The Role of Agricultural Science and Technology in Climate 21 Project Implementation

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Introduction

By David Baltensperger

Agriculture is central to climate mitigation and adaptation and is a net sequestration sink for carbon dioxide emissions from combustion of fossil fuels. Agriculture can provide 10–20% of the additional sequestration and emissions reductions needed to achieve net zero emissions by 2050. While the U.S. Department of Agriculture (USDA) has not historically been at the center of the public conversation on federal climate policy, the Department has discretionary financial resources and agency expertise. These resources and expertise enable USDA to (1) partner with agriculture producers to reduce atmospheric greenhouse gases (GHGs) through carbon sequestration and emissions reductions; (2) reduce GHG emissions from rural energy

cooperatives; (3) bolster the resilience of private working lands and public forests and grasslands to the effects of climate change; (4) promote sustainable bioenergy, wood products, and other bio-based materials, (5) contribute to the scientific understanding of climate change, and (6) invest in climate-smart economic development in rural communities.

Importantly, given current economic conditions, investments in climate change at the USDA can support and create rural jobs in agriculture, forestry, conservation and related businesses, thereby contributing to the economic viability of rural America. In fact, based on MIT research, investments in agriculture including forestry and conservation produce 20 to nearly 40 jobs per $1 million in expenditure. It is critical that agriculture, forestry, and other rural stakeholders view themselves as partners to the USDA to achieve climate goals.

The transition team for the Biden Administration introduced the Climate 21 Project[1] as the blueprint for how the USDA can help advance the role of agriculture and forestry to mitigate and adapt to climate change pressures. The key program recommendations and opportunities for the USDA signal climate change as a top priority for the department. This order from the Secretary directs the department to invest in natural climate solutions, incentivize climate smart agriculture, rural investment through financial tools, decarbonize rural energy, promote green energy and smart grids, and prioritize federal investment to address wildfire. Agricultural science and technology play a critical role in each of these priorities that the administration plans to implement in the first 100 days.

This paper explores the potential for the USDA to emphasize collaboration, incentives, the historic resiliency and innovation of agriculture and forestry, and the critical role that rural America can play in helping address climate change while creating jobs and economic opportunity. The report summarizes each of the key recommendations and priorities where current agricultural science and technology can be applied and where new investments in agricultural science and technology will be critical to meeting the goals of the administration. Our report showcases where CAST and CAST members can be a critical resource to the USDA to meet these goals and to indicate to the USDA and Congress where funding is needed to meet these goals.

To accomplish our objectives, CAST sought authors that are recognized for their research and leadership in managed plant landscapes, animal systems, agricultural technology, food systems, and carbon markets based on alterations in managed agricultural systems. These authors reflect a breadth of scientific expertise across CAST membership areas including our individual members, corporate partners, and scientific society members.

The target audience of the report is the USDA and staff that are appointed or assigned to work on the Climate 21 Initiatives. Additionally, federal legislative staff that will be involved in funding new Climate 21 initiatives. Finally, scientists, stakeholders, non-governmental groups, and industry can use the report as a guide to where they can provide support and engage in the Climate 21 initiatives.

Role of Agriculture in Mitigating Climate Change and Achieving A Sustainable Food System

By Charles W. Rice, Marty Matlock, Sally Flis, and Manojut Basu

Plant and Soil Management

Agriculture and forestry is the only sector that has the potential to be a net sink for greenhouse gases because of the ability to sequester carbon in soil and plants and reduce methane and nitrous oxide emissions. Climate-smart agriculture is an approach to respond to changing environments

[1] https://climate21.org/documents/C21_USDA.pdf

and meet the needs of a growing population. Climate-smart agriculture has three components: (1) sustainably increases productivity, (2) enhances resilience, and (3) reduces greenhouse gases where possible. Soil carbon sequestration as a potential for mitigating climate change has received a considerable amount of research interest. Crop and soil management in intensively managed systems has the greatest potential for carbon sequestration. Increases in soil carbon is the result of increased plant inputs or reduced losses. Increased plant inputs include cover crops, crop rotations, and increased crop productivity. Reduced losses included a reduction in tillage intensity, such as no-till systems. The use of reduced or no-till systems has the added benefit of using less fuel, which reduces CO_2 emissions by the agricultural sector. Adding carbon to the soil has the additional benefits of improved soil quality (or health). Soil carbon significantly influences soil structure, soil fertility, microbial processes, and other important soil properties. Thus soil carbon provides additional ecosystem services and makes the soil more resilient.

Conservation agriculture is a cropping system that promotes minimum soil disturbance (no-tillage), permanent soil cover, and crop rotation diversification. Conservation agriculture enhances biodiversity and biological processes, contributing to increased water and nutrient use efficiency and improved and sustained crop production. Conservation practices over the years have improved soil health and soil carbon. Research has shown that decreasing tillage and increasing crop diversity improves the cropping system's resilience to climate variability and reduces losses of soil and nutrients from the landscape. Conservation tillage, specifically no-tillage, conserves soil carbon and nitrogen. In addition, conservation tillage conserves soil water which allows intensification and diversification of the cropping systems. For example, no-tillage allows for double cropping in some regions of the country, thus retaining more crop residue on the soil surface. More diverse cropping systems allow for rotation of herbicides, thus slowing the development of herbicide-resistant weeds. With less tillage and retention of more crop residue, soil health is improved. Soil carbon is the food for the soil microbiome but also improves soil structure. Improved soil structure allows for increased infiltration to capture rainfall under more intense rain events, preventing runoff and retaining water during the subsequent dry periods. Retention of water increase water use efficiency and improves yield and income stability providing resilience to climate variability. Research, extension, and policy incentives are needed to achieve greater adoption of more intense, diversified cropping systems. In addition, research is needed to enhance root systems for greater soil carbon sequestration and enhanced nutrient and water use efficiency. Adoption of perennial crops in the rotations would also promote carbon sequestration and efficiencies. These cropping systems will improve productivity, resilience and produce additional ecosystem services, including water quality, reduce erosion and flooding, and improved wildlife and pollinator habitats.

Restoration of degraded lands to forest or grasslands has a high potential to sequester carbon and restore ecosystem function. One policy example is the Conservation Reserve Program (CRP), which was established in the Food Security Act of 1985 (also known as the1985 Farm Bill), and allows farmers to withdraw certain highly erodible lands from production. This program has increased soil carbon and reduce nitrogen losses. There are many other policy programs that promote carbon sequestration and reduce greenhouse gas emissions.

Nutrient Management

Optimizing nutrient use through grower implementation of nutrient management planning in crop and forestry production improves efficiency per acre and has economic, environmental, and social benefits. Growers in the United States are using precision agriculture tools, advanced weather forecasting, digital data collection, and record keeping to make nutrient management more adaptive to a changing landscape. Research has linked improved nutrient management practices to reduced losses of nitrogen and phosphorus to water sources, decreases in nitrous ox-

ide emissions from nitrogen applications, and improved crop performance. Better use of nutrients by crops because of nutrient management benefits the grower, the community, and the consumer. Farmers and their trusted advisers have the data to help supply up-to-date information on what is working on the ground and what realistic baselines are for continuous improvement to reduce emissions and loss to water supplies, while also increasing soil health.

While growers have adopted these practices successfully across many crops and geographies there is a lack in research data that would allow all crops and growers to participate in the emerging ecosystem markets. These markets require data to calibrate models and baseline data that can be used by all growers to measure progress. Currently the data that is available for this is limited by crop and the data collection dates. Growers make annual progress in nutrient management and nutrient use efficiency and the data available to compare to as a baseline is at a minimum six years old. Improved data collection from growers to set baselines and research to measure the emissions and soil carbon sequestration performance of practices in a wider variety of crops is essential to the success of these markets and the continued progress by growers.

Use of Pesticides in Agriculture and Pest Management

U.S. farms are on the frontlines of the impacts created by climate change and could face effects that are detrimental to their agricultural production. Increases in climate variability could result in shifting growing seasons and reduce yield, making life difficult for farmers, many of whom are already operating on razor-thin margins (USDA 2018). Shifts in climate could also make pests, including insects, weeds, and disease, more active, more reproductive, and ultimately more expensive to control (Bayer 2020). Despite these challenges, however, U.S. agriculture is uniquely positioned and has a tremendous opportunity to play an active role in combatting climate change.

Use of Pesticides in Agriculture

Pesticides are a critical tool used by both organic and non-organic farmers to protect their crops from diseases, pests, and weeds as part of a larger integrated pest management system. Pesticides help farmers to produce more food and fiber, using fewer resources and without bringing more land into cultivation. Over the past 50 years, pesticides and genetic improvements have more than tripled agricultural yield (CropLife International 2020). Without these tools used in integrated pest management, farmers would need twice as much land to grow the same amount of food and fiber, requiring the clearing of forests and wetlands, as well as significantly increasing the demand for water for irrigation. It would also require twice as much fuel than is currently used and increase the amount of carbon released into the air (CropLife America 2020). By using pesticides, agriculture can reduce its reliance on fossil fuels and positively impact climate change.

Traditionally, growers have used tillage systems to remove plant residue from a previous season, curb weed growth, and loosen compacted surface soil in preparation for planting. While tillage is a critical component in a successful farming operation, minimizing mechanical operations and soil disturbance in a field can lead to both financial and ecological benefits such as reduced soil erosion; reduced air and water pollution; lower costs of production and fuel consumption; and reduced soil compaction from mechanical passes. These benefits can be achieved through conservation tillage.

Conservation tillage, in contrast to traditional tillage practices, is a system of strategies and agricultural techniques aimed at reducing or eliminating the amount of soil disturbance needed to sow and grow a crop. There are several forms of conservation tillage, each aimed at the elimination or reduction of the number of passes needed by farm equipment and minimizing soil

disturbance. None of these conservation tillage practices, however, could be utilized by farmers without the use of pesticides for clearing weeds and controlling insects, and fungal pests.

Tillage reduction can also be achieved by using cover crops. While the cover crops grow, they minimize the effects of water and wind erosion on the soil (by approximately 90%), while helping the soil retain more water and nutrients (USDA 2018). Not only does this improve soil health, but it also reduces associated air and water pollution attributed to runoff (SARE 2017). When used alongside pesticides, cover crops are also an effective tool to throttle weed growth, resulting in an increased crop yield potential for the field. In addition to increasing agricultural productivity and maintaining soil health, conservation tillage and cover crops can also lead to net carbon capture and sequestration. Forests and stable grasslands are well known carbon sinks because they can store large amounts of carbon in their vegetation, root systems and the organic matter which accumulates in undisturbed soils. Farm soil is a lesser-known category for carbon sequestration and has the potential to become one of the largest terrestrial sinks for atmospheric carbon on the planet (Utkina 2017). This creates an incredible opportunity for agriculture to play a larger role in the capture and sequestration of carbon. By adopting tillage practices that minimize soil disturbance and the use of cover crops, farmers can improve soil health, greatly reduce erosion, and have greater resilience during droughts while at the same time making an important contribution to the mitigation of climate change (Schahczenski and Hill 2009).

Beyond the benefits of carbon sequestration through soil, conservation tillage minimizes on-farm fuel consumption and labor requirements. This reduces CO_2 emissions by cutting tractor runtime, saving farmers time and energy while being more sustainable. According to the USDA, no-till farming saves a combined 812.4 million gallons of fuel each year—roughly the annual amount of energy required by 3.2 million homes— and reduces CO_2 emissions by 9.1 million tons, the equivalent annual emissions of 1.9 million passenger cars (USDA 2016).

Conclusion

The effects of climate change on agriculture are far-reaching, increasing the number of challenges that already confront our farmers. Continuing to innovate and invest in new technology, farms can make more efficient decisions on things like pesticide rates and placement. These data-driven advances result both in significant cost savings, as well as improved environmental outcomes (Pinguet 2020). Bolstered by minimum tillage, cover crops, and responsible pesticide use, farmers can play a critical role in the reduction of the amount of greenhouse gases emitted by on-farm operations, capture atmospheric carbon, and maintain high levels of productivity.

Animal Systems

By Juan M. Tricarico

Animal Agriculture can Contribute to Reversing Climate Change While Increasing Global Nutritional Security

The current climate crisis presents a unique set of challenges and opportunities for animal agriculture. The impacts on climate change of producing, processing, distributing, and consuming milk, meat, eggs, and the foods derived from them is under scrutiny. Animal agriculture represents 14.5% of man-made greenhouse gas emissions globally when direct and indirect emissions are considered, including emissions resulting from land use change (Gerber et al. 2013). The major greenhouse gases emitted by animal agriculture are methane, nitrous oxide, and carbon dioxide representing 44, 29, and 27% of global animal agriculture sector emissions,

respectively. Approximately two-thirds of global animal agriculture emissions are from cattle (beef and dairy), while buffaloes, small ruminants, pigs, and poultry all contribute no more than 10% each.

Public dialogue on animal agriculture and climate change focuses primarily on the emissions associated with production and consumption of animal-sourced foods. This emphasis on emissions is leading to growing consumer sentiment that favors limiting, or in its most extreme case eliminating, animal agriculture and the food products derived from it to solve climate change (Willet et al. 2019). However, this simplified perspective understates the contributions that animal-sourced foods make to global nutritional security, and especially to vulnerable populations such as children under 5 years of age, pregnant women, and the elderly (FAO 2017) safe and affordable nutrients that are critical to preventing human undernutrition and malnutrition (FAO 2011). These are several essential nutrients including protein, calcium, phosphorus, and various trace minerals, vitamins, and essential fatty acids. Provision of these essential nutrients is particularly important in low- and middle-income countries (Bailey et al. 2015) where the demand for animal-sourced foods is rising rapidly because of population and income growth. Therefore, sustainable intensification of animal agriculture is particularly important in low-income countries to meet the growing demand of food with less resources and emissions (Garnett et al. 2013; Tricarico et al. 2020).

Climate change and variability can also negatively impact the productivity of animal agricultural systems (Ghahramani and Moore 2016). These impacts not only include changing precipitation and cropping patterns, increased heat stress, and pathogen pressure, but also the occurrence of extreme weather events leading to drought, flooding, and other natural disasters. Therefore, mitigating greenhouse gas emissions while adapting to changing climate conditions will be critical for animal agriculture to continue providing nutritious foods while reducing and eventually reverting climate change.

Animal agriculture across the world relies on a variety of different production systems that include grazing, and mixed cropping and animal feeding operations (Seré et al. 1996). Therefore, animal agriculture is not only a source of greenhouse gas emissions but can also function as a carbon sink and contribute to reversing climate change (Le Quéré et al. 2018). Agricultural soils used to cultivate animal feed crops are capable of sequestering atmospheric carbon. In addition, methane mitigation at rates greater than its natural rate of decay can reduce atmospheric methane concentrations effectively reverting climate change effects (Lynch et al. 2020). This opportunity to contribute to reverting climate change by focusing on soil carbon sequestration and methane mitigation places animal agriculture in a unique position to convert climate impact into societal benefit.

Animal Agriculture Needs Focus and Investment to Accelerate its Contributions to Reverting the Climate Crisis

Mitigating and capturing greenhouse gas emissions, as well as adapting to changing climate conditions, requires concerted efforts by the animal agriculture sector across various disciplines. Discovery of new technologies and practices alone is not enough to elicit the results needed to successfully address the climate crisis. Practices and technology also need to be deployed by a substantial number of animal agriculture operators to achieve desired results at the scale required to reverse the current climate trajectory. This monumental task will become feasible when innovation in the biological and physical sciences, leading to the development of new practices

and technology in animal husbandry and resources management, is accompanied by socioeconomic innovation.

Increasing feed efficiency or the feed conversion ratio by all food animal species provides opportunities to reduce nitrous oxide, carbon dioxide, and methane emissions while improving the use of natural and financial resources and the production of nutritious foods by animal agriculture (Basarab et al. 2013). Greater feed efficiency can be achieved by improving nutrient requirements and nutrition models across all species, and by enhancing feed quality and digestibility of forage crops consumed by cattle. Research on breeding, harvesting, and storage of feed crops can also improve their nutrient quality and digestibility to enhance feed efficiency and its effects on emissions. Developing genomic markers for feed efficiency and incorporating this information into selection indexes will be particularly useful for beef and dairy cattle breeders and lead to cumulative gains over time. Reproductive efficiency also influences the use of natural and financial resources and the production and sale of nutritious foods by animal agriculture operations. For example, improved estrus detection, estrus synchronization, and prevention of early embryonic death in cattle using automated measures and new animal breeding technologies is desirable.

Enteric methane is the second largest contributor to agricultural emissions in the United States after nitrous oxide emissions from agricultural soils (US EPA 2021a). In addition, methane's relatively rapid rate of decay in the atmosphere represents an opportunity to reduce climate change in the short-term through its mitigation. Consequently, understanding how the ruminal microbiome affects enteric methane emissions by cattle is a worthy research goal that could deliver climate change benefits rapidly. Knowledge gaps in this area include improved understanding of the relationships between fungi, bacteria, protozoa, and archaea (i.e., methanogens), microbe-animal (host) interactions, ruminal biochemical transactions including their thermodynamic regulation, and how the microbiome is influenced by the host, dietary manipulation, and feeding practices. Information on the production rates of volatile and branched-chain fatty acids resulting from ruminal fermentation is also warranted.

Innovation in economic and social fields is critical to creating favorable environments where adoption of new mitigation practices and technology by farmers and ranchers is incentivized. The desirable goal is to empower farmers and ranchers to incorporate mitigation practices and technology into their operations because they are environmentally and productively advantageous, recognized through measurement and recording, and financially and reputationally rewarded. Transparency concerning production practices and climate change mitigation efforts by animal agriculture is indispensable to ensure that consumers trust the agricultural system that nourishes them. Innovation, consensus building, and clear communication is critical for animal agriculture supply chains to meet their social responsibility requirements. Under these circumstances, scientists in academia, industry, and government need to effectively contextualize their scientific findings to relate with policymakers, the media, and the public who are ultimately impacted by them.

The importance of measurement, within this context, cannot be overstated. Biophysical research to explore and develop new sensing technology or new uses for existing sensing technology is fundamental for accurate and robust measurement of both the emissions and mitigation of greenhouse gases. Data collection, sharing, aggregation, and synthesis are also crucial to increasing confidence in the estimates of improvement related to mitigation. Increasing confidence in these estimates is needed to explore and develop socioeconomic innovation that encourages mitigation of and adaptation to climate change. For example, the development of

robust and verifiable methodologies (i.e., reduction protocols) to quantify greenhouse gas mitigation can contribute to the creation of ecosystem service markets to trade emissions reductions and carbon sequestration. The yet untapped transformational potential in animal agriculture to revert climate change will only be unleashed when confidence in the magnitude of the reductions is sufficiently solid for transactions to occur between diverse economic actors.

Successful incorporation of greenhouse gas mitigation into business models through pricing is essential, but it isn't the only requirement to accelerate the contributions from animal agriculture to solving climate change. High cost and complexity of adoption associated with many mitigation practices also represent significant barriers (Niles et al. 2019). For example, existing mitigation practices for animal manure emissions such as anaerobic digestion, or even simpler technology such as solid-liquid separators or storage cover and flare technology, are not widely adopted due to high capital costs (Montes et al. 2013). This means that attention is also needed to develop and test alternative financial mechanisms, various modes of delivering technical assistance, and innovative approaches to partnerships to address existing barriers.

The accurate estimation of both the impacts and contributions to solving climate change by animal agriculture also requires integrated systems approaches. Discovery and adoption of greenhouse gas mitigation practices and technology must be evaluated within the context of each operation and the landscape in which it operates. Quantifying the impacts of adding, removing, or changing individual practices is extremely difficult without the ability to model whole-farm systems (Kebreab et al. 2019). Whole-farm models are also required to evaluate connections between system components that field research cannot practically investigate and, in many instances, they can provide information cheaper and faster than physical experimentation. Research is needed that supports the development of integrated models that simulate the flows of carbon, nitrogen, phosphorus, and water through various animal agriculture systems under different management and environmental conditions. These models could benefit from the extensive amounts of data currently collected on commercial animal agriculture operations to identify methods to mitigate greenhouse gas emissions while improving whole-farm production efficiency. In addition, it's essential to understand the implications that mitigation efforts could have on the local, regional, and global food systems. These different scales, or levels of aggregation, represent an important challenge that can only be addressed through the development, validation, and application of landscape, and even sector-wide, mathematical models. At least some of these models also need to be capable of evaluating and estimating trade-offs between mitigation and the supply of nutrients to the populations those animal agriculture systems serve (White and Hall 2017).

Focus and innovation is also required in the regulatory environment. More agile regulatory mechanisms need to be developed and tested to nurture an environment that incentivizes innovation and allows farmers and ranchers to test, under commercial conditions, the technical solutions that already achieved the proof of concept stage. For example, the current regulatory environment doesn't include clearly defined pathways specific for technology that targets greenhouse gas mitigation. Animal feed and health companies currently need to pursue regulatory pathways that were developed to establish functional claims for drugs (i.e., feed ingredients to cure, prevent, treat, or mitigate disease conditions or change bodily structures or functions). The importance of climate crisis merits consideration and evaluations of alternative regulatory pathways that are specific for environmental claims.

Finally, progress on all the above will only occur if heightened focus is also accompanied by larger financial investments. Private companies are currently investing in animal agriculture to

develop solutions that can capitalize on market opportunities such as in new technologies and the consolidation and disruption of markets. Associations and non-governmental organizations are also investing in research to measure, test, and understand both the impacts and opportunities afforded practices and technologies that promise greenhouse gas mitigation. Yet simultaneously, public spending on agricultural research and development to address climate change while increasing food production is shrinking and currently below private sector investment (Clancy et al. 2016; USDA ERS 2019). Government is a critical funder of research that in some cases, such as with basic research and some fundamental applied research, represents the only funder available. As such, there is a need to increase and reorganize public funding to encourage scientific pursuits that can build the basis for biological, physical, and socioeconomic innovation by private funders looking to capitalize on marketplace opportunities.

Public-Private Partnering and Market Focus are Essential to Accelerate Climate Action by Animal Agriculture

The potential for animal agriculture to respond to and contribute to reverting the climate crisis is real. This opportunity exists in every dimension of the effort—research, innovation, measurement, education, technology transfer, and adoption, creation of new business models and markets, and financial and reputational recognition. The overarching objective is to create environments in which positive climate action by economic actors in animal agriculture can be clearly identified, and their contributions quantified and rewarded both financially and in the climate change narrative.

Collaboration and coordination among government, industry, and academic scientists are critical for climate action while continuing to improve the availability of safe and nutritious foods from animal agriculture. Collaboration is meant to establish and articulate a clear path forward for coordinated action among stakeholders in the public and private sectors. Its purpose is to catalyze progress in planning, executing, and utilizing resources to create favorable environments for climate action that will be rewarded in the marketplace.

Various efforts by animal agriculture to address climate change through collaboration are already in place. For example, the Dairy Sustainability Alliance, and the US Roundtables for Sustainable Beef and Sustainable Poultry and Eggs are organizations that convene stakeholders to advance, support, and communicate continuous improvement of sustainability in each respective value chain. The Global Feed LCA Institute is another example of collaboration to support improvement of sustainable animal feed through development and databases and measurement tools for assessing and benchmarking feed industry impact. Climate change (i.e., greenhouse gas emissions) is undoubtedly one of the most, if not the most important, sustainability indicator for all these collaborative efforts.

Public-private partnerships, particularly with the USDA but also with other agencies, represent the largest opportunity for strategic collaboration to revert the climate crisis in a coordinated fashion. These partnerships have the potential to benefit all stakeholders, including government, by allowing planning, execution, and communication on a larger scale more efficiently. Potential objectives for these partnerships could include developing scientific knowledge, conducting cooperative research programs and information exchanges, identifying and co-funding joint research priorities, developing joint programming of outreach activities, collecting and synthesizing stakeholder input, and sharing subject-matter expertise broadly to mitigate emissions and adapt to climate change while meeting demands of domestic and global markets for foods produced by animal agriculture. CAST is well-positioned within this context to play a

significant role by convening and coordinating networks of experts to assemble, interpret, and communicate credible and unbiased science-based information on animal agriculture science and technology.

Agricultural Technologies

By J. Alex Thomasson, Addie M. Thompson, and Jianming Yu

Cutting-edge agricultural technologies including precision agriculture (PA) and advanced crop breeding have the potential to positively influence the carbon cycle by reducing the net amount of fossil fuels consumed in agricultural production and by increasing the amount of carbon that plants convert to stored biomass from CO_2 in the atmosphere. PA brings together a host of technologies including positioning systems like GPS, various sensors for proximal and remote sensing, computing tools including artificial intelligence and geographic information systems, and robotics. Taken together, these technologies enable farm inputs like seed, water, fertilizer, crop protectants, tillage, etc. to be placed at the right location, in the right amount, and at the right time to maximize economic productivity and minimize environmental risk at the finest scale possible, even someday on a plant-by-plant basis. Advanced crop breeding is done both by using autonomous sensing systems in the observation and identification of valuable genotypes and by employing genetics to isolate specific genes responsible for desirable plant responses, such as storing more carbon in various plant components.

Precision Agriculture

The carbon cycle is a relatively new consideration regarding the role of PA in optimizing farming's effect on the environment, yet multiple researchers have addressed this topic with respect to several increasingly common PA activities (Balafoutis et al. 2017). Five of these activities involve varying the placement of specific farm inputs, while the other involves the efficiencies brought about by the precise equipment steering available with automatic guidance systems. In general, when PA is used in fertilizer application, variable-rate (VR) technologies are used and tend to reduce the overall application of nitrogen fertilizers, reducing emissions of GHGs from farmland and from production of the fertilizer. According to Wood and Cowie (2004), fertilizer production generates roughly 1.2% of global GHG emissions. Methane is commonly used to provide a large portion of the hydrogen required to produce ammonia, a prime ingredient of nitrogen fertilizers, resulting in a large amount of CO_2 emitted to the atmosphere. When nitric acid is generated during fertilizer production, the process results in emissions of N_2O, another important GHG (Bentrup and Paliere 2017). Advances in manufacturing technology have reduced GHG emissions, but fertilizer manufacturing remains a significant source. Fertilizer-based emissions of GHGs also occur on the farm. Nitrogen in the soil, originating from applied fertilizer or animal manure or crop residues, can be converted by biochemical processes and released as N_2O (Schepers and Raun 2008). One study estimated that roughly 1.2% of total nitrogen added to soils is released as N_2O (Ogle et al. 2010). Multiple studies have shown that farmers often over-apply nitrogen fertilizers (Bausch and Delgado 2005; Millar et al. 2010; and Ribaudo et al. 2011), potentially exacerbating soil denitrification, so reductions in overall application through PA technologies tend towards reductions in GHG emissions. VR fertilizer application enables the optimal amount of nitrogen to be applied according to crop needs, typically reducing the quantity applied along with associated GHG emissions. A study by Brown and colleagues (2016) showed that VR fertilizer application by automatic section control with a lightbar, providing the ability to spray more precisely, reduced the over-application of fertilizer. Bates and colleagues (2009) found that VR fertilizer application could reduce the GHG emission rate by up to 5% without af-

fecting crop yield, and Sehy and colleagues (2003) reported that VR fertilizer application reduced N_2O emissions by up to 34% in low-yielding areas of fields. Methane, another principal GHG, is emitted during manure decomposition, so VR manure application can also reduce methane emissions from farm fields.

Improving the efficiency of water use through improvements in the precision of irrigation with PA technologies can reduce the amount of energy required to pump water from wells and reservoirs. This energy typically comes from the burning of fossil fuels, so PA can reduce CO_2 emissions. Furthermore, PA-based irrigation scheduling can maintain soil-water availability at levels that tend to reduce N_2O emissions (Trost et al. 2013). Studies have shown that irrigation efficiency (the ratio of water used by crop plants over the water applied) can be increased by up to 14% with PA technologies (LaRue and Evans 2012). Simulations have shown that PA-based control of irrigation according to zones in a farm field can reduce water requirements by up to 26% (Evans et al., 2013), and actual field studies showed a reduction of up to 20%, with larger reductions on individual fields in cotton production (HydroSence 2013). Soil type, and its variability within a field, is a major factor in the effectiveness of PA technologies for reducing water usage, with sandier soils enabling greater water savings than heavier (clay type) soils (Balafoutis et al. 2017).

A noteworthy success story in PA is the common adoption and use of GPS-based guidance on field equipment, which provides for extremely precise (within 2 cm) maneuvering in the field. The result is a significant improvement over human-driver performance in minimizing overlaps and gaps in the application of inputs and field operations like planting, tillage, weeding, and harvesting (Abidine et al. 2002). Improved precision through automatic guidance saves fuel and inputs (e.g., fertilizer or pesticide), particularly when combined with VR application. Shockley and colleagues (2011) modeled a no-till corn and soybean farm with automatic guidance for planting and fertilizer application and showed more than 10% savings for fuel, providing for a direct reduction in GHG emissions. Field studies have shown that automatic guidance can reduce fuel consumption by more than 6% (Bora et al. 2012). Brown and colleagues (2016) compared two levels of automatic-guidance precision and VR application to conventional farming practices in terms of the associated GHG-emission reduction. They found that high-precision automatic guidance provided the greatest improvement (nearly 3%) in the carbon ratio, a measure of the carbon input to the system over the carbonaceous biomass output of the crop.

When PA technologies are used to protect crops against diseases, insects and weeds, VR application is employed to place the pesticide only where needed by the crop. Thus, the overall amount of pesticide applied is typically reduced, while the yield is not reduced. Several studies have shown herbicide reductions in the range of 11 to 90% (Chen et al. 2013; Dammer and Wartenberg 2007; Gerhards et al. 1999; Gil et al. 2007; Heisel et al. 1999; Llorens et al. 2010; Solanelles et al. 2006; and Timmermann et al. 2003). Other studies have shown reductions in insecticide use of over 13% (Dammer and Adamek 2012), and that spray overlap is a principal factor in reducing total pesticide use (Batte and Ehsani 2006). While the effect of VR pesticide application is significant on pesticide reduction, its effect on reducing GHG emissions is small because, while GHGs are a factor in production of pesticides, the quantities applied in the field are very low, so the net effect on GHGs in the field is very limited (IPCC 2007).

Precision mechanical weeding technologies can reduce GHG emissions by reducing the application of herbicides, but as stated previously, these reductions would be small. On the other hand, when compared to conventional mechanical cultivation, the amount of fuel required would be reduced through the reduction in draft forces from the cultivation equipment (Peteinatos et al.

2015). Precision thermal weeding uses fuel to burn weeds but reduces GHG emissions compared to non-VR weed burning systems that use a continuous flame. If thermal weed control replaces mechanical or chemical weed control, it is likely that GHGs emissions will be increased (Balafoutis et al. 2017). As with VR pesticide application, the reduction in GHG emissions with VR weeding is likely to be low.

The effect of PA technologies on planting and seeding may or may not result in a reduction of the quantity of seed applied, so any reduction in GHG emissions related to production of the seed is uncertain and likely to be small. On the other hand, VR planting and seeding can result in significant yield improvements. When PA technologies like this result in higher yield (Hörbe et al. 2013), the net effect is a reduction in GHG emissions by way of fewer net inputs per unit crop harvested.

Advanced Plant Breeding Technologies

The overarching goal of plant breeding is to improve the genetic potential of plants for human benefit (Bernardo 2019). This goal can be accomplished by developing new cultivars with improved traits (e.g., carbon sequestration, yield, radiation use efficiency, etc.) over parent cultivars in each subsequent generation, or breeding cycle. Improving crop plants to contend with climate change involves developing plants that are more capable in multiple respects: resilience to climatic effects, ability to sequester carbon in the soil, and ability to rapidly build carbonaceous biomass aboveground that may be used as a source of energy or materials to replace fossil fuels (Mullet et al. 2014).

The ability of crop plants to assimilate carbon, transfer it to various parts of the plant, and store either in above-ground or below-ground biomass has recently come under increasing study (De Deyn et al. 2008). The carbon-related phenotypes of potential cultivars, such as the depth and bushiness of the root system (Kell 2011), are determined not only by their genetics, but also by field environment, management practices, and the interactions among these factors. As a result, it is crucial to obtain accurate estimates of the genetic contribution to a trait of interest and also to make efficient and effective selections. In selecting promising genotypes to improve the role of crop plants in the carbon cycle, the most obvious approach relies on phenotype and requires direct measurement of the trait of interest in large populations over several years in many locations. However, this approach is often unacceptably slow and inordinately costly. Fortunately, advanced breeding technologies have created multiple shortcuts that save time and money, while achieving equivalent or even better results.

One shortcut is the use of phenomics (the comprehensive toolbox of efficient methods for measuring plant phenotypes) often referred to as high-throughput phenotyping. These approaches typically involve an autonomous platform (drone/unmanned aerial system, robot, robotic greenhouse) carrying sensors (cameras, spectral imaging sensors, laser- or stereo imaging-based sensors) that collect data on various plots or even individual plants (Furbank et al. 2019; Shi et al. 2016; and Yang et al. 2020). The goal of phenomics is to create metrics that are accurate and reliable, efficient in time, money, and labor, and relate to or are predictive of the trait(s) of interest, if not a direct measurement. The new data types generated can be extraordinarily complex, driving a need for improved algorithms, analytical approaches (van Eeuwijk et al. 2019), data processing and sharing, and even socio-cultural questions of data ownership and rights. Furthermore, phenotypes related to carbon sequestration, such as the amount of root biomass, can be extraordinarily difficult to measure. As a result, advanced plant breeding has become an interdisciplinary field of study, relying on engineering, bioinformatics, and computer sciences to apply modern technolo-

gies and analysis to questions in plant sciences (Kusmec. et al. 2021). Current analysis approaches include machine learning and deep learning (Ubbens and Stavness 2017), latent space phenotyping (Gage et al. 2019), and techniques to integrate information from multiple traits across time.

As an example, different cultivars of crop plants exhibit different root architectures (Zhang and Forde 1998), a key trait regarding a plant's ability to sequester carbon in the soil. By combining phenomics with high-throughput genotyping (sequencing the DNA to score markers at random or pre-determined regions of interest throughout the genome), breeders can identify associations between changes in the DNA and observed differences in phenotype, such as root architecture (Topp et al. 2013). A key difficulty then is in efficiently measuring root architecture non-destructively (Atkinson et al. 2019). Assuming that is possible, Quantitative Trait Loci (QTL) mapping and Genome-Wide Association Studies (GWAS) can be used to identify genetic regions contributing to phenotype changes (Tanksley et al. 1982; and Tibbs Cortes et al. 2021), and markers can be developed for marker-assisted selection. This genotype-phenotype association can also be applied agnostically, with effects of all scored markers being used to predict the phenotype and applied to genomic prediction of unobserved phenotypes. Then, genomic selection can be based on the predictions to make breeding decisions (Crossa et al. 2017; Xu et al. 2020).

Hybrid technologies have advanced through sterility systems and into the use of haploids, allowing rapid development of inbred lines to test as parents in a hybrid breeding program. Now, use of doubled haploid technology is common (Chaikam et al. 2019), as is early-stage screening with both genomics (seed chipping) and phenomics (phenotyping facilities indoors or drones/robots outdoors). Further promise of rapid progress lies in genome editing, particularly with CRISPR-Cas9 (Zhu et al. 2020), where a future pipeline might involve using a marker-based mapping approach to identify candidate genes controlling a trait of interest, applying gene editing to modify that trait (increasing or decreasing its expression or expressing it in a new place or under a new condition), then using high-throughput phenotyping to test the effect of the gene.

If this becomes the pipeline of the future, what is the most efficient and accurate way to identify the most impactful candidate genes controlling the traits of interest? If the traits are complex and affected by the environment, the question becomes even more complex. A potential solution is through integration of process-based modeling and sensitivity analysis with genomics and phenomics to incorporate environmental data and determine the impact of changes in soil, temperature, water, humidity, and other factors on various component traits and how they impact the plant growth and development, and ultimately its yield and biomass (Bustos-Korts et al. 2019; Jarquin et al. 2020; Li et al. 2021; Messina et al. 2018; and Yang et al. 2021). This approach has the benefit of being able to directly model and incorporate complex interactions between the plant and its environment, including carbon cycling. But big questions remain: How to meaningfully model and predict Genotype x Environment x Management interactions; How to efficiently identify impactful genes of interest; and How to maximize success and efficiency in doubled haploid and genome editing. New approaches in high-throughput genotyping and phenotyping, cutting-edge technologies and sensors, and accurate and meaningful modeling and prediction algorithms support success in all these areas.

Conclusion

While many aspects of PA, such as fully autonomous field machines, remain in their infancy, several aspects are relatively mature, and thus conclusions have been drawn about their effect on carbon cycling. In summary, PA technologies can have significant effects on GHG emissions,

mainly through the efficiencies gained by automatic guidance and direct and indirect emissions reductions through VR fertilizer application and VR irrigation.Other PA technologies like VR pesticide application, VR weeding, and VR planting and seeding are unlikely to have a significant effect on agricultural GHG emissions. Advanced crop breeding, on the other hand, is new enough that firm conclusions about its effects on the global carbon cycle are not yet available, but a review of the burgeoning science suggests that the opportunity exists for it to have a major positive impact.

Food Supply Chain and Waste in Climate Mitigation

By Allison Thomson, Zhengia Dou, David Galligan, and Gerald Shurson

The food supply chain in the United States has been actively partnering with farmers and ranchers to reduce the environmental impact of agricultural operations in the United States over the past 15 years. Food supply chains from the field to the plate are complex, with many different arrangements ranging from direct contracts between growers and food brands common in specialty crops, to the large-scale commingling of commodity grains used in food, feed and fuel that makes traceability of food products back to an individual farm challenging. The private sector has been taking on this challenge in order to meet environmental commitments, including corporate objectives and science-based targets to reduce GHG emissions, increase soil carbon sequestration, and improve soil health. Commitments to reducing emissions from food production must include an accounting for on-farm production of the raw ingredients and interventions that reach a diverse community of private landowners and managers.

To meet these commitments, grower organizations and the food supply chain are actively working to engage farmers in projects and programs to accelerate the transition to more sustainable and regenerative farming practices such as reductions in tillage, increases in rotation complexity and introduction of cover crops and grazing, that are collectively referred to as “climate smart” (Lipper et al. 2014). This definition means that the practices either help to mitigate climate through emissions reductions or carbon sequestration or that they make farms more resilient to the impacts of climate change.

Private sector efforts involving corporations in the food supply chain to advance adoption of climate smart agriculture have included piloting science-based approaches to measuring outcomes and reporting on progress, engaging growers in on-farm research and trials, testing digital technology for measurement (Thomson et al. 2019) and investing in development of voluntary carbon markets. This experience provides a robust foundation for learning about successful strategies to engage and support producers in making practice changes.

While much has been learned, there are significant limitations to the scope of voluntary programs related to the reach and influence of the corporations to influence farmers and the information available on creating successful interventions (Friedberg 2018). The scope of the research necessary to move past some of these limitations requires investments that would collectively benefit all farmers and actors in the food supply chain. Government supported research programs in rural sociology, agricultural economics and social sciences that seek to understand the barriers to adoption and sustained use of regenerative and climate smart agricultural practices in diverse farming communities is needed. Providing a roadmap and establishing public-private partnerships will increase the effectiveness of private sector efforts. Reaching and enrolling farmers to participate, gathering sufficient data to measure or calculate GHG emissions and soil carbon, and

[2] https://sdgs.un.org/goals

appropriately incentivizing practice changes that improve these outcomes could all be enhanced with evidence-based strategies for collective action.

Another barrier is in the efficient and accurate calculation of environmental outcomes and monitoring for improvements that is necessary to ensure interventions are achieving the desired goal. Development of agroecosystem simulation models and modeling approaches that reduce barriers to use in a decision support context is therefore a critical need. One major obstacle in this work is the limited availability of field-based research data for widespread calibration and validation of such tools across the full scope of farming systems and geographies of U.S. agriculture. Enabling field research on climate smart agriculture practices around the country, standardized data and metadata collection protocols, and a centralized data repository to ensure field data is readily available to model and decision support tool developers will improve the accuracy of GHG emissions and soil carbon estimates from farms and enable science-based feedback to producers about the practices most effective at reducing emissions from their operations.

Food waste and carbon footprints

With roughly one-third of food produced for humans lost or wasted, our ability to end hunger, protect the environment, conserve natural resources, and mitigate climate change impacts is greatly undermined. GHG emissions attributed to food loss and waste (FLW) account for 8–10% of global anthropogenic emissions (UNEP 2021), making it the third largest emitter behind China and the United States if FLW was a country (FAO 2013). In addition, FLW has dramatic effects on depleting finite essential resources such as phosphorus (Leinweber et al. 2017), and aggravating nitrogen pollution problems (Reis et al. 2016; Sutton et al. 2021). The UN Sustainable Development Goals (SDGs) Target 12.3 calls for halving per capita food waste at retail and consumer level by 2030 and reducing food loss along the production-supply chain. Reducing food wastage and re-purposing non-preventable food loss to the highest value possible will directly or indirectly address carbon, nitrogen, phosphorus, and all of the 17 SDGs.

Food waste prevention is at the top of food recovery hierarchy in addressing food's climate and sustainability challenges. However, progress in waste prevention has been extremely slow. Except for a few bright spots, the world overall is far behind where it needs to be toward achieving SDG Target 12.3[2]. In the United States, food donation and various food rescue efforts helped to save up to 2 million tonnes (4.4 million pounds) food from being wasted (Dou et al. 2018). The amount is significant for helping food insecure families, but very small comparing to the magnitude of the problem–60 million tonnes (132 million pounds) of edible food is lost/wasted at the consumption stage annually (Buzby, Wells, and Hyman 2014). The reality is that cities in America and elsewhere must deal with large streams of food waste generated throughout the food system, particularly from homes, restaurants, wholesale and retail outlets, now and for the foreseeable future. The question is: How can societies manage the food waste streams in ways that extract the maximal value while alleviating climate and environmental burdens?

Food Waste Treatment Technologies as Climate-smart Solutions

Food waste generated at the consumer level is a heterogenous mixture of cooked and uncooked, edible and inedible, animal- and plant-based food materials of different sizes and moisture content. These materials are generally rich in energy (dry matter [DM] 18-29%, carbohydrates 36–59% DM), proteins (14–22% DM), and minerals such as calcium and phosphorous (Dou and Toth 2021). When landfilled, these materials become a source of methane emission and nutrient pollution. Use of proper processing technologies can divert the materials away from landfills to

be used as valuable resources for more sustainable food production while mitigating climate impact.

Aerobic composting (AC) and anaerobic digestion (AD) are popular alternatives to landfilling for managing food waste. In AC, aerobic microbes decompose organic matter, producing compost that can be used as soil amendments to offset synthetic fertilizer and enhance soil organic matter (Kibler et al. 2018). In AD, organic matter is degraded under oxygen-free conditions through microbial processes of hydrolysis, acidogenesis, acetogenesis, and methanogenesis to produce biogas (53–70% methane and 30–50% CO_2 [Lin et al. 2018]) for heat or electricity generation; the remaining residues can be applied to soils, similar to compost. AC and AD help mitigate climate burdens by reducing landfill methane emissions as well as through life-cycle carbon (LCC) reductions via fertilizer and/or energy substitution (Shurson 2020; Kim and Kim 2010]. Compared to the downcycling processes of AC and AD, a more advantageous approach is to upcycle food waste by re-purposing into animal feeds (referred as Re-Feed hereafter) via proper thermal processing to allow greater resource recovery, climate mitigation, and efficient production of meat, milk, and eggs for people (Dou, Toth, and Westendorf 2018; Dou 2020).

With Re-Feed, species-specific feeding strategies allow matching food waste types/sources with animal species to support maximal extraction of the biological value of nutrients while minimizing animal and public health risks. For example, plant-based food discards such as unsalable fruits and vegetables [roughly 13%–14% of supermarket inventories (Buzby et al. 2016)] are relatively high in dietary fiber content and thus most suitable for ruminants, given the animals' ability to use fiber as an energy source. Other discarded food products, such as meat, dairy, and bakery waste from supermarkets, together with post-consumer food waste from homes, restaurants, etc., can be made into highly nutritious feeds for monogastric animals. About 45% of consumer food waste in South Korea has been reportedly converted into feeds for livestock (Ju et al. 2016; Kim and Kim 2010; Padeyanda et al. 2016). The modern treatment processes used in South Korea include sorting, screening, grinding, dewatering, heating, and drying, which differ drastically from the age-old practice of "swill feeding" or "garbage feeding" to backyard pigs. Feeding of thermally treated feeds are safe for animals and public health risks are minimal (Shurson 2020).

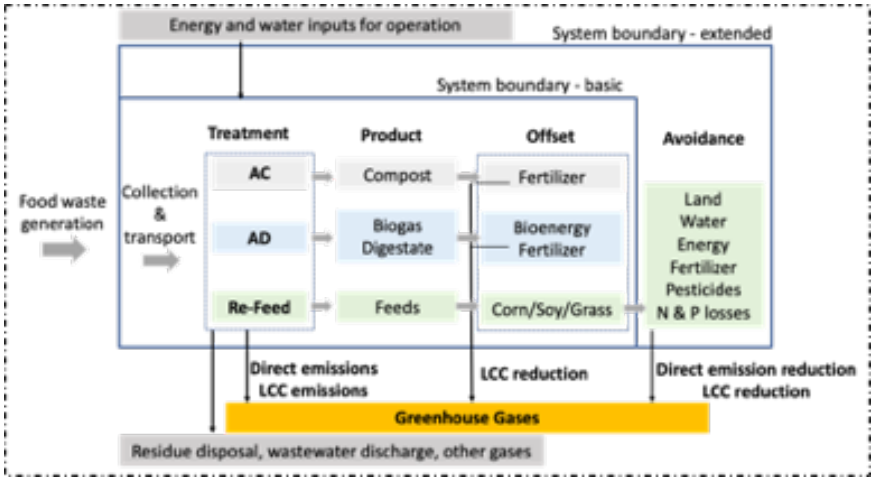

Figure 1. A schematic illustration of food waste treatment technologies as climate smart solutions. Systems-based analysis identifies life-cycle carbon (LCC) reductions from (i) products (compost, digestate, conventional feedstuffs) offsetting commodities (fertilizer, bioenergy, corn/soy/grass), and (ii) the avoidance of land, water, fertilizer etc. that are otherwise needed for producing the conventional feedstuffs. Detailed treatment processes are not shown. AC: aerobic composting; AD: anaerobic digestion; Re-Feed: re-purposing food waste for animal feeding.

Extended systems-based analysis indicates that Re-Feed can bring additional LCC reduction credits, offering a potentially transformative pathway for addressing food waste and sustainability challenges (Figure 1). Substitution of conventional feedstuffs

(e.g., corn, soybean meal, forages) with food-waste-derived feeds will reduce land, fertilizer, pesticides, energy, water that are otherwise needed for producing the conventional feedstuffs, thereby 'sparing' relevant climate, resource, and environmental burdens. Re-Feed as a robust solution for addressing multiple objectives has been described in several studies (Dou 2020; Salemdeeb et al. 2017; Shurson 2020; and zu Ermgassen, Balmford, and Salemdeeb 2016). Collectively, AC, AD, and Re-Feed are all valid recycling options as independent or integrated technologies that can help societies unlock resources embedded in food wastes for improved sustainability and food system resilience in the face of climate change.

Urgent Action is Needed

A national framework that focuses on creating and/or expanding commercialization of food waste recycling options that are appropriate for specific waste streams, with the goal of optimizing resource recovery; reducing carbon, nitrogen, and phosphorus footprints; and mitigating climate impact.

- Develop and implement government policies and entrepreneurial incentives at local, state, and national levels that encourage investment and commercialization in higher value food waste re-purposing and nutrient recovery practices (i.e., conversion into animal feed).

- Engage FDA/CVM in addressing biosafety concerns including (1) applying FSMA regulations to food waste for animal feed, (2) re-evaluate the applicability of the Swine Health Protection Act, (3) re-evaluate current thermal processing conditions to ensure compliance with the highest biosafety standards, (4) define low bio-hazard food waste stream sources, and 5) develop science-based Hazard Analysis and Risk-based Preventive Controls for food waste processing facilities.

- Invest in research and technological innovation to establish LCC reduction credits of food waste recycling options; document socioeconomic, environmental, and climate impacts of the various options; and foster technological integration for greater synergy and less tradeoffs.

- Create educational programs and promotions to change societal perceptions from thinking that food waste is "garbage" toward considering it as a valuable "green" resource for soil amendment/fertilizer (composting), biogas (anaerobic digestion) and animal feed.

How do we Make Carbon Markets Work for Agriculture?

By Cristine Morgan and Debbie Reed

Carbon Markets Are One Mechanism to Help Scale Climate Agricultural Climate Solutions

Carbon markets began approximately 25 years ago to help mitigate emissions across national boundaries and in sectors with lower cost mitigation opportunities. Interest in agriculture's role in carbon markets has peaked recently, as has additional scrutiny on how to accurately measure, report, and verify (MRV) changes in GHG from agriculture, including for soil carbon sequestration.

To help the nascent carbon markets work for agriculture, lessons learned from the past 25 years, as well as advancements in agricultural science and technology can be applied to promote market liquidity and allow these markets to viably function at scale within the next 3–5 years. The

USDA support can leverage significant private sector investments in private voluntary carbon markets, particularly by investing in research, data sharing, and technical and financial support to U.S. farmers and ranchers to contribute important atmospheric carbon removals through increased sequestration, as well as through reduced emissions of carbon dioxide, nitrous oxides and methane from agricultural sources.

What Makes a Market Successful?

Appropriate standards and adequate supply and demand are essential for successful markets. Existing international accounting and market standards underpin global carbon markets. The re-entry of the United States into the Paris Agreement, a legally binding international climate change treaty among parties to the UN Framework Convention on Climate Change (UNFCCC), means the United States is adopting policies and programs and a commitment to combat climate change and to limit global warming to well below 2 degrees Celsius. The Accord addresses the use of carbon sinks and reservoirs (e.g., soil carbon sinks) and voluntary market-based mechanisms, such as carbon markets, to enable countries to set climate mitigation targets and activate programs and policies to achieve emissions reductions and increased sequestration outcomes. Environmental integrity, transparency, robust accounting and the continued use and development of international standards that govern these markets are required to credibly establish and meet these goals, globally and in the United States. The agricultural sector, as both a GHG source and a sink, can contribute both increased soil carbon sequestration and reduced GHG emissions.

The International Panel on Climate Change (IPCC), comprised of scientific experts advising the UN on the science of climate change, agreed in their most recent assessment identified carbon sinks and agricultural GHG mitigation as critical to keeping global warming below 2 degrees Celsius (Smith et al. 2014).

These advancements provide the impetus for supply and demand for emissions reductions via market mechanisms, and conclusive agreement that the agricultural sector has a significant role to play. In its 2018 State of the Voluntary Carbon Markets report, Forest Trends reported that Forestry and Land Use were the market leaders in actual credit transactions and issuances in 2018—marking a clear preferential shift to Natural Climate Solutions (which include agricultural credits) by buyers compared to prior years and trends (Donofrio et al. 2020).

Stimulating Agricultural Credit Generation in Nascent Carbon Markets in the United States

Carbon credits from agriculture can be generated by increasing soil carbon sequestration (termed as “removals” in carbon markets, due to the ability of soils to remove carbon dioxide from the atmosphere) and from reduced emissions of GHG (termed as “reductions” in carbon markets), including from nitrous oxide and methane.

Given that the global warming potential of nitrous oxide and methane are significantly higher than carbon dioxide (US EPA 2021b)—approximately 30 times higher and 300 times higher than CO_2, respectively—emissions reductions from these gases in agriculture should not be overlooked as climate change solutions. A recent trend in carbon markets towards systems-based approaches to quantifying changes in all GHG and away from single-practice and single-GHG outcomes is a positive one that will benefit scaling of agricultural practices. However, the ability to discern changes in removals and reductions due to “additionality”, or new practices, and to subtract out non-additional or business as usual removals and reductions – which are not creditable in carbon markets, complicates quantification approaches.

Soil Carbon Credits

The focus of this chapter will be on the mitigation potential offered from increased soil carbon sequestration. Accurate quantification of soil carbon is critical to the integrity and credibility of

soil carbon credits in carbon markets. Carbon markets generate intangible products that are bought and sold in the absence of a physical product changing hands. Biological GHG emissions and emissions reductions from agriculture exhibit high spatial and temporal variability. The ability to quantify uncertainty in estimating or measuring agricultural GHG emissions and changes in emissions is important for market-based accounting. Global accounting and carbon market standards ensure quality, standardization and comparability, and thus fungibility of credits across all sectors and all countries. Because soil carbon stocks are at risk of intentional or non-intentional losses or reversals from storage, market standards require that they be monitored and replaced if transacted credits representing increased soil carbon are lost for any reason.

In-field Measurement vs Modeling to Quantify Soil Carbon Stocks

Currently there are two approaches to assess changes in soil carbon as a result of changing management—measurement and modeling. Measurement-based assessment includes traditional soil coring (which is destructive to the sample), non-destructive proximal soil sampling, and remote sensing. Modeling refers to the use of a process-based model, or a biogeochemical model, which requires inputs on weather, soil, and management history to simulate soil processes that alter soil carbon cycling and storage. The complexity of process-based models, and hence the temporal and spatial information that goes into them varies tremendously (Parton 1998; Powlson, Smith, and Smith 1996; Swan et al. 2015).

Measurement- and modeling-based methods represent a spectrum of cost, feasibility of implementation, and level of certainty in estimating soil carbon stock changes (Table 1). The complexity of measuring changes in soil carbon stock over time is because soil carbon stocks likely vary more in three-dimensional space than in time. The carbon concentration in soil can vary by greater magnitudes in space than depth. In a single farm field, it is not uncommon for soil carbon to vary from 2 to 6% in the east and west direction and from 6 to 2% by depth. In a five-year period, we may expect an addition of up to 2.5% carbon from 5 years of adding no till and cover cropping (Chambers, Lal, Paustian 2016). This natural spatial variability prescribes an optimized spatial soil sampling method that selects both the number of soil samples needed and the specific location each sample should be taken. For sampling algorithms to be effective for market purposes, inputs include prior knowledge of the spatial variability of soil carbon, the accuracy of the soil sampling method, and any uncertainty-based constraints in the stock estimate. As spatial variability in soil carbon stock increases and the uncertainty cap decreases, more measurement locations are needed.

Modality	Spatial Coverage	Costs	Uncertainty Limitation
Soil Coring + Lab Measurement	Limited	Greatest	Cost of sampling
Proximal Sensing	Moderate	Moderate	Measurement precision
Remote Sensing	Best	Least	Extrapolation across management histories
Biophysical Modeling	Based on model inputs	Least	No clear protocol for quantifying uncertainty

Table 1. Qualitative summary of measurement and model based estimates of soil carbon sequestration.

To support carbon markets the methods chosen to quantify changes in soil carbon stock will have to be implementable cost-effectively at scale. The standard method to measure soil carbon stock is to pull a soil core that represents a defined volume of soil and measures both the bulk density and carbon concentration (Nelson and Sommers 1996). Table 1 shows measurement precision for the soil sample collected. It is important to note the relatively small soil sample represents a large volume of soil in the farm field. Collecting enough soil samples to calculate a mean change and certainty estimate can be expensive due to labor for on-site sample collection, transport, and laboratory processing.

Alternative quantification approaches will optimize the returns between accuracy and cost. Proximal soil sensing is a less accurate method of soil carbon stock measurement is using proximal soil sensing. Proximal methods require on-site access but remove costs of labor from pulling soil samples and laboratory analyses. The tradeoff between soil coring with laboratory analyses and proximal methods is cost and accuracy. To overcome less accuracy with proximal sensing, more proximal observations are needed. Usually proximal sensing costs are fixed, hence the cost of one more measurement is far less in proximal sensing than soil sampling.

Remote sensing offers another alternative. Remote sensing estimates can provide fine resolution estimates of soil carbon stock over large spatial extents, and are thus scalable, but estimating uncertainty is difficult. A remotely sense product will use data from the top of the soil surface to calibrate with measurement of soil carbon stock to a given depth (30 cm or greater). However, tillage, cropping, and manuring history of agricultural soils will vary between management units (farm fields, paddocks) resulting in differences in soil carbon stock with depth. Without knowing how the vertical distribution soil organic carbon stock changes with depth, the uncertainty of a remotely sensed image is problematic without ground truthing by management unit. Ultimately this means collecting soil samples via soil coring and lab measurement.

Biophysical models are another method to quantify soil carbon changes. Spatial resolution of model products are only limited by the resolution of data used as inputs. Weather data are readily available for many parts of the globe, as are gridded maps of soil characteristic to 30 m resolution (Soil Survey Staff, e.g., gSSURGO; Hengl et al. 2017 e.g., SoilGrids). Model based estimates of soil carbon stock can quantify uncertainty using protocols agreed in carbon markets to date.

Research and Development Opportunities for Soil Carbon Quantification

Pedometricians—scientists with applied expertise in soil science, spatial statistics, mathematics, and sensing technologies—have been working to reduce spatial soil sampling costs for 25 years. The consensus to reduce soil sampling costs and maintaining high accuracy is to employ integrated quantification approaches, such as a soil sampling design using legacy soil maps or accessible spatial data (e.g., yield maps or remote sensing) combined with a proximal sensing and/or modeling. While proximal sensing is less accurate than soil sampling, the additional observations needed to provide a given certainty in the estimate are less costly than soil sampling. Spatial soil sampling strategies will continue to change as new spatial information types are created and accessed. Proximal sensing technologies that are most promising today include those based around visible, near, and mid infrared spectroscopy (Ackerson, Morgan, Ge 2017; Viscarra Rossel et al. 2008; Viscarra Rossel et al. 2016) and inelastic neutron scattering (Wielopolski et al. 2000).

Spectroscopy tools are commercially available now (Gehl and Rice 2007); but since spectroscopy-based proximal sensing only gathers soil C concentration data, additional sensors are needed to measure bulk density for a soil carbon stock estimate (Wijewardane et al. 2020). No market-ready proximal sensors exist today, but continued investments can lead to technologies emerging in future.

Funding Needs to Cost-Effectively Scale Agricultural Participation in Carbon Markets

Robust public-private partnerships are encouraging rapid translation of disciplinary expertise to develop soil carbon stock and other GHG quantification solutions in real-world practical settings. Continued applications in carbon markets will enable GHG accounting and market monitoring, verification and reporting standards to reflect these advances, which will further enable scaling. Market programs such as the Ecosystem Services Market Consortium (ESMC), a public-private partnership funded through the Foundation for Food and Agriculture Research (FFAR) together with agricultural supply chain corporations, producer groups and stakeholders across the agricultural value chain are investing in many market approaches and advances to ensure the success of ecosystem services markets for agriculture. Delivering economic value to farmers and ranchers whose actions provide desired outcomes is key to delivering carbon and ecosystem services from agriculture; but the actions required of producers must also provide long-term benefits on-farm to ensure adoption retention and resilience.

Scientific uncertainty about soil carbon sequestration, including where accumulation occurs, how it migrates across stratification layers in the soil profile, and how to cost-effectively and accurately quantify soil carbon and changes in soil carbon at scale across regional and production system gradients is a high priority for further investment. Federal government investment through the U.S. Department of Energy Advanced Research Projects Agency-Energy (ARPAE) programs and FFAR have catalyzed the development of soil sensing and modeling technologies and advancements. Additional private investments have further catalyzed soil and data scientists and technologists to harvest artificial intelligence and machine learning to improve our understanding of biological and physical processes that drive carbon cycling and storage in soil. The future of measurement-based carbon stock assessment is likely to evolve into integrated soil coring with lab testing, process-based modeling, and remote and proximal sensing to ensure credibility of market-based credits.

Conclusion

This paper provides a summary of different ways the agricultural sector can provide mitigations to climate change and sequester carbon dioxide. In crop agriculture, pesticides are a critical tool used by both organic and conventional farmers to protect their crops from diseases, pests, and weeds as part of a larger integrated pest management system. In addition to helping farmers grow more with less, pesticides enable farmers to employ conservation tillage practices by clearing weeds and controlling pests. Bolstered by minimum tillage, cover crops, and responsible pesticide use, farmers can play a critical role in the reduction of the amount of greenhouse gases emitted by on-farm operations, capture atmospheric carbon, and maintain high levels of productivity.

Animal agriculture can contribute to reversing climate change while increasing global nutritional security. This opportunity to contribute to reverting climate change by focusing on soil carbon sequestration and methane mitigation places animal agriculture in a unique position to convert climate impact into societal benefit. Animal agriculture needs focus and investment to accelerate its contributions to reverting the climate crisis. Scientists in academia, industry, and government need to effectively contextualize their scientific findings to relate with policymakers, the media, and the public who are ultimately impacted by them.

Public-private partnering and market focus are essential to accelerate climate action by animal agriculture. CAST is well-positioned within this context to play a significant role by convening and coordinating networks of experts to assemble, interpret, and communicate credible and unbiased science-based information on animal agriculture science and technology.

Large amounts of food wastes routinely generated must be recovered and repurposed to the highest value possible for climate mitigation, food security and sustainability. A potentially

transformative pathway is species-specific livestock feeding that matches food waste types with animal species for maximal use of biomass nutrients with minimal health risks. Urgent action is needed to build a national framework that focuses on creating and expanding commercialization of food waste re-use options that are appropriate for different waste streams, with the goal of optimizing resource recovery and reducing climate footprints of the agri-food system.

With recognition from global scientists that all tools and technologies are required to combat climate change, and that increased soil carbon sequestration is a low-cost, high benefit means of immediately drawing down atmospheric carbon, there is significant interest in carbon markets generating soil carbon credits to help mitigate climate change. To meet market standards and to generate high-quality, high integrity, internationally fungible credits, robust yet cost-effective quantification and verification of changes to soil carbon stocks are required.

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