude of environmental and societal benefits agricultural technology can provide. **The purpose of this report is to examine the intersection between agriculture, technology, environment, and society, particularly how these areas can support and enhance one another**.

The report provides a high-level overview of four agricultural technology fields: artificial intelligence (AI), robotics and automation, biologicals, and genetics. While these fields cover an array of emergent discoveries, the report focuses on field crop applications, with some livestock applications. The report briefly describes each technology field's functions, applications to the agricultural industry, future advancements, and associated challenges.

Taken together, the four technology fields support the innovative management practice of precision agriculture. Precision agriculture allows farmers to specify when, where, and how much input (e.g., water, fertilizer, pesticides, soil amendments, feed, and other products) to apply to their fields or livestock operations. Not only does this practice save time and resources, but it also has environmental and societal benefits. This integrated lens supports the practice of agroecology.

The Food and Agriculture Organization of the U.N defines agroecology as, "a holistic and integrated approach that simultaneously applies ecological and social concepts and principles to the design and management of sustainable agriculture and food systems. It seeks to optimize the interactions between plants, animals, humans, and the environment while also addressing the need for socially equitable food systems within which people can exercise choice over what they eat and how and where it is produced."

The report investigates how technology can contribute to four specific agroecological goals: reduce water use, support soil and plant health, control pests and diseases, and reduce agricultural greenhouse gas (GHG) emissions. These goals and the four technology fields are all highly interrelated, as shown in **Figure ES-1** below.

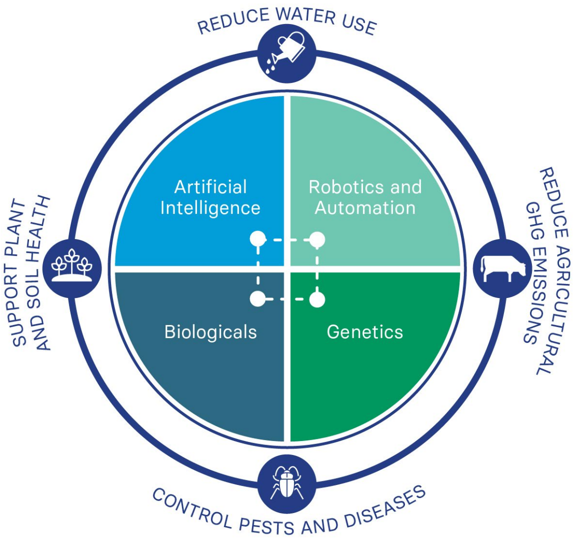


Figure ES-1. Agricultural Technology Fields and Connected Agroecological Goals

The first agroecological goal is to reduce water use. Agricultural water use accounts for 60 to 70 percent of total water use worldwide. Reducing agricultural water demand saves farmers money while increasing water availability for other uses such as environmental flow and community drinking water. Technology such as AI, soil moisture sensors, and flow meters can provide farmers with valuable information on when and where to irrigate their crops, helping reduce water use. In one case study, AI insights led to 20 percent water savings (Karasekreter et al., 2012).

The second agroecological goal is to support soil and plant health. Soil health is integral to agricultural productivity (i.e., plant health), ecosystem function, and human health; however, it is in decline due to practices such as tillage and pesticide use. Technology can enhance soil and plant health through monitoring and data collection, provision of alternatives and additives, and improvements to select traits. Recent advancements in biological and genetics technologies support products that are safer for humans and the environment. Biologicals have the potential to reduce fertilizer use and sequester carbon, both of which contribute to climate change mitigation. For example, a corn farmer in the U.S. has reduced his nitrogen use by more than a third with the help of biologicals (Farm Journal Editors, 2019). While this is a promising example, biological efficacy is variable and uncertain. More research and regulatory support is needed to demonstrate scalable and repeatable benefits of biologicals.

The third agroecological goal is to control pests and diseases. Pests and diseases are among the top challenges farmers face, as crop damage and loss can significantly impact revenue. Pest and disease control is also an environmental and societal concern, given their connections to pesticide use and food security. Technology offers a suite of tools that can identify, monitor, control, and remove pests, as well as improve plant resilience. New technologies can efficiently and rapidly assess pests and diseases, thereby reducing labor needs and improving response times. Further, genetic technologies can enhance plant resistance to biotic stress. For example, field trials showed that genetically edited rice, when introduced to a common disease, had 50 percent greater yield compared to the control (Karavolias et al., 2021).

The final agroecological goal is to reduce agricultural GHG emissions. Given that the agriculture sector accounts for 14 percent of worldwide GHG emissions and 10 percent of U.S. emissions, there is a clear need for technology solutions (FAO, 2021; EPA, 2022). The technologies employed to reduce agricultural GHG emissions depend on the emission source. For nitrous oxide, technologies focus on soil management, namely reducing fertilizer use. For methane, technologies focus on livestock operations. For example, methane technologies can monitor and quantify emissions, stop emissions at the source (i.e., the animal), and capture and convert emissions from manure. Promising technology advancements in AI, drones, and wearable devices can more accurately monitor and verify of methane emissions.

While there are demonstrated ways in which agricultural technology can support agroecology, the benefits may not be fully realized. "Taking [technology] advantages to the farm will depend, not only on the willingness of producers for adopting new technologies in their fields, but also on each specific farm potential in terms of scale economies, as profit margin increases with farm size" (Saiz-Rubio & Rovira-Más, 2020). It is imperative to identify and strengthen practices that deliver agroecological benefits as technology becomes both more available and integrated with farm operations.

EDF and the climate-smart agriculture community can use this foundational research to advance agricultural technology in ways that equitably and safely achieve benefits. Such strategies include, but are not limited to, identifying technology opportunities to support within the Farm Bill and state incentive programs, conducting a technology needs assessment for small and/or disadvantaged farmers, and profiling promising technologies that go beyond precision agriculture to achieve broader agroecological goals.

INTRODUCTION

Technology, specifically in support of precision agriculture, is considered by many as the third modern agricultural revolution (Saiz-Rubio & Rovira-Más, 2020). This revolution is needed now more than ever as climate change and population growth hinder the ability to provide food security while maintaining a hospitable planet.

The purpose of this report is to examine the intersection between agriculture, technology, environment, and society, particularly how these areas can support and enhance one another. This multidimensional lens is uncommon, as industry reports often focus on the bottom line or maximizing yield, and not the entire picture. Yet, using technology as a vehicle to drive both yield and environmental benefits is not just possible, it is essential. As the agricultural technology field grows, it is imperative to identify and strengthen these ties such that multiple benefits are at the forefront of every technological advancement.

> "It is no longer possible to look at food, livelihoods, health, and the management of natural resources separately. Embracing systems–thinking through holistic approaches is needed to address these complex and interdependent challenges." – Food and Agriculture Organization of the U.N.

This report provides a high-level overview of how four technology fields, artificial intelligence (AI), robotics and automation, biologicals, and genetics, can be valuable tools in agricultural operations. This review is focused primarily on field crop applications, with some livestock applications. Other agricultural sectors, such as aquaculture and greenhouses, could be the subject of future research to expand on this report. The technologies and associated products are discussed broadly, as the field is ever changing, and company names were removed where possible to keep the report current and unbiased.

The report then identifies how the technologies support four agroecological goals: reduce water use, support soil and plant health, control pests and diseases, and reduce agricultural greenhouse gas (GHG) emissions. These goals and the four technology fields are all highly interrelated, as shown in **Figure 1**. In connecting technology with agroecological goals, the report makes use of both peer reviewed and anecdotal evidence. Anecdotal evidence from companies and farmers is often the only information available for emergent technologies. Additionally, example technologies and case studies have an emphasis on the U.S. and some other developed nations, such as the European Union, Australia, and Israel. These countries are both leaders in and the primary market for agricultural technology.

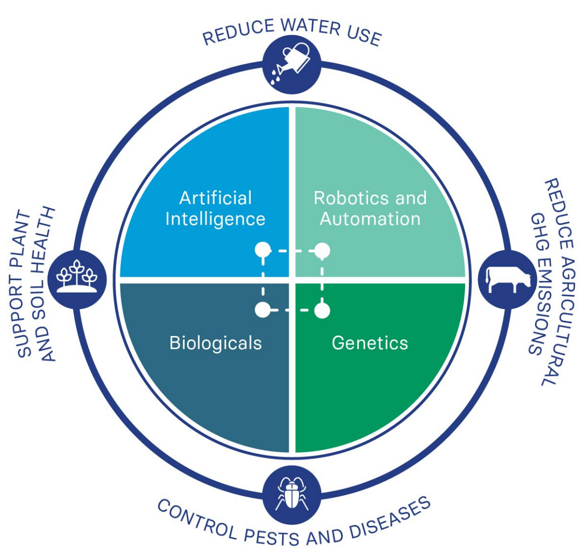


Figure 1. Agricultural Technology Fields and Connected Agroecological Goals

AGRICULTURAL TECHNOLOGY OVERVIEW

Technology in the agriculture sector is increasingly used to complement and augment traditional land management practices and knowledge. Agricultural technology can provide new insights that improve the efficiency, productivity, and sustainability of agricultural operations, a management practice known as **precision agriculture** (Nowak, 2021).

Precision agriculture allows growers to answer the questions of when, where, and how much input (e.g., water, fertilizer, pesticides, soil amendments, feed, and other products) to apply to their fields or livestock operations (Saiz-Rubio & Rovira-Más, 2020). As a result, farm operation accuracy is improved, and cost savings are achieved (Schimmelpfennig, 2016).

> Across the U.S., corn growers who have adopted precision agriculture receive **$163 more profit per hectare** than non-adopters, on average.
>
> (Schimmelpfennig, 2016)

This report reviews four prominent agricultural technology fields – **AI, robotics and automation, biologicals, and genetics.** The following sections provide a high-level overview of each field, examining its role in agriculture and common challenges. Note that the four fields do not encompass the entirety of agricultural technology; some fields, such as sensors and the internet of things, are only briefly mentioned. These technologies could represent an area for future EDF research and exploration.

Underpinning these technologies is data management and analysis. Agricultural technologies help farmers obtain vast amounts of data, but proper storage and interpretation is not guaranteed. "…The challenge for retrieving data from crops is to come out with something coherent and valuable, because data themselves are not useful, just numbers or images" (Saiz-Rubio & Rovira-Más, 2020). The report focuses on the above four technologies and associated products but recognizes that farmers play a vital role in making sense of and acting on technology outputs.

When examining the four technologies, it is important to keep equity in mind. Inequities in technology can limit adoption and can exacerbate existing inequities in the agriculture sector. Agricultural technology equity concerns include:

- **Cost:** Agricultural technology is often expensive to purchase and maintain, making it unavailable to many farmers.
- **Internet access:** Numerous technologies rely on internet connectivity to function, but rural, agricultural areas may lack reliable access.
- **Property size:** Agricultural technology is often developed for large commercial farms and may not translate well to the needs and capacity of small farms.
- **Specialized skills:** Agricultural technology may require a specialized skillset that the farmworker labor force does not possess or could not easily acquire.
- **Language access:** Agricultural technology programs and software are often in English and may not be provided or usable in the farmers' native language.

This report recognizes and briefly speaks to these challenges but does not review them in detail. Future EDF work may seek to address equity in agricultural technology.

Artificial Intelligence

AI is a broad technology field used in nearly every industry today, including agriculture. AI refers to a set of technologies that have the "ability to interpret external data correctly, to learn from such data, and to use those learnings to achieve specific goals and tasks through flexible adaptation" (Kaplan & Haenlein, 2019).

Although AI has been around since the 1950s, it was only recently incorporated into the agriculture sector. The first use of AI in agriculture began in 1985 with a cotton crop model and has since expanded to other areas, especially robotics. Over the past several decades, AI has been increasingly used in the agriculture sector to support decision making and to advance the practice of precision agriculture. AI supports all aspects of agricultural production with its ability to monitor, diagnose, and optimize operations. Simply put, AI can help assess the complex interactions between inputs and outputs in agricultural systems (Pallathadka et al., 2021).

A large subset of AI is a branch known as machine learning (see **Figure 2**). What distinguishes other AI from machine learning is the ability to self-improve over time. This characteristic makes machine learning useful in crop management, which includes yield prediction (Liakos et al., 2018). Deep learning is a newer branch within machine learning. Deep learning is more sophisticated than machine learning because it "emulates complex human functions such as pattern generation, cognition, learning, and decision making" (Liakos et al., 2018). Deep learning in agriculture has applications for pest and disease monitoring and identification, among others. This report uses the term AI to refer to all three branches, unless otherwise specified.

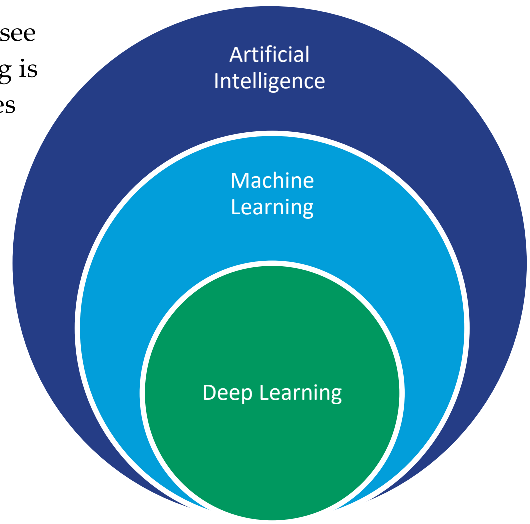


Figure 2. The relationship between AI, machine learning, and deep learning, from Pallathadka et al., 2021.

Regardless of the branch, AI does not itself perform tasks. It is up to a secondary actor to carry out the AI-informed task. This process can be compared to the human brain; our brain takes in signals (data), makes sense of it, and tells the body what to do. As such, AI is not a standalone technology but rather is integrated into other technologies. AI relies on inputs (such as cameras and sensors) and outputs (such as robotics) to execute tasks.

There is notable AI integration into various current and emergent technologies. Global Navigation Satellite Systems, when paired with AI, can create fine-scale maps of field conditions and allow machinery to autonomously navigate (Mahato et al., 2019). Another example is variable rate technology, which allows growers to apply inputs at different rates across a field depending on soil and plant conditions. In the U.S., between 30 to 40 percent of the largest corn farms (over 2,900 acres) used variable rate technology between 2010-2012 (Schimmelpfennig, 2016). The adoption rate has likely grown over the past decade as the technology becomes more advance and cost-effective.

On the emergent technology side, one of the newest AI applications is digital twins, a software that uses data to create a digital equivalent of a real-life object. This software is mostly conceptual, with some application to specialty crops, but has the potential to support various aspects of autonomous farming (Verdouw et al., 2021).

In the coming years, AI in agriculture is expected to grow at a compounded annual growth rate of 25.5 percent from 2020 to 2026 (Research and Markets, 2020). However, this growth is likely limited to areas that are already primed for adoption, such North America and Europe. With continued research, development, and application, improvements to AI technology are expected but will take time. Sophisticated AI processes, like deep learning or digital twins, often get overburdened trying to leverage vast datasets, resulting in limited outputs. AI will require further development before its wide-scale use in agriculture (Shead, 2022). Still, AI holds the promise of supporting a farming transformation where practices are “more productive in output, efficient in operation, resilient to climate change, and sustainable for future generations”(Liu, 2020).

Challenges Associated Artificial Intelligence

Several factors can limit AI’s usefulness in the agriculture sector. The primary issue is the technology itself. AI in agriculture has less than 40 years of application. While significant advancements have been made, there are still significant hurdles to move the technology from the lab to the field.

- **Data Availability and Reliability**: AI requires large datasets to produce information; however, there may not be data available or of sufficient quality to train the algorithms. Biases in research and development, such as a preference for staple crops and a focus on developed nations, limits AI’s usefulness to certain crops and regions. In extreme circumstances where poor data is used, AI could provide incorrect information that could lead to excessive fertilization and soil microbiome degradation (Tzachor et al., 2022).

- **Cost**: There is both an upfront and maintenance cost to creating these complex AI models (Ben Ayed & Hanana, 2021). It is difficult to define a price range for AI, as it is both nuanced and often intertwined with other technologies. For example, the cost of AI may be reflected within the cost of a smart robot or software system. However, AI is generally considered a technology that can provide cost savings through efficiencies, often offsetting the initial expense.

- **Internet Access**: AI is meant for the digital world, as it requires broadband to operate. Rural locations, particularly those in developing nations, often do not have reliable internet connections, leading to slower and unequal adoption and furthering the divide between commercial and subsistence farmers (Tzachor et al., 2022; Zha, 2020). Given this challenge, small-scale framers in the Global South are particularly likely to be excluded from AI-related benefits (Tzachor et al., 2022).

- **Security**: Even if a grower is fortunate enough to use AI on their field, the private information gathered can be subject to cyberattacks. A cyberattack could cause entire operations to halt or be undermined. The ramifications of a cyberattack could result in financial loss and even food shortages. This situation has already unfolded with cyberattacks on JBS, the world’s largest meat producer, and New Cooperative, a corn and soy farmers alliance, in 2021 (Tzachor et al., 2022).

There are solutions to the issues presented above, such as data standardization and community-led technology design in developing regions, to name a few (Tzachor et al., 2022). However, it will take new policies and shifts in current practices to implement these solutions such that AI benefits in agriculture, the environment, and society are equitably and safely achieved.

Robotics and Automation

Robotics is a discipline that combines software, mechanical, and electrical engineering to provide precision and automation within tasks. Robots have multiple roles in the field—from monitoring conditions, to applying fertilizer, to harvesting—which minimize the impact of labor shortages.

There are three general processes that a robot undergoes to complete a task: perceive, plan, and control (Dai & Lee, 2020). The first step involves the robot intaking information through other technology such as cameras, ultrasonic sensors, and light detection and ranging (LiDAR). With this information, the robot then determines what action it should take using AI. For example, the robot must decide if a fruit is ready to harvest, or determine if an object is a plant or weed. The final step is to for the robot to complete the task in the most efficient and safe way possible.

Photo credit: scharfsinn86/Adobe Stock

While robotics and automation are interrelated, it is possible to achieve automation without a robot. Automation technology involves an instrument that can be either physically or remotely controlled. Automation is more sophisticated than turning a device on and off; for example, "the modern combine harvester has automatic control of header height, travel speed, reel speed, rotor speed," and so on (Nof, 2009). In agriculture, automation is commonly used in irrigation systems and farm machinery.[1]

Nearly all modern farms, regardless of crop type or farm size, take advantage of robots and automation. The most common agricultural robots are drones and automated tractors or sprayers, but there are specialized robots as well. The specialized, cutting-edge robots are not as common since they may still in development or are too expensive for most farmers. Robotics and automation are generally limited to developed countries due to issues surrounding access.

Agricultural robotics is a rapidly developing field, improving upon existing applications and expanding to new areas. Currently, robots are not proficient in the act of mimicking a human grasp, which limits their usefulness in harvesting small, delicate fruits (Buchanan, 2021). Several companies are working to advance robotics technology such that robots can perform fruit harvesting at a rate equal to or faster than a human. Other developments include pollinator drones, crop-planting drones, dynamic variable rate irrigation systems, and more.

With new or improved designs, robots will perform a wider variety of tasks and do so more efficiently. In addition to cost savings, robotic innovations also provide farmworker benefits. Robots can reduce farmworker exposure to hazardous conditions which can result in fewer farmworker injuries, illnesses, and fatalities. For more on farmworker benefits, see the On-Farm Benefits section.

[1] Note that there are numerous robotics and automation applications in the agricultural processing and packaging industry, but they are outside the scope of this report.

Challenges Associated with Robotics and Automation

While commonly used in agriculture, robotics and automation still face technological and societal challenges.

- **Technology hurdles**: Agricultural fields have uncontrolled and unpredictable factors that can impact a robot's functionality (Zha, 2020). For example, rugged, uneven terrain can impact a robot's ability to move through a field. Significant advancements have been made in the past few decades, but additional research and development is needed before agricultural robots are a worthy investment for farmers.

- **Cost**: Robots are expensive, as they require a high amount of research and development investment. For example, a soil sampling robot could cost a grower around $30,000 while a sophisticated tractor with automated spraying could cost around $500,000 (Wilde, 2020). These price tags do not include things like maintenance and repairs, which further increase life cycle costs. As such, these technologies are cost prohibitive to all but a few large, commercial farms. Several companies recognize this issue, and instead are offering their products as a service. In this case, a farmer would hire the company and their machinery to come do an assessment, such as fly a drone or run a soil sampling robot, allowing the farmer to access the technology for a fraction of the price.

- **Labor Replacement Concerns**: Robots can accomplish many of the same tasks as humans, but in less time and with greater accuracy. As robots become more commonplace in agriculture, there is a fear that they will replace human labor, eliminating jobs and threatening local economies. From a farmer perspective, this is a non-issue, as they often face labor shortages and robots offer a solution. Further, humans are still needed at some point in the process if robots are not fully autonomous. This type of work requires a different, more technical skillset than typical farm work, such as drone operation or software engineering. As such, farmworkers may increasingly need additional training to engage with robotics and automation, or else may be forced to leave the industry.

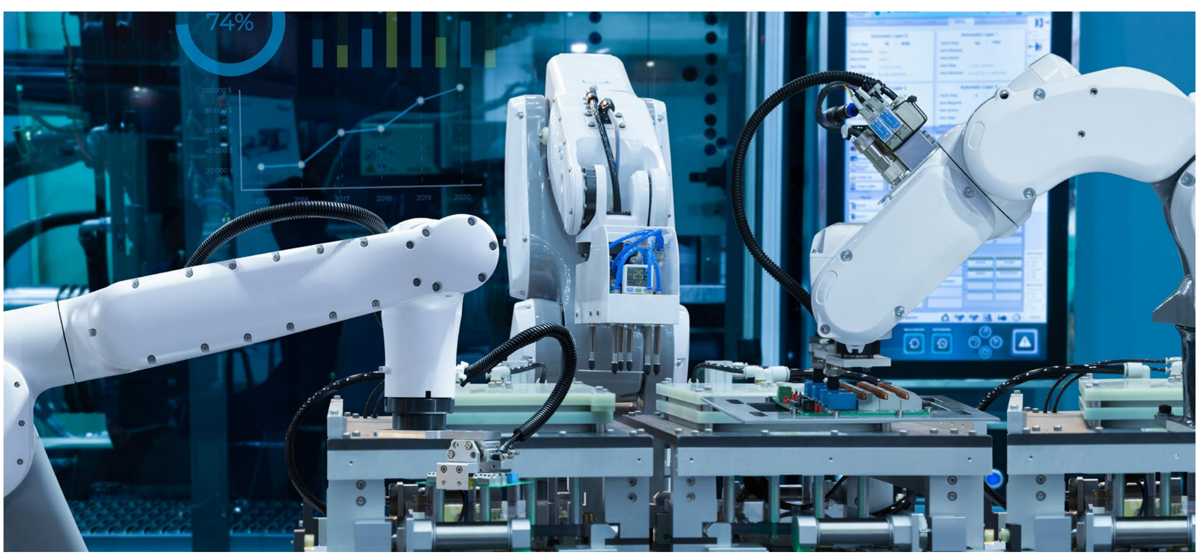


Photo credit: Kinwun/Adobe Stock

Biologicals

Biologically active agricultural inputs, commonly called biologicals, offer a natural alternative to traditional agricultural inputs. According to the Biologicals Products Industry Alliance, biologicals are "naturally occurring compounds or synthetics that act the same as the natural compounds." These compounds are commonly derived from seaweed, fungi, bacteria and microorganisms, amino acids from animals, and chitin (an amino sugar found in fungi cell walls and arthropod exoskeletons) (du Jardin, 2015; Yakhin et al., 2017). There are three main types of biologicals:

- **Biopesticides** protect plants from pests and disease.
- **Biofertilizers** provide plant nutrition.
- **Biostimulants** stimulate growth, mitigate stress-induced limitations, and increase yield (Yakhin et al., 2017).

Biostimulants are the most difficult to define, both from a regulatory and scientific standpoint, in part because they can accomplish the same goals as biopesticides and biofertilizers, but through different mechanisms (du Jardin, 2015; Yakhin et al., 2017). Both biofertilizers and biostimulants can increase plant growth, but biofertilizers do so through the provision of nutrients whereas biostimulants promote plant growth through other means. Similarly, biopesticides and biostimulants both limit the impact of pests on crops, but biopesticides do so through toxins that kill or disrupt the pest's lifecycle, whereas biostimulants increase plant strength and resistance (Yakhin et al., 2017).

Like their conventional counterparts, biologicals often come in the form of a liquid. This liquid can be applied through the irrigation system (fertigation) or by sprayers. Biologicals can also take the form of a seed coating. Yet unlike their counterparts, biologicals can be applied at all stages of agricultural production, even during harvesting, due to their low toxicity and rapid degradation in the environment (Yakhin et al., 2017). These traits allow growers flexibility in their practices, reduce worker exposure to harmful chemicals, and minimize residue on crops (Leahy et al., 2014).

Growers also benefit from the lower cost of biologicals when compared to conventional inputs. Anecdotal evidence from a corn and soybean farmer said that his biological treatment "literally costs a couple of bucks, versus the old treatment that could reach $15 to $30 per bag of beans" (Farm Journal Editors, 2019). When applied over thousands of acres, year after year, biologicals can provide significant savings when used in lieu of or in combination with conventional inputs.

Since biologicals are natural compounds or synthetics of natural compounds, they are generally non-harmful to the environment, and in some cases can be beneficial. When discussing benefits, it is important to keep in mind that biologicals do have some issues around efficacy (see Challenges Associated with Biologicals section below). Additionally, they are often used as a compliment to, not a replacement of, conventional synthetic fertilizers and pesticides (Cely et al., 2016).

Biologicals are used on all crop types across the world. However, biologicals are predominantly used on fruits and vegetables, accounting for 76 percent of the global market share. Biologicals' low toxicity and residue are ideal for fruits and vegetables because they are often consumed in raw form and consumer demand for organics has increased (*Markets For Biological Products: Agriculture | Biological Products Industry Alliance*, n.d.). For biostimulants, the market is substantial and rapidly growing, with the European Union comprising the largest share (around 42 percent in 2015), followed by North America (22 percent) and Asia-Pacific (20 percent) (Yakhin et al., 2017). As the market expands, improvements in biological research and performance can be expected.

Challenges Associated with Biologicals

Biologicals have interrelated scientific, regulatory, and perception issues.

- **Scientific uncertainty**: Biologicals comprise a broad group of compounds that work in a multitude of ways. There is still scientific uncertainty as to how biologicals function given the complexities of natural systems (du Jardin, 2015; Yakhin et al., 2017). What works well in a lab, or one sample plot, may not translate when applied at a larger scale or across different crops. Further, there is limited data transparency from biological producers. Our narrow understanding of how biologicals interact with multiple systems has implications for efficacy, regulation, and adoption.

- **Regulatory challenges**: For biostimulants, there is a global lack of consistent terminology and regulation (du Jardin, 2015). Since biostimulants can provide similar functions to both biofertilizers and biopesticides, they often are conflated with one another and placed in the same regulatory framework. This has led to inappropriate oversight that can delay a product's approval, under or overstate its risk, and allow developers to make claims that are not scientifically sound (du Jardin, 2015). In the U.S., there is a bill (H.R. 7752) that would clarify biostimulant terminology and direct studies on biostimulants and soil health. As of December 2022, the bill is waiting review by the Subcommittee on Biotechnology, Horticulture, and Research.

- **Varied perceptions**: Due to inconsistent regulations and scientific uncertainty, biologicals often have perception problems. Both peer-reviewed articles and anecdotal evidence note that biologicals are often considered "snake oil" (du Jardin, 2015). But as technology advances, perceptions are starting to shift. A survey of 672 growers performed by the U.S. agriculture trade journal, Farm Journal, found that thirty five percent of respondents saw the potential in using biologicals, compared to only four percent who saw no benefit. However, the majority of respondents said that they needed more information before they would apply biologicals on their farm (Farm Journal Editors, 2019).

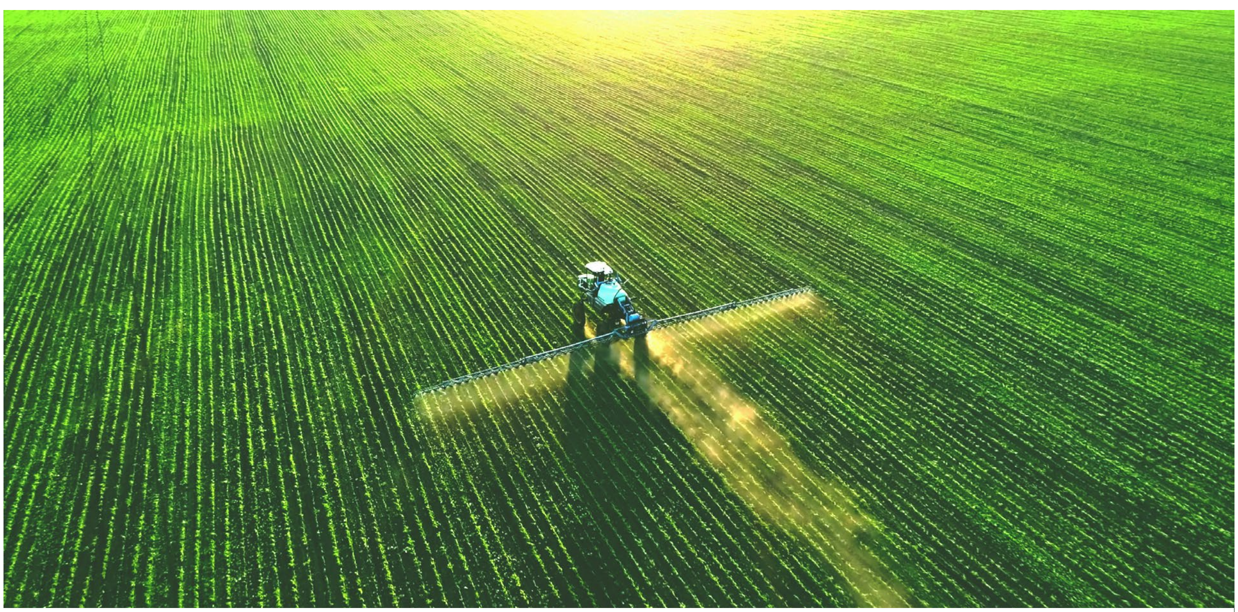


Photo credit: Mose Schneider/Adobe Stock

Genetics

Genetic modification is not new to agriculture; humans have been modifying plants and animals for desired traits since ancient times. More recently, the field of genetics has advanced and expanded with the help of technology. Rather than provide an overview of the entire genetics field, this section is focused on one emergent gene editing technology known as CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats). There are other genetic technologies such as ZFN (Zinc Finger Nucleases) and TALEN (Transcription Activator-Like Effector Nucleases), but the focus is on CRISPR because it is the most effective and accurate technology. CRISPR technology, often referred to as the CRISPR/Cas system, is a genetic engineering tool that uses a CRISPR sequence of DNA and its associated protein to edit the base pairs of a gene.

CRISPR was first identified in *E. coli* by Japanese scientist Yoshizumi Ishino and his team in 1987, but their function remained unknown. In subsequent years, CRISPR was further characterized by several scientists, including Francisco Mojica. These studies found that bacteria had repeating DNA sequences that stopped evading viruses (Ishino et al., 2018; Molteni & Huckins, 2020).

However, it wasn't until 2012 that scientists Jennifer Dounda and Emmanuelle Carpenter separately discovered that CRISPR allows edits to the genome by removing, adding, or altering sections of the DNA sequence (Mittal, 2019). A basic overview of the CRISPR editing process goes as follows. First, guide RNA acts like a genetic GPS by finding and binding to the target DNA section. Then the Cas (CRISPR-associated) protein cuts the DNA like a pair of molecular scissors. At this point, scientists can edit the organism's genome.

Through CRISPR technology, genes can be turned on and off, enhanced, or replaced. What makes CRISPR more effective than other gene editing processes is its precision, speed, affordability, and ability to alter multiple genes at once (Mittal, 2019; Molteni & Huckins, 2020). It is important to note that the CRISPR gene editing process is done within organisms; it does not require the introduction of foreign material to make edits, which is how traditional genetically modified organisms are created. This distinguishing factor is important for regulations, as discussed further in the Challenges Associated with Genetics section.

Dounda and Carpenter's gene-editing finding is considered a revolution and has since spurred prolific research in the agricultural sector and beyond. **Figure 3** shows the top CRISPR patent applicants in the plant category, as of October 2020. These patents, along with additional research, exemplify that significant advancements have been made in a relatively short amount of time. Researchers have shown that crops can be genetically edited for a wide variety of benefits including yield augmentation, pest resistance, nutrition enhancement, stress tolerance, and more. Further, CRISPR has been used to improve livestock traits such as heat tolerance and disease resistance. These modifications can be an important strategy in food security and climate change adaptation (Karavolias et al., 2021).

> Traditional breeding can take multiple years, and in some cases decades, to produce the desired trait. CRISPR can significantly reduce the timeframe from years to months.
> - Interview, CRISPR researcher

Despite these advancements, most CRISPR-edited crops are not yet commercially available. According to the Global Gene Editing Regulation Tracker, only one CRISPR-edited product is commercially available in the U.S.; "a soybean oil that contains up to 20 percent less saturated fatty acids compared to commodity soybean oil." Japan also has a commercially available, CRISPR-edited tomato that has a higher nutritional content compared to a standard tomato (Ladenheim, 2022). As CRISPR-research progresses, more commercialized products will likely hit grocery store shelves, pending regulatory approval.

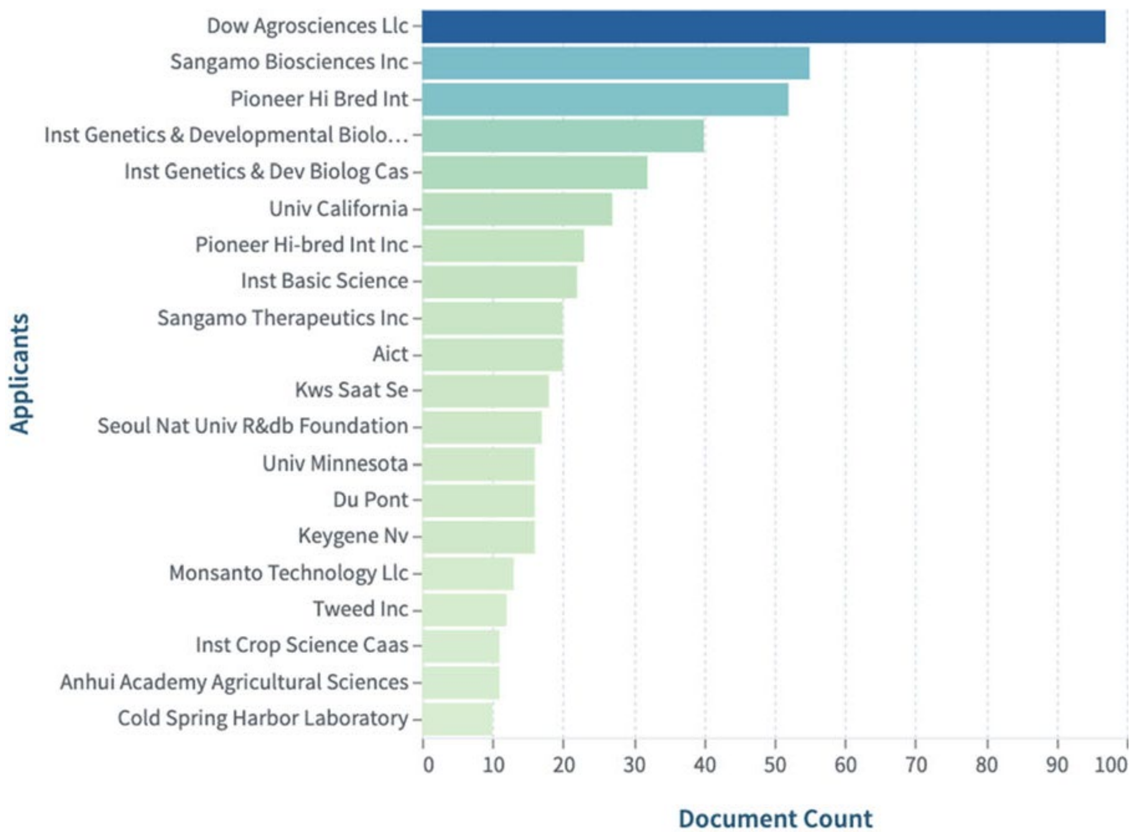


Figure 3. CRISPR Patent Applicants in The Plant Category as of October 2020. Image Credit : Jefferson et al., 2021

Challenges Associated with Genetic Technology

There are four notable challenges associated with CRISPR, as discussed in detail below. However, many of these challenges relate to other genetics technologies as well.

- **The science is still developing**. CRISPR gene editing is a relatively new technology, having only been discovered a decade ago. Therefore, there is still much to learn about how CRISPR works. One limiting factor of CRISPR technology is that it is not 100 percent effective. In addition to efficacy issues, CRISPR can also edit genes outside the gene of concern, an issue known as an off-target effect. If additional genes are edited, it could have unintended consequences such as increased disease sensitivity. Off-target effects are a concern in livestock gene editing, but not plant editing as the mutations tend to be in genes similar to the targeted gene and can be identified using genome sequencing. Scientists are developing solutions to these issues which includes more effective and accurate Cas proteins and guide RNA.

- **Inconsistent regulations:** There are disparate regulatory frameworks across the globe which create confusion and delays, limiting CRISPR research and commercial use. For up-to-date CRISPR regulatory information, see the Global Gene Editing Regulation Tracker.
    - Prior to CRISPR, many countries had established regulatory frameworks for genetically modified organisms. Some counties, such as the EU and Mexico, have maintained their regulations, treating the CRISPR process and products like any other genetic modification. These countries often cite concerns over pest resistance and other environmental and human risks. In the EU, CRISPR is limited to research exclusively, making it all but impossible to use the technology as a regional food security and climate change strategy. However, a 2021 study found that EU regulations did not match the science and changes are needed. A new policy proposal is forthcoming in 2023 and is likely to loosen some policies (*Global Gene Editing Regulation Tracker*, 2020).
    - Conversely, there are other countries, such as the U.S. and Japan, whose regulations acknowledge that CRISPR is a different type of gene-editing technology and thus are more relaxed. In 2020, the USDA adopted new regulations, known as the SECURE Rule, which exempt gene-edited plants that otherwise could have been developed through conventional breeding; a CRISPR-edited crop is "substantially equivalent" to a non-edited crop (Movement of Certain Genetically Engineered Organisms, 2020). However, the SECURE Rule only applies to plants; animals are significantly more regulated. The U.S. has continued to emphasize biotechnology, including CRISPR, as evidence by President Biden's Executive Order which seeks to increase domestic research and development.

- **Access and intellectual property limitations:** Although CRISPR is a relatively fast and inexpensive technology, it is not readily accessible. CRISPR patents are mostly held by large corporations and academic institutions in developed countries such as the U.S., Australia, and China (refer to patent holders in **Figure 3**). Further, large corporations tend to only focus on increasing yield in commercial crops (Halterman et al., 2016). According to the most recent IPCC report, "modern biotechnology has not demonstrated the scale neutrality need to serve smallholder dominated agroecosystems. The benefits from genetically modified crops tend to be captured disproportionately by farmers with more land, wealth, and education."

- **Mixed perceptions:** In the EU, and in some segments of the U.S., there is a cultural distrust of genetically modified organisms. Their attitudes downplay advantages of genetically modified organisms, while focusing on and inflating the risks. The strong cultural aversion to genetically modified organisms has implications to CRISPR regulations and commercial viability. As previously mentioned, CRISPR uses a different process to genetically alter an organism, mitigating several of the risks associated with traditional genetically modified organisms. However, this difference is potentially too nuanced for the general population. Thus, "consumers may not distinguish [CRISPR-edited crops] when purchasing or consuming food" (Shew et al., 2018). If this holds true, "CRISPR's full market potential may never be reached" (Shew et al., 2018).

For Consideration: Connecting Technology and Climate-Smart Agriculture

Although this report focuses on modern agricultural technology innovations, technology itself is a broad term that includes a range of innovation and practices. "Low" technology solutions are often rooted in natural processes that are more in balance with the ecosystem. Climate-smart agriculture is an approach that provides food security in a changing climate, with three main objectives: "sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas emissions, where possible"(FAO, 2021a). Examples of climate-smart agriculture include no till, crop rotation, mixed planting, cover crops, and other practices. The Sixth Annual IPCC report finds that, "ecosystem-based approaches such as diversification, land restoration, agroecology, and agroforestry have the potential to strengthen resilience to climate change with multiple co-benefits, but trade-offs and benefits vary with socio-ecological context."

> "A critical factor in the success of regenerative agriculture for growers will be how, as an industry, we can provide demonstrable benefits over the short-and long-term. It will be insufficient to utilize regenerative agriculture simply as a marketing buzzword, but rather, we must demonstrate that this way of growing provides measurable gains to the market"
>
> Michael Pratt, Commercial Director, Lallemand Plant Care as quoted in the *Irrigation Technology Annual Report*

While climate-smart agriculture is rooted in cultural knowledge and ecological processes, there is a place for modern technology through the provision of information. High technology can provide meaningful and declarative evidence for climate-smart agriculture practices, overcoming doubts, concerns, and risks. High technology also provides an opportunity to enhance the performance of climate-smart agriculture with data insights. And the reverse can be true as well, where high technology can be improved upon by understanding and incorporating climate-smart agriculture principles and practices.

A prime example of technology supporting climate-smart agriculture comes from numerous comparisons between conventional and regenerative farms. Using technology to gather and analyze parameters such as soil health, mineral micronutrients, and omega-3 fats, scientists can quantify the benefits of climate-smart agriculture. Across all farm types and locations, climate-smart agricultural practices were found to enhance the nutritional profiles of crops and livestock (FAO, 2021a; Montgomery et al., 2022). These technology-supported findings reinforce and promote climate-smart principles.

Cover crops integrated in an EDF Orchards Alive participating pecan orchard, where plant species are providing valuable resources for native pollinators while sustaining crop productivity Photo: Rex Dufour, NCAT

TECHNOLOGY TO ADVANCE AGROECOLOGICAL GOALS

In 2020, U.S. crop farms spent **$56.4 billion on combined crop inputs** (chemicals, fertilizers, and seeds), accounting for nearly a third of total farm expenses, and $**27.0 billion on labor**, accounting for almost 14 percent of total farm expenses.

(USDA, 2021)

The primary market driver for developing and adopting agricultural technology is to increase output while reducing input costs, including labor. While there is clear demand for these agronomic benefits, agricultural technology has the potential, and imperative, to provide additional benefits to both society and the environment. To convey the connection between agriculture, society, and the environment, this report uses the encompassing term agroecology. The Food and Agriculture Organization of the U.N defines agroecology as, "a holistic and integrated approach that simultaneously applies ecological and social concepts and principles to the design and management of sustainable agriculture and food systems. It seeks to optimize the interactions between plants, animals, humans and the environment while also addressing the need for socially equitable food systems within which people can exercise choice over what they eat and how and where it is produced."

This section examines agricultural technology's ability to meet four priority agroecological goals:

1. **Reduce Water Use**
2. **Support Plant and Soil Health**
3. **Control Pests and Diseases**
4. **Reduce Agricultural Greenhouse Gas Emissions**

Agricultural technology also provides broader environmental and societal benefits both on and off the farm. These benefits—like improving farmworker safety, supporting biodiversity, and increasing food security—are also important and are briefly described in Additional Benefits of Agricultural Technology.

Photo credit: Artiemedvedev/Adobe Stock

Agroecological Goal 1: Reduce Water Use

Water is unlike every other agricultural input; it is uniquely irreplaceable. The necessity of water to agriculture is evident in the extent of its use. Around the world, agriculture accounts for 60 to 70 percent of total consumptive water use. Analyses indicate that agricultural water use will increase globally due to cropland expansion and intensification plus climate change-induced changes in water requirements (Martina Angela Caretta et al., 2021).

> "Without water, we would not have a crop. Any other input we use can be had at a price, but water is different."
>
> John Warmerdam (Manager, Kings Orchard in Hanford, CA) as quoted in *Irrigation Technology Annual Report*

Climate change will intensify the hydrologic cycle and adversely impact agriculture; it has been linked to prolonged droughts, periods of more intense rainfall, an increase in evapotranspiration, and more. According to the IPCC Sixth Assessment Report, *Climate Change 2022: Impacts, Adaptation and Vulnerability*, agriculture has already experienced climate change-related consequences, a situation which is only expected to worsen. "Between 1983 and 2009, approximately three-quarters of the global harvested areas (approximately 454 million hectares) experienced yield losses induced by meteorological drought, with the cumulative production losses corresponding to… $166 billion"(Martina Angela Caretta et al., 2021).

To confound the issues brought on by climate change, farmers are also facing increased costs to obtain access to scarce water supplies. Innovation in water technology is needed both from an environmental perspective to mitigate the impacts of climate change, and from an agroeconomic perspective to reduce water-related expenditures.

How Technology Can Reduce Water Use

Water-related technology has been around for millennia but has mostly focused on the transportation of water from one area to another. Major innovations such as aqueducts, hydropower dams, and electric pumps have expanded agriculture throughout the world. However, it is not until recently that technology has focused on water savings. Agricultural technology can help answer the questions of when, where, and how much water to apply to a field.

> A study on AI and a Turkish strawberry orchard found that AI successfully determined a new irrigation schedule that achieved **over 20 percent water savings** and **nearly 24 percent energy savings.** (Karasekreter et al., 2012)

Water application is typically a function of monitoring; growers look at soil, plant, and atmospheric conditions to determine irrigation schedules. There are various monitoring technologies that can inform growers' decision making—weather stations, soil moisture sensors, telemetry, drones, and satellites are among the most common technologies (*Irrigation Technology Annual Report*, 2021). These technologies are not necessarily cutting-edge, but they are becoming more sophisticated and integrated with one another over time.

Using monitoring data from the above-mentioned sources, AI can effectively compute evapotranspiration rates. Evapotranspiration rates provide a reliable estimate of crop water requirements and are a useful tool in determining irrigation schedules.

Other areas of innovation relate to irrigation automation. Flow meters paired with telemetry, zone valve and pump automation, thermal imagery, and computer models can provide landscape-level irrigation control (*Irrigation Technology Annual Report*, 2021). Through automation and other technologies, the process of applying water is done in a data-driven, automated way, creating both efficiencies and cost savings. For example, advanced metering infrastructure consists of sophisticated flow meters which use remote monitoring (telemetry) to measure how much water is applied and when. In turn, this information can support enhanced water management, advance conservation efforts, and help meet regulations. On top of water savings, irrigation automation provides labor saving benefits as it eliminates the need for a worker to manually go into a field and adjust equipment settings.

In addition to supporting the timing and quantity of water application, technology can also help with irrigation system maintenance. A poorly maintained irrigation system can cause a variety of issues including yield and quality reductions, nutrient leaching, and higher energy costs. To assess system performance, irrigators look for irrigation uniformity, which indicates how evenly water is being applied throughout a field. Technology such as pressure transducers and soil moisture sensors support uniformity tests. With this information, irrigators can determine if leaks or blockages are present and find remediation solutions (*Irrigation Technology Annual Report*, 2021). The overall intent is that additional information, either about the irrigation system or about field conditions, will translate into water savings.

Despite the agroeconomic benefits outlined above, there has been limited adoption of these water technologies. In a comprehensive 2018 USDA survey of irrigators in the U.S. (see textbox), technology was not included in the top four methods used to determine irrigation schedules (USDA, 2019). For example, adoption of soil moisture probes in the U.S. is around ten to fifteen percent, a rate which has remained steady for decades (Irrigation Innovation Consortium, 2022). When growers were asked why they had not made improvements to reduce energy or conserve water, cost-related concerns were two of the top three answers (USDA, 2019).

Irrigation Method Used in the U.S. Based On 2018 USDA Survey*

1. Condition of crop (180,560 farms)
2. Feel of soil (93,052)
3. Personal calendar (46,477 farms)
4. Scheduled by water supplier (38,566 farms)
5. **Soil moisture sensing device (27,629 farms)**
6. Commercial or government scheduling service (18,773 farms)
7. Reports on daily crop-water evapotranspiration (16,701 farms)
8. When neighbors decide to irrigate (12,765 farms)
9. Plant moisture sensing devices (5,199 farms)
10. Computer simulation models (1,928 farms)

*Irrigators could select more than one irrigation method. N = 231,474 farms.

Ease of use is another common adoption barrier as exemplified by two pilots run by The Nature Conservancy and Natural Resource Districts. These pilots offered cost-share programs in Nebraska to improve irrigation efficiencies. The program results showed that soil moisture sensors can save one to four inches of water depending on the location. However, most growers returned the probes when the program ended because they, "weren't worth the hassle" (Irrigation Innovation Consortium, 2022).

Despite these challenges, technology adoption *can* be driven by the right incentives. For example, the critically-overdrafted Oxnard and Pleasant Valley basins in Ventura County, California, threaten a vibrant $2.1 billion agricultural economy. The agency that oversees basin management, Fox Canyon Groundwater Management Agency (FCGMA), has piloted a water market as one means to stabilize the basins. Critical to the success of the market is technology that can accurately track water use. FCGMA required that all active agricultural wells install tamper-proof advanced metering infrastructure. To support adoption and water market participation, the requirement included financial assistance in the form of rebates (Heard et al., 2019). The FCGMA example demonstrates how regulation and water scarcity together can drive technology implementation.

Agroecological Goal 2: Support Soil and Plant Health

Soil is foundational to agricultural productivity, ecosystem functions, and human health (Banerjee & van der Heijden, 2022; Lehmann et al., 2020). It plays a critical role in nutrient cycling, carbon sequestration, soil hydrologic cycling, pest and disease suppression, and more (Bot & Benites, 2005). Soil health is defined as "an integrative property that reflects the capacity of soil to respond to land management" (Kibblewhite et al., 2008).

Inextricably linked to soil health is plant health. In fact, 18 of 29 essential plant elements are obtained from the soil (Banerjee & van der Heijden, 2022). Plant health encompasses a wide array of metrics including nutritional content, tolerance to stress and disease, root mass, and more. This section is specifically focused on yield and abiotic stress tolerance. Plant nutrition, provided though fertilizer application, is also briefly discussed here and in the Reduce Agricultural Greenhouse Gas Emissions section.

Globally, soil health, and thus plant health, has been declining because of human activity. Practices such as crop tilling, fertilizer and pesticide use, planting of monoculture crops, and burning crop residue negatively impact the soil's biomass production, organic matter, and decomposition rates (Bot & Benites, 2005). The consequences of human activity are compounded by climate change. The latest IPCC report finds that climate change will have "significant impacts" on soil health. For example, precipitation and temperature extremes can reduce soil biological function (Kerr et al., 2021). Already, soil has lost significant carbon content. Estimates of worldwide soil carbon loss vary, with more recent models indicating 133 gigatons of carbon loss (Sanderman et al., 2017).

There are dedicated efforts to improve and restore soil health, many of which promote climate-smart agricultural practices such as no till and cover crops. However, there is a place for technology as well.

Photo credit: pingpao/Adobe Stock

How Technology Can Support Plant and Soil Health

Agricultural technology can support soil and plant health through monitoring and data collection, provision of alternatives and additives, and improvements to soil and plant traits, as described in the sections below.

Monitor and Collect Data

Understanding soil and plant conditions generally requires time-consuming and expensive measurements; someone must go in a field and collect dozens of samples that then need analyzed. With the use of technology, however, soil and plant insights can be achieved in less time, at a lower cost, and with more accuracy (Liakos et al., 2018).

There are numerous technology innovations that are helping farmers understand soil characteristics. Some companies combine satellite imagery, drones, and soil sensors to create a digital twin of the soil profile without digging a single hole. For growers who prefer tangible samples, there are other companies that focus on improving soil sampling with AI-embedded robots. These autonomous, GPS-guided machines take hundreds of samples in a short period of time. Both technology approaches are providing growers with insights on soil composition, temperature, moisture levels, nutrient levels, and carbon content. Yet, both soil sampling robots and soil profile digital twins are relatively new in the agricultural industry and not yet widely available.

From the soil data, growers can make informed decisions about soil management, potentially reducing fertilizer use and increasing soil carbon sequestration. Anecdotally, one farmer found that a soil sampling robot **reduced his fertilizer and soil amendment inputs from about $85 to $60 per acre without sacrificing production**. This translates to $13.50 to $17.40 per acre return on investment (Wilde, 2020).

In addition to providing a snapshot of current soil conditions, technology can improve our understanding of soil carbon sequestration, an area of uncertainty in the soil sciences. When paired with soil samples, AI technologies can help scientists better define soil carbon sequestration potential. Filling this knowledge gap may support emerging carbon markets, an increasingly popular climate mitigation strategy.

For plant health, drones paired with AI can support farmers by assessing large areas of land quickly. Data captured from drones can be reported as a vegetation index which farmers can use to make decisions about when to irrigate, apply fertilizer, and harvest. More sophisticated AI can move beyond simple indices and even predict crop quality and nutrient deficiency. With this information, AI can predict yield with a high degree of accuracy (around 80 percent) (Liakos et al., 2018). Yield predictions can inform crop management and have implications on farm financials, food security, and more.

A study on wheat and AI found that AI was able to identify **wheat health with over 97 percent accuracy** and **nitrogen stress with over 99 percent accuracy.** This type of insight can influence crop waste and fertilizer use. (Pantazi et al., 2017)

Upcoming drone technology will be able to do more than monitor and inform; new drones are being developed to plant, pollinate, and fertilize crops (Spires, 2020; Vega, 2017). If successful, pollinating drones could significantly support plant health, complimenting natural pollinators whose populations are declining.

Outside of drones, companies have developed robots that sow seeds and harvest crops. Robots that sow seeds are an emerging area of robotics, but early studies demonstrates that they support soil health by minimizing compaction and disruption (*Project Xaver*, 2022). Similarly, harvesting robots can minimize disruption, only selecting the crops ready for harvesting. Harvesting robots have the added benefit of addressing labor shortages, improving worker conditions, and enabling the practice of strip cropping.

While harvesting robots offer many benefits, their use in fruits and vegetable fields is not commercially available due to technology limitations (Beg, 2022; Kootstra et al., 2021).

Supply Alternatives and Additives

There is no substitute for soil rich in organic matter, however, there are products that can improve soil health. Biostimulants can be added to the soil to promote beneficial biological activity and stimulate plant growth (Bot & Benites, 2005; Yakhin et al., 2017). Yet due to complex soil-plant interactions, biologicals have variable impacts.

Biofertilizer and biostimulants also provide crop nutrients, promote root and top growth, and increase yield. This is accomplished through various mechanisms including an increase in nutrient uptake, enhancement of photosynthesis, and germination simulation (Yakhin et al., 2017). For example, the corn industry standard is to apply 1.1 pounds of nitrogen (N) per bushel to achieve maximum yield. Yet with the support of biologicals, a grower in Illinois has reduced his fertilizer application to 0.7 pounds of N over six years. His goal to use 0.5 N pounds, **reducing his fertilizer use by over half the industry standard** (Farm Journal Editors, 2019).

Commercial seaweed extracts increased **tomato weight yield by 30 percent** and **bean yield by 24 percent** over the controls. (Crouch et al., 1992; Nelson & van Staden, 1984)

Biologicals further support plant health by increasing tolerance to stress such as drought, salinity, and heat (du Jardin, 2015; Yakhin et al., 2017). This is accomplished through physiological changes to the plant that allow for survival in extreme conditions such as drought or heat. One study found that application of amino acids and yeast helped wheat overcome the deleterious effects of drought and improved productivity and quality (Hammad & Ali, 2014). Resilience to stress is an important climate adaptation mechanism, but more research on biological products is needed to quantify environmental outcomes such as nitrous oxide emissions and nitrate leaching.

Improve Soil and Plant Traits

Genetics technology has demonstrated the ability to improve soil and plant health by identifying desired traits and enhancing them.

For soil health, genetics technology is helping sequence the soil microbiome. According to Fierer 2017, "Soils can contain large amounts of microbial biomass, including fungi, protists, viruses, bacteria and archaea. Most of these taxa currently remain undescribed and have physiological and ecological attributes that are unknown." Genetic sequencing may provide insights on which microbes are responsible for disease suppression, carbon sequestration, and more. Yet translating soil microbial data into actionable information is challenging as it is context specific and there is no "ideal" soil microbial community (Fierer et al., 2021)

In the future, biologicals could be designed to promote specific microbial communities that sequester carbon. This is still a relatively new concept, with a handful of startups working on prototypes. There is debate as to how much and for how long the carbon would be stored, but the goal of these agricultural technology companies is to provide long-term stable carbon storage.

In terms of plant health, genetics technology has demonstrated significant improvements in crop yield, nutrition content, and abiotic stress tolerance. These advancements are new and mostly limited to scientific field studies but are nonetheless promising as a viable food security and climate change adaptation strategy. One such advancement relates to salinity tolerance. Climate change is increasing soil salinity levels, negatively impacting crop yield and growth. Scientists have successfully developed a rice varietal that is more salt tolerant without impacting yield, plant biomass, or grain quality (Karavolias et al., 2021). Another CRISPR-edited rice varietal has improved drought tolerance and yield (Joshi et al., 2020).

Numerous CRISPR-edited rice varietals have demonstrated **yield increases between 11 and 68 percent.**

(Karavolias et al., 2021)

In addition to drought and salinity tolerance, scientists are using CRISPR to develop crops that can more readily withstand natural disasters. During strong wind events, such as hurricanes and typhoons, crops can buckle or uproot, particularly if they are bearing heavy fruit. Scientists have genetically-edited a semi-dwarfed banana varietal that reduces crop breakage (Karavolias et al., 2021). The banana and rice examples are just two of the many advancements in improving plant tolerance to intensifying abiotic stressors.

Photo credit: Environmental Incentives/Patricia Sussman

Agroecological Goal 3: Control Pests and Diseases

Pest and disease control are a top challenge farmers face. They can negatively impact everything from crop value to ecosystem stability to food security. One particularly challenging pest is weeds. Weeds compete with crops for scares resources which can significantly disrupt the crop, even to the point of complete yield loss if left uncontrolled. Weeds have caused major economic losses across the world, with annual estimates of $11 billion in India to $33 billion in the U.S. (Chauhan, 2020). In addition to economic devastation, weeds-induced crop loss threatens food security.

It is estimated that up to **40 percent** of global crop production is lost to pests, annually. Each year, plant disease costs the global economy **over $220 billion**, and invasive insects at least **$70 billion.**
(FAO, 2022)

Climate change is expected to worsen pest and disease outbreaks; pest occurrence and distribution will be altered and their control will become costlier (Kerr et al., 2021). "For example, a single, unusually warm winter may be enough to assist the establishment of invasive pests"(FAO, 2022). Climate change will also increase abiotic plant stress, making plants more susceptible to disease.

With these harsh consequences and predictions of worsening conditions, significant resources are spent on pest and disease management. In modern agriculture practices, pests and diseases are typically controlled through pesticides. In 2020, U.S. farmers spent $16.5 billion on agricultural chemicals to control pests (USDA, 2021). However, controlling pests and diseases through conventional pesticides has its own set of consequences, such as pollinator population declines, water quality impairment, soil degradation, and increasing pest resistance.

For farmers, pest resistance is a growing concern. The rapid efficiency of pesticides, like glyphosate, has led to overuse, thus supporting the evolution of pesticide resistant weeds (Perotti et al., 2020). Palmer amaranth is one example of a glyphosate-resistant weed. This is problematic given how fast it grows and spreads; a single plant can have 250,000 seeds (USDA, 2017). As a result, Palmer amaranth is difficult to eradicate once established, causing significant yield loss across the U.S. According to the USDA, yield losses have been reported up to 91 percent in corn and 79 percent in soybeans.

To deal with the interrelated issues of pest resistance and environmental degradation, some farmers are adopting a more holistic management approach to pest control called integrated pest management or IPM. IPM refers to an "ecosystem based strategy that focuses on long-term prevention of pests or their damage through a combination of techniques such as biological control, habitat manipulation, modification of cultural practices, and use of resistant varieties" (UCANR, 2022). Pesticides are used sparingly and only as a last resort for more effective control. Technology supports IPM by making it easier to adopt, more affordable, and more effective at lasting pest and disease control.

How Technology Can Control Pests and Diseases

Technology can identify, monitor, control, and remove pests and diseases, as well as improve plant resilience to pests and disease.

Identify and Monitor

Drones and other remote sensing technologies can efficiently detect, identify, and monitor pests and diseases over large landscapes. This rapid assessment benefits farmers by reducing labor needs and providing current condition data that can improve management response times. As a result, technology can translate to reduced crop losses and improvements in food security.

> Several studies of AI and wheat were able to identify a common wheat disease, yellow rust, with **over 99 percent accuracy**. (Liakos et al., 2018)

AI can help at the individual crop scale as well. With the use of a smartphone camera, farmers across the world have access to AI-powered apps that can accurately diagnose numerous diseases across many crop types by simply analyzing a photo. The benefit of this technology application is that it is relatively low cost and can be used on small farms. Some apps even are produced in numerous languages, increasing access to farmers who are typically left out of more niche technology solutions.

Additionally, AI can classify a plant as either a crop or weed, which then enables robots to remove weeds more accurately. This is a newer application of AI as it requires pattern recognition and other complex functions. For example, a crop in the germination phase looks significantly different than the same crop in the reproduction phase, and AI needs to recognize both as the crop. Studies have shown that AI can effectively and accurately identify weeds in pilots, but commercial use of this AI application is limited (Liakos et al., 2018).

Control and Remove

Once the pest or disease is identified, technology provides insights about where and when to apply pesticides. Farmers typically apply pesticides according to general industry guidelines that may not reflect farm specific soil and climate characteristics. This general guidance often results in excess use with negative economic and environmental consequences. With technology, inputs can be applied with extreme precision, benefitting the soil, water, and air, while saving farmers money. For example, a leading robotics company has found that their tractor equipment **reduces pesticide and fertilizer use by up to 95 percent** (Ecorobotix, n.d.; Verdant Robotics Delivers First Multi-Action Autonomous Farm Robot for Specialty Crops, 2022).

Biologicals, specifically biopesticides, are a useful tool in IMP. Unlike conventional pesticides, which use a broad spectrum of chemicals to eradicate pests, biologicals use a targeted approach unique to the pest of concern (EPA, 2015). This difference in approach is why biologicals promote a less toxic and more diverse environment. Biologicals also play an important role in managing pest resistance. When paired with conventional pesticides, biologicals can lengthen the effectiveness of all products before resistance is met (Biopesticide Industry Alliance, n.d.).

Some technologies do not need any chemicals to control weeds. New farm machinery combines AI, robotics, and laser technology to mechanically eliminate weeds with a high degree of accuracy and success. These machines also can apply targeted pesticides and fertilizers, if desired. Using ultra-precise machinery has numerous benefits including cost savings, improved soil, and plant health, and more. However, only a few start-ups are producing these sophisticated products so commercial availability is still limited.

Improve Plant Resilience

Genetic technologies do not target the pest or disease but support the plant itself by improving resilience. This is an important distinction, as genetic enhancements offer a permanent, non-chemical solution. As such, reduced pesticide use, and cost savings can be achieved.

Over the past several years, researchers have demonstrated improved disease resistance in numerous genetically edited crops, including but not limited to banana, cacao, cassava, cotton, cucumber, rice, potato, and wheat. One promising success is with a CRISPR-edited rice varietal that is resistant to bacterial leaf blight, the leading rice disease globally. Field trials showed that this rice varietal, when introduced to bacterial leaf blight, had 50 percent greater yield compared to the control (Karavolias et al., 2021).

This impressive result demonstrates that CRISPR-edited crops are an important climate adaptation and food security strategy. In the rice example, CRISPR allowed researchers to respond quickly and effectively to a known disease that threatens food security. As new pests and diseases emerge under climate change and the population grows, it will be essential that resistant crops are rapidly developed and deployed.

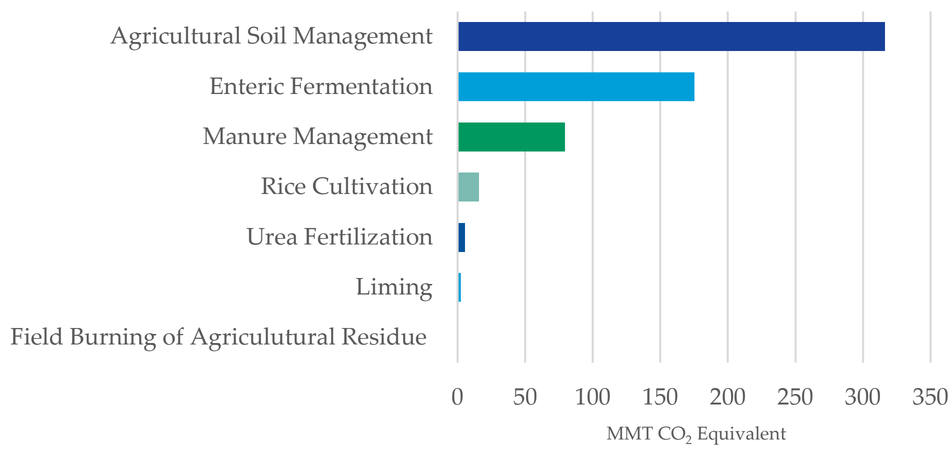
Photo credit: Scott Book/Adobe Stock

Agroecological Goal 4: Reduce Agricultural Greenhouse Gas Emissions

Agriculture accounts for 14 percent of GHG emissions and 10 percent of U.S. emissions (FAO, 2021b; EPA, 2022). The two main GHGs produced through agricultural activity are methane and nitrous oxide. **Figure 3** lists the U.S. sources of agricultural GHG emissions and the associated million metric tons of carbon dioxide equivalent (MMT CO_2 Equivalent or MMT CO_2e).

Agriculture accounts for 40 to 46 percent of total global methane emissions and around 36 percent of U.S. methane emissions. Sources of agricultural methane emissions include livestock—both enteric fermentation (70 percent of total agricultural methane emissions in the U.S.) and manure management (24 percent) —rice cultivation (6 percent), and field burning of agricultural residues (less than 0.5 percent) (EPA, 2022).

For agricultural nitrous oxide emissions, there is one primary source, soil management activities. Soil management activities involves practices that increase nitrogen in the soil, such as synthetic fertilizer application and tillage. Nearly three quarters of all U.S. nitrous oxide emissions can be attributed to soil management activities. A small amount of nitrous oxide emissions come from manure management and agricultural field burning (less than 6 percent of U.S. agricultural nitrous oxide emissions combined) (EPA, 2022).



Note: Field Burning of Agricultural Residue released 0.6 MMT CO_2 Equivalent but shows as zero at this scale.

Figure 3. 2020 Agriculture Sector Greenhouse Gas Emission Sources from EPA, 2022

Given the agricultural sector's contribution to GHG emissions, there is both a need and opportunity to reduce emissions. Yet unlike the previous three agroecological goals, the effort to reduce agricultural GHG emissions does not usually have a direct agronomic incentive for farmers. For nitrous oxide, emissions reductions come via fertilizer reductions, which do provide cost savings. For methane, the agronomic incentive is more abstract. As highlighted in the IPCC Sixth Assessment Report, "Methane emissions significantly impact crop yields by increasing temperatures as a GHG and surface ozone concentrations as a precursor" (Kerr et al., 2021).

Based on EDF analyses, the U.S. agriculture and forestry sectors could reduce 230 MMT CO_2e by 2030 (Eagle et al., 2022). Technology plays an important role in meeting this emissions reduction target, as described in detail below.

How Technology Can Reduce Agricultural Greenhouse Gas Emissions

The strategies and technologies employed to reduce agricultural GHG emissions depend on the emission source. For nitrous oxide, the emphasis is on soil management, namely reducing fertilizer use. For methane, the emphasis is on livestock operations. Methane technologies are used to monitor and quantify emissions, stop emissions at the source, and capture and convert emissions once they have been produced.

Support Soil Management

Technology offers several solutions to reduce nitrous oxide emissions through improved soil management. As mentioned throughout the report, AI and robotics offer advanced ways to deliver precise amounts of fertilizer, tailored to the plant's needs. As a result, most of the fertilizer is used by the plant, reducing nitrous oxide emissions. EDF analyses indicate that known nitrogen management strategies have the potential to reduce U.S. nitrous oxide emissions by 27 MMT CO_2e (Eagle et al., 2022).

Other, new technologies are challenging the need for synthetic fertilizer by promoting natural fertilization processes. Within nature, there are microbes that can convert atmospheric nitrogen into a form that is available to plants (ammonia) through a process known as biological nitrogen fixation. Biological technology is increasing the quantity of these nitrogen-fixing microbes with success.

> On 1,000 farms across 31 states, corn treated with a biological had equal or greater amounts of in-plant nitrogen versus standard practice, despite a **35-pound reduction in synthetic nitrogen.**
> (Proven 40 Performance Report, 2021)

Similarly, genetics technology can improve biological nitrogen fixation, even in crops that do not have this ability. Nitrogen-fixing crops have been limited to the legume family (beans, lentils, alfalfa, etc.) until recently. Cereal crops, such as rice, are being genetically modified to increase biological nitrogen. A new rice varietal has been shown to increase yield in nitrogen-limited conditions (Yan et al., 2022). Should this advancement lead to wide-scale adoption, there is enormous potential to reduce nitrous oxide emissions. Note that this is still ongoing research and there are not quantified remission reduction estimates from genetically edited crops.

Monitor and Quantify Methane Emissions

In the effort to reduce methane emissions, it is important to understand where they are coming from and how much is being produced. AI and robotics are being used across grazing operations, dairy farms, and rice fields to monitor and measure methane emissions (Abbasi et al., 2019; Jeong et al., 2022; Ober, 2022). New methods and improved technologies are making it possible to obtain farm and animal specific emission estimates and at a lower cost. With more accurate emission measurements, it will be easier to regulate methane sources and track progress towards targets.

Stop Methane at The Source

There are current and emerging technologies that reduce methane, specifically enteric methane, by stopping it at the source (i.e., the animal). These include enteric methane inhibiting products (feed additives), genetic modification, and health improvements. Combined, these enteric methane emission solutions have the potential to reduce 34 MMT of CO_2e in the U.S. (Eagle et al., 2022).

Enteric methane is directly linked to feed intake and diet composition, thus feed additives are the most common method for achieving enteric emissions reduction (Zha, 2020). Studies have shown that the additive 3-NOP (3-Nitrooxypropanol) can reduce enteric methane by an average of 25 to 40 percent. 3-NOP is already approved in the European Union and several South American countries and is expected to obtain U.S. approval in the coming years. Seaweed is another common feed additive that can reduce enteric methane emissions by 50 to 80 percent, but there is scientific uncertainty around its efficacy. Note that feed additives are only applicable to confined feed operations; different technology and more research is needed for grazing livestock. For more information on feed additives and technology strategies, see EDF's report, *At a Glance: Enteric Emissions Reduction Opportunities*.

In addition to feed intake, enteric methane can be reduced through changes in physiology and genetics (Searchinger et al., 2021; Zhang et al., 2020). Modifying rumen genetics can be accomplished using CRISPR and selective breeding. However, many countries have strict regulations on CRISPR-edited animals so selective breeding is a more viable strategy. Simulations demonstrate that selecting for methane-related traits can reduce enteric methane emissions, but more genetics data is needed to ensure the breeding is effective. Selective breeding, unlike other technology innovations, is a one-time, low-cost, permanent solution that has an additive effect (de Haas et al., 2021). As such, it is an important component of methane emissions reduction strategies.

Genetic modifications to limit methane emissions also applies to rice. One of the main methods to reduce rice-related methane emissions is to minimize the amount of water applied to the fields. When there is less water on the field, oxygen is introduced into the soil and methane-producing conditions are minimized. This practice is known as alternative wet and dry. While numerous studies have shown the practice to be effective in reducing methane emissions, it could negatively impact rice yield. New genetics research has led to a rice varietal that can tolerate water stress and reduce methane emissions. This rice varietal is already used in several China provinces and has the potential for expansion (Searchinger et al., 2021).

Capture and Convert Methane Emissions

There are manure management technologies to capture, destroy, or convert methane, thereby reducing emissions. In confined livestock operations, manure is disposed of in large, open lagoons where microbes break down the waste, releasing methane in the process. Dairy digesters and vermifiltration are two technologies that can reduce methane emissions from manure.

Dairy digesters cover manure storage pits, trapping the methane. The trapped gas is either burned off or converted into biogas and used as a renewable energy source. The level of sophistication in digester technology varies, as does the efficacy and cost (Searchinger et al., 2021). The more advanced digesters can have a high upfront capital cost and must meet complex regulations and standards (Jeong et al., 2022). To make the technology more affordable and increase adoption, the U.S. is expanding their various loan and grant programs. For example, over a ten-year period, the Rural Business Cooperative Service supported $117 million in loans and grants for methane-reducing anaerobic digester projects. In 2021, the Rural Business Cooperative Service upped its support for loans and grants for these purposes to $240 million (*U.S. Methane Emissions Reduction Action Plan*, 2021).

While digesters contribute to climate mitigation, they can create unintended consequences to the environment and community including odors, byproducts, and more. Vermifiltration offers a low-cost alternative to digesters without many of the unintended consequences. The practice involves spreading wastewater over a filtering system containing earthworms. Vermifiltration reduces methane emissions and recovers nutrients from wastewater, creating a usable product, vermicompost (Dore et al., 2022). Vermifiltration for dairy wastewater is a novel use and is expected to grow in the future.

ADDITIONAL BENEFITS OF AGRICULTURAL TECHNOLOGY

Agricultural technology can provide on-and off-farm benefits in addition to the four agroecological goals. This section outlines some of those benefits.

On-Farm Benefits

Agricultural technology can reduce on-farm energy demands and farmworker exposure to toxic chemicals. For example, automated tractors, solar-powered robots, and battery-operated drones reduce GHG emissions and improve air quality, while also reducing fuel costs. Depending on the robot, studies and field tests have shown that **robots can reduce fuel use between 50 and 90 percent** (Gonzalez-de-Soto et al., 2016; *Project Xaver*, 2022).

Similarly, gains in water efficiencies can reduce energy use and fuel costs. "According to the Natural Resources Conservation Service (NRCS), in certain areas of the United States, **switching from high- to low-pressure sprinkler systems can save as much as $55 and 770 kWh per acre annually**" (Morris & Grubinger, 2019). Even though on-farm energy is a minor overall contributor to GHG emissions (1.3 MMT CO_2e in the U.S.), implementing on-farm energy-saving technologies is an easy climate change mitigation strategy (EPA, 2022).

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Agricultural technology also promotes farmworker health and safety. When robots are used to apply targeted fertilizer and pesticides, it limits exposure to toxic chemicals. If biologicals are applied, the benefits are even greater, as biologicals have a significantly lower toxicity when compared to conventional products (*Biological Crop Protection & Plant Health Annual Report*, 2021). This is evident by the fact that biopesticides must meet a requirement of "no unreasonable adverse effects" to humans and the environment to be sold in the U.S. (Leahy et al., 2014) . Reduced chemical exposure benefits consumers as well. Biopesticides are exempt from residue limits in the U.S. because the leave little to no residue on food (Biopesticide Industry Alliance, n.d.).

In addition to reducing exposure to harmful chemicals, technology can reduce farmworker exposure to other hazardous conditions such as extreme heat, heavy machinery operation, and intense repetitive work. Robots that sow seeds or harvest crops alleviate the need for humans to perform these activities, which can result in fewer farmworker injuries, illnesses, and fatalities.

Off-Farm Benefits

Agricultural technology benefits extend beyond the farm, furthering their usefulness. As described throughout the report, precision agriculture reduces fertilizer and pesticide inputs. In addition to contributing to the four agroecological goals, chemical input reduction has a positive impact on an array of natural resources including water quality, air quality, and biodiversity. To augment these benefits, agricultural technology also supports food security. A brief discussion on biodiversity, plus food security, is provided below.

Biodiversity Support

Technology is both mitigating biodiversity loss and supporting biodiversity practices such as cover crops and no till agriculture. It is well documented that pesticides negatively impacted biodiversity. "Pesticides have been identified as the most significant driver of soil biodiversity loss in the past decade," which is an extreme issue considering that nearly a quarter of the planet's biodiversity is found in soil (Gunstone, 2021). For perspective, there are more than 50,000 species in a single gram of soil (Banerjee & van der Heijden, 2022). In addition to supporting soil microbial biodiversity, reduced pesticide use also benefits species up the food chain – including insects, birds, and mammals.

Food Security

Agricultural technology promotes food security, specifically quantity and quality. This is an essential function of agricultural technology given that nearly one in three people faced food insecurity in 2020 (FAO, IFAD, UNICEF, WPF, and WHO, 2021). In terms of food quantity, AI, robotics, biologicals, and genetics technologies can increase yield and protect against crop losses from pests and diseases. These production-related technologies are augmented by food system technologies that improve food processing and delivery, such that the food reaches people in a timely and safe manner. In terms of food quality, technologies such as CRISPR have been shown to directly improve a plant's nutritional composition. Other technologies, such as biologicals, indirectly improve nutrition through supporting soil health. Studies have shown direct links between soil health and the nutritional density of vitamins, minerals, and phytochemicals (Montgomery et al., 2022).

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CONCLUSION AND RECOMMENDED NEXT STEPS

Emergent agricultural technology is often defined by market opportunities that focus on maximizing yield. This narrow, extractive view fails to recognize and harness the multitude of environmental and societal benefits agricultural technology can provide. The four technology fields described in this report—AI, robotics, biologicals, and genetics—can be used to help unravel the complexities of the agricultural system and achieve interrelated agronomic, environmental, and societal goals. There are three common ways in which these agricultural technologies can improve agricultural operations: monitor and verify practices, apply precise inputs, and improve desired traits.

1. **Monitor and Verify Practices**. Through data collection and interpretation, farmers can more effectively manage their practices such as fertilizer and pesticide application, irrigation schedules, grazing patterns, and more. Quantifying best management practices and agricultural GHG emissions are important to climate change adaptation and mitigation.
2. **Apply Precise Inputs**. Technologies such as AI and robotics offer farmers tailored methods for water, fertilizer, and pesticide application, while biological technology offers natural alternatives. Precision agriculture has an array of benefits including cost savings, water quality protection, farmworker health and safety improvements, and GHG emissions reduction.
3. **Improve Desired Traits**. Genetics technologies have expanded and enhanced our ability to select for desired traits in both plants and livestock. Emergent technologies such as CRISPR allow scientists to improve plant tolerance to abiotic and biotic stress and reduce enteric methane emissions, thereby contributing to climate change adaptation and mitigation strategies.

While agricultural technology can provide numerous benefits, "taking these advantages to the farm will depend, not only on the willingness of producers for adopting new technologies in their fields, but also on each specific farm potential in terms of scale economies, as profit margin increases with farm size." (Saiz-Rubio & Rovira-Más, 2020). There are many strategies that EDF and the climate-smart agriculture community can investigate and promote such that agricultural technology benefits are equitably and safely achieved. A few are provided below.

- **Identify technology opportunities to support within the Farm Bill and state incentive programs**. For example, there may be an opportunity to improve access to agricultural technology and equipment through cost share programs. This next step may rely on several intermediary steps, such as stakeholder conversations and economic analyses.
- **Conduct a technology needs assessment for small and/or disadvantaged farmers.** As demonstrated throughout the report, there are substantial access and equity barriers associated with agricultural technology. A needs assessment would help clarify those barriers and identify opportunities for improvement. This work could be done in collaboration with the National Center for Appropriate Technology (NCAT), land grant technology incubators, the EDF venture capitalist network, historically black colleges or universities, and other partners.
- **Profile promising technologies that go beyond precision agriculture to achieve broader agroecological goals.** For technology benefits to be viewed in a holistic manner, additional research and policies are needed. Consistent, reliable, and quantifiable technology benefits allow scientists and decision-makers to understand technology's potential.

As agricultural technology becomes increasingly available and integrated with agricultural operations, it is imperative to identify and strengthen practices that deliver agroecological benefits.

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