Novel technologies for emission reduction complement conservation agriculture to achieve negative emissions from row-crop production

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Plants remove carbon dioxide from the atmosphere through photosynthesis. Because agriculture's productivity is based on this process, a combination of technologies to reduce emissions and enhance soil carbon storage can allow this sector to achieve net negative emissions while maintaining high productivity. Unfortunately, current row-crop agricultural practice generates about 5% of greenhouse gas emissions in the United States and European Union. To reduce these emissions, significant effort has been focused on changing farm management practices to maximize soil carbon. In contrast, the potential to reduce emissions has largely been neglected. Through a combination of innovations in digital agriculture, crop and microbial genetics, and electrification, we estimate that a 71% (1,744 kg CO_2e/ha) reduction in greenhouse gas emissions from row crop agriculture is possible within the next 15 y. Importantly, emission reduction can lower the barrier to broad adoption by proceeding through multiple stages with meaningful improvements that gradually facilitate the transition to net negative practices. Emerging voluntary and regulatory ecosystems services markets will incentivize progress along this transition pathway and guide public and private investments toward technology development. In the difficult quest for net negative emissions, all tools, including emission reduction and soil carbon storage, must be developed to allow agriculture to maintain its critical societal function of provisioning society while, at the same time, generating environmental benefits.

agriculture emission reduction | innovation | crop genetics | soil health | electrification

All sectors must reduce their emissions to avert the negative consequences of climate change (1). Although essential, food production and agriculture must participate in this reduction, as emissions from this sector alone will exceed the carbon budget for acceptable temperature increases (2). To this end, it is important to develop technical roadmaps that preserve economic productivity while reducing emissions.

Agriculture has a unique potential to provide beneficial contributions to the global carbon budget because its fundamental unit of productivity, carbon fixation through photosynthesis, removes CO_2 from the atmosphere. To reduce its environmental footprint, agriculture has two options: dramatic emissions reduction through new technologies and the adoption of methods guided by preagriculture ecosystems to build soil organic carbon stocks. When soil organic carbon accumulation exceeds emissions, the sector will be among the few to achieve net negative emissions and lead in the climate change solution.

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Unfortunately, current agricultural practices are optimized primarily for yield and use large amounts of fossil energy to produce fertilizers, chemicals, and mechanical energy. Consequently, row-crop agriculture contributes nearly 5% of emissions in the United States and European Union (EPA/Eurostat). A small number of producers have achieved negative emission production using practices that are often termed "regenerative agriculture" (3). Although there is no formal definition of regenerative agriculture, these systems tend to use cover crops, no tillage, and crop rotation while minimizing chemical inputs and emphasizing soil stability for carbon storage and water stewardship. Many regenerative producers incorporate livestock grazing in their operations.

Despite its appeal, regenerative agriculture will take a long time to scale broadly as change of this magnitude is challenging, expensive, involves long-term soil dynamic processes, and requires new supply chains (4) and new understanding of farm practices in many geographies. Many of the benefits of these systems take time to accumulate, and there is a lack of incentive to invest in practices with a long-term return on investment (5) on rented land (6). As a final challenge, there is significant debate on the magnitude of soil carbon sequestration (7–10). Outside common row crops, other low- or negative-emission production systems such as perennial grasses for bioenergy are available (11, 12), but farmer adoption is limited because economic viability depends on the development of new markets, end uses, and logistics chains.

Fortunately, slow adoption is not a general feature of agriculture and the potential for rapid change should encourage technology developers and policy makers. Producers are quick to adopt new technologies when they are profitable and the annual planting cycle for most row crops enables rapid proliferation of new technology. As an example, adoption of genetically modified row crops grew to over 90% in a matter of 10 y (13). Similarly, Global Positioning System–guided tractors and yield monitors saw rapid adoption as older equipment was replaced (14). Thus, there is an opportunity to improve the environmental footprint in the near term by developing targeted technologies that are readily adoptable and fit within current production systems and established grain markets.

In addition to new technology, the transition to negative carbon agriculture requires a value proposition. There is significant interest and market development for emission credits to meet the environmental targets of corporations and other large entities. This new market will promote adoption of new low-emission technologies. Public policy is a second lever that can incentivize transition through payments for ecosystem services, grain valuation methods that incorporate environmental footprint, insurance adjustments, lending/interest rates, grant support, and renewable energy generation credits.

Soil carbon storage is a major focus of several voluntary markets due to the negative emission potential. In contrast, technical innovations that reduce emissions receive much less attention although their combination could yield benefits on the same order as most predictions of enhanced soil carbon storage. In this paper, we describe a suite of technologies to dramatically reduce farm emissions that includes digital agriculture for precision input application, crop and microbial genetics for input efficiency and N fixation, and electrification of ammonia synthesis and farm equipment. To estimate the impact of technology adoption on the emission footprint of grain production, we used current maize feedstock emission values from the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model (*SI Appendix*) as a benchmark representing the national average emissions.

These benchmark values highlight the importance of N fertilizer in farm emissions. It is the largest contributor to row-crop emissions (Fig. 1) because of energy expenditure during manufacture and the emission of nitrous oxide (N_2O) from the soil. N_2O is a potent greenhouse gas with 265 times the global warming potential of CO_2 and a long atmospheric half-life. While N_2O emissions are already recognized as a large component of global GHG emissions, actual emissions may be higher, as a recent global inventory estimated that this emission source is underestimated (15). It is important to avoid N_2O emissions, because unlike direct air capture for CO_2 there is not a technology sector focusing on removing N_2O from the atmosphere.

Rather than suggest a single set of futuristic low-emission technologies we chart a green transition for agriculture that can progress through three phases (optimize, replace, and redesign). Each phase provides meaningful improvements in the emission footprint of grain production (Fig. 1 and *SI Appendix*) and is defined by the technical readiness of the enabling technology (Fig. 2). Based on these inventory assessments, new product innovation can reduce farm emissions by 71% (1,744 kg CO_2e/ha; Fig. 1 and *SI Appendix*, Table S1) from current US maize default values.

By rewarding gradual improvements, ecosystem markets that include emission reduction can facilitate difficult transitions through graded change and initiate a virtuous cycle whereby payments create receptivity to new technologies and promote further improvements (16). By combining deep cuts to emissions with practices that build soil carbon, agriculture has the potential to generate net negative emissions at a large scale.

Phase 1: Optimization for Efficiency Using Current Technologies

The initial step toward net negative agriculture will focus on reducing agrochemical use, mainly N fertilizer. Improving N fertilizer timing, placement, and formulation using commercially available N fertilizer additives (e.g., nitrapyrin) can reduce N_2O emissions by delaying nitrate delivery to the roots and increasing plant N uptake. In the US Midwest, 50% of the N fertilizer applied to low-productivity areas is lost and does not improve crop yield. Thus, reducing emissions is achievable with limited productivity tradeoffs (17).

Digital Agriculture for N Fertilizer Reduction. Fertilizer guidance focuses on application of the right input, at the right rate, right time, and right place, in the right way (5Rs). The key technical enablers of N-demand forecasting are digital agriculture and agronomic modeling. These technologies inform intensification in high-productivity areas and diversification (bioenergy crops and pollinator habitat) in low-productivity areas. High-resolution geospatial monitoring systems are used by dynamic process-based crop simulation models that predict maximal plant N responses based on soil, weather, terrain, and crop demand (18). N fertilizer application based on subfield spatial variability and biological demand can reduce N application by 36% for a 23% emission reduction (578 kg CO_2e/ha; Fig. 1 and *SI Appendix*, Table S1). Precision N application relies on current-generation equipment and near-term adoption is possible for many producers.

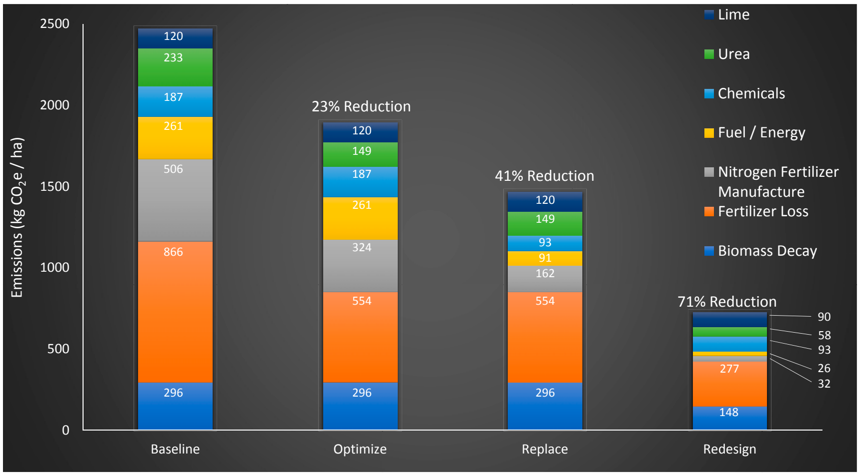

Fig. 1. **Technical improvements facilitate deep decarbonization of grain production. Numbers are shown as kilograms of CO_2e per hectare and are separated by the emission source. The phases (optimize, replace, and redesign) are distinguished by the technical readiness of the enabling innovations. Implementing the optimization phase is largely possible using current technology, while replacement-phase technologies could be available in 2 to 5 y and redesign-phase technologies in 5 to 15 y.**

Phase 2: Replacement of Current Technology with Near-Mature Low-Emission Alternatives

In response to new value drivers and/or policies, technologies that are currently in a prototype stage would find broad markets. These second-generation technologies are greener "drop-in" substitutes for current tools and have low barriers to adoption. Implementing these changes would allow emissions to be reduced by 41% (1,003 kg CO_2e/ha; Fig. 1 and *SI Appendix*, Table S1). This set of technologies is well-suited for small business innovation grants and for private equity/venture capital that can build business strategies around novel income streams from emission reduction.

Crop Genetics for Improved N Use Efficiency. New phenotyping technology focused on roots and underground processes

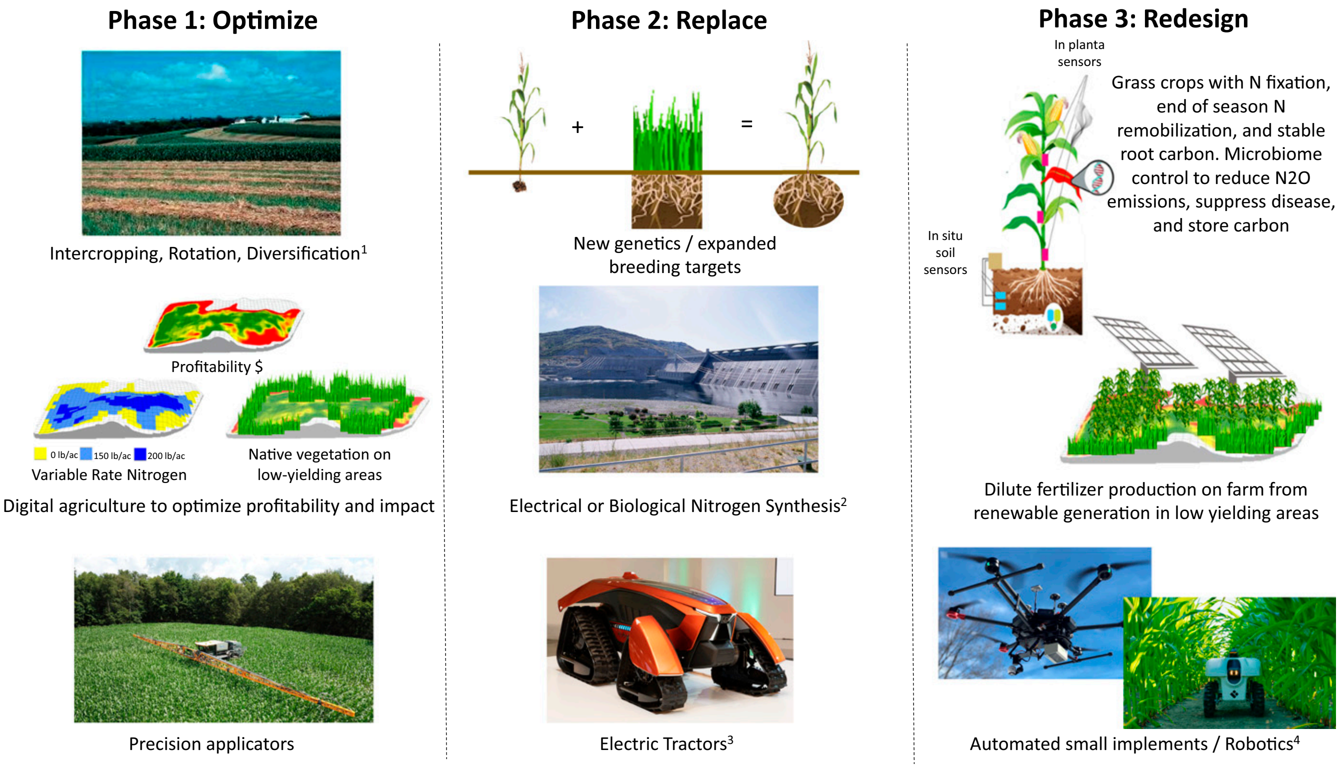

Fig. 2. **Descriptions of the technologies that will be adopted in each phase in response to new policy and farm economics. The combination of technology in each system will lead to a dramatic reduction in farm emissions. [1]Intercropping, rotation, and diversification image credit: Wikimedia Commons/Natural Resources Conservation Service. [2]Electrical or biological nitrogen synthesis image credit: Wikimedia Commons/US Fish and Wildlife Service. [3]Electric tractor image credit: Kubota. [4]Automated small implements/robotics image credit: Chinmay Soman, Terrasentia.**

makes it possible to customize plant genetics and root traits to improve N use efficiency. Recently developed field-deployable instruments allow direct monitoring of root system architecture and have uncovered large variation in root growth patterns within elite commercial germplasm (19, 20). This information can be used to select genotypes whose roots optimize nutrient extraction based on the soil structure and topography of a specific field (18). Moreover, these tools confer the ability to directly monitor root responses to water status (20) or crop additives such as microbes, organic extracts, fertilizer stabilizers, and mineral fertilizers to identify combinations of genetics and chemical and biological additives that enhance N use efficiency.

Any new trait package must be confirmed by extensive field testing for yield. Direct phenotyping will guide the advancement of crop varieties with altered root systems and assess the efficacy of treatments that enhance root growth.

Electrical Synthesis of Ammonia. The Haber–Bosch process revolutionized agriculture by creating plentiful N fertilizer. This chemical process converts atmospheric N (N_2) to ammonia (NH_3). Haber–Bosch uses a large amount of fossil energy and is responsible for ~1% of global emissions (21). Because most of the chemical ammonia produced is used in agriculture, policies and markets that include fertilizer production have significant potential to address these emissions.

Conventional Haber–Bosch manufacturing plants generate hydrogen and produce significant emissions through steam methane reforming. Water electrolysis is an alternative source of hydrogen, and if the energy driving the reaction is from renewable electricity the resulting "green" hydrogen enables alternative processes for ammonia production with significantly lower emissions (22). Electrical synthesis of ammonia can proceed through multiple pathways, and commercial deployment requires novel catalysts, reactors, and separation technologies (21).

To produce concentrated fertilizers required for current agronomic practices, first-generation electrical ammonia synthesis facilities will be large and require batteries and ammonia concentrators (23). The cost of additional unit operations will limit adoption, but the emission reduction potential is high, and payments for these reductions could create favorable economics at large operations. In addition to new routes to ammonia, electrical methods using plasma reactors are under development that directly synthesize nitrate, potentially simplifying the production of N fertilizers (24). Green N fertilizers are indistinguishable from currently used chemicals and there is no barrier to adoption.

Biological Synthesis. Microbially derived N is another potential low-emission N source. Some soil microbes, in addition to those that form nodules, possess the ability to fix N and adding these microbes to the soil can reduce the need for chemical fertilizer. The carbon and energy for N fixation is supplied by the plant and it is likely that this fertilizer will be efficient because of its proximity to the root system (25). Plant roots exude large amounts of photosynthate (26), and a portion of this exudate can likely be directed to N fixation without much trade-off. If new N fixing plants or microbes are designed to increase exudates to increase this source, yield reduction may occur, and this trade-off must be considered against the environmental benefits.

Electric Implements. Farm operations consume fossil fuels and emit CO_2. Equipment manufacturers are exploring electrification for performance advantages, and similar to electric cars, tax incentives could drive adoption of electric tractors. The emissions of these vehicles depend on the electricity mix, and using renewable power could create zero-emission farm equipment (27).

Phase 3: Redesign for Low Emissions

The third phase of agriculture's green transition entails a complete system redesign of agricultural practices for emission reduction and soil carbon storage. Much like the distributed characteristics of renewable power, emission-optimized agriculture will not rely on scale or concentration for efficiency and will use small, distributed, precision systems. Ultralow emission production will use fewer chemicals and novel inputs such as locally produced, low-concentration fertilizers, biological amendments, and genetics specifically bred for this agronomic system. Crop management will entail precise application of fertilizer and chemicals aided by small, automated implements that are guided by distributed sensors and mesh networks. At full implementation, these technologies can reduce field emissions by 71% (1,744 kg CO_2e/ha; Fig. 1 and *SI Appendix*, Table S1).

For soil carbon storage, new agronomic insight will assist adoption of cover crops, no-till, and other soil health and carbon sequestration management practices. Technologies will promote soil carbon storage, and crop genetics may be specifically designed to boost soil carbon sequestration in cash crops and cover crops (28).

While this production system would be difficult to adopt today, years of transition, preparation for these tools, ecosystem service payments, and sector interest will make adoption significantly easier. Substantial and ongoing technical innovation is required for this phase of the agricultural transformation, and confidence in a receptive user base is necessary to encourage technology developers to undertake 5- to 10-y development cycles. Given their high potential but significant risk, these technologies are ideal targets for public support, philanthropic investment, and patient private capital.

Genetics to Support Low and Negative Emissions. Crops designed for low-emission production systems will combine high yield and N use efficiency (29). In addition to optimizing root growth, novel genetics may allow N fixation by cereal crops with improved nutrient use efficiency (30). In developing these traits, it is critical to consider the cropping system, as traits that are beneficial in one crop to reduce emissions can boost emissions in another crop (31).

End-of-season biomass decay is a significant source of N_2O emissions. Perennial grasses mobilize N to the root system, preserving it for the following season and avoiding a large portion of this emission source (32). Through genetic modification this trait has been introduced into model crops and could reduce emissions by moving N to the root system or to the grain (33). On a longer timeframe, instead of introducing perennial traits to annual crops, it is possible that perennial grains will replace annuals. Broad adoption relies on boosting grain productivity for perennials, and this is a slow process given the lifecycle of these crops. Modern breeding techniques including genomic selection are accelerating improvement (34).

Like N use efficiency, soil carbon accumulation is affected by root genetics that control depth and mass (35, 36). To promote emission reduction by boosting carbon storage, breeders will broaden the root trait targets to incorporate traits that further boost soil carbon storage by promoting root carbon stability or increasing exudates. Additional trait discovery tools allow laboratory-based determination of root anatomy and composition, which may facilitate soil exploration and inform breeding strategies for soil carbon deposition (37). Soluble organic components in root exudates can migrate deep into the soil profile where microbes may incorporate it into long-term soil organic matter (38). Further study to determine optimal routes to different soil carbon pools will guide plant trait development for carbon storage.

The breeding pipeline will expand beyond cash crops and include cover-crop improvement. Improved cover crops will have higher productivity and significant N fixation. Breeding attention will enhance cover crops' capacity to suppress weeds, ensure soil integrity, and promote water quality. Intensified breeding of these species creates the potential that they may become cash crops through off-season grain or forage production.

As many of these novel breeding targets do not directly focus on yield, there is a high potential that gains currently directed toward yield improvement will be distributed across new yield and low-emission optimization. Possible trade-offs must be managed in the overall economic, policy, and climate decisions that will affect all sectors.

Low-Concentration Fertilizers and Microbial Amendments. In contrast to centralized facilities that produce concentrated fertilizers, distributed facilities producing low-concentration N fertilizer could operate at a field level. The land requirement to supply enough energy for fertilizer production using solar panels is 1 to 5% (less for wind) of the farmed area (23).

The combination of renewable generation and crop production is called agrivoltaics and is a potential landscape design that maintains productivity and enables broader electrification. Using digital agriculture, low-yielding portions of fields can be used for electricity generation rather than crop production. In this system there will not be competition with other sectors for renewable electricity and agriculture does not need to expand its land footprint. Prototype agrivoltaic systems permit the growth of vegetation underneath solar panels, a mutualistic system that provides benefits to the solar panels and plants growing underneath them (39). These sites could include pollinator or wildlife habitats, although significant development will be required to ensure that an economically optimal solution balances both services.

Novel microbial inputs or microbial biostimulants that encourage a beneficial soil microbiome could replace chemicals and create new options to suppress disease, improve nutrient availability, and boost soil carbon storage. Development in this area requires understanding of the interactions among microbes, between climate and microbes, and methods to stably modulate microbial communities (40).

Smaller Implements/Autonomy. Meeting the biological need of crops with low-concentration fertilizers requires frequent application. Although this is challenging, it can improve efficiency because more-frequent applications reduce the risk of loss due to runoff, leaching, or denitrification. Innovation in equipment that allows frequent N application will manage the fertilizer supply in response to plant demands and weather patterns.

It is critical to have small implements that do not compact soils, and electrification promotes this transition because it is simpler to reduce the size of platforms that use electric motors in place of combustion engines. Digital soil and plant health maps will be updated by real-time field sensing and automated systems will guide these implements based on sensor output.

A new paradigm of many small implements may replace the current trend toward larger equipment (41). Perception algorithms that allow these robots to "see, reason, and act" are required. Implements enabled by computer vision and automated actuation will dramatically improve pesticide and nutrient efficiency by replacing broad application with precision/on-demand spraying. With this equipment, it is possible to advance complex systems like intercropping, where distinct operations are performed in overlapping areas.

While this technology will require multiple cycles of development, an important aspect of the small-implement paradigm is a faster adoption cycle driven by lower costs of any specific piece of equipment. Furthermore, there will be significant acceleration because improvements will come from updates to software rather than hardware, allowing iterative improvements independent of new equipment purchases.

Conclusions

We describe an innovation pipeline to dramatically cut agricultural emissions that can be combined with soil carbon sequestration to achieve net negative emissions in row-crop agriculture. The estimated reductions are based on average values from broad acre practices for corn in the United States (17, 42). While this paper describes a suite of solutions that will work for a farm on average, it is not a roadmap that can be precisely followed for any particular field. Every field is unique and individualized emission reduction plans will be needed that optimize the combination of technologies.

The need for an individualized plan highlights a significant social barrier to adoption of new technology. Producers will need information to adopt new practices, and while many of these technologies represent low-emission "drop-in" inputs (e.g., green ammonia and new seed genetics) others require new management practices. Other technical barriers that may prevent adoption include access to broadband internet and data management platforms and expertise. Technical solutions such as edge computing will address some data management issues, but they highlight the need for additional skillsets to realize the technical potential. Broad adoption of low-emission production will require agricultural extension agents, consultants, and educators to provide local knowledge for deploying novel technologies. Furthermore, any trade-offs, including higher food prices or reduced yields, need to be considered in optimizing for the environmental footprint.

Regional differences in agronomic practice will require additional technical thrusts. Irrigation is an energetic practice that is not included in the default average figures because irrigated acres comprise a minority of US grain production. However, in certain geographies irrigation is a significant factor in farm energy use (43). The associated emissions from pumping water can be addressed through a similar path as fertilizer, first through optimized application and subsequently through conversion to renewable energy.

This technical path facilitates broad adoption by proceeding through gradual steps and has practical advantages for early marketplaces. Compensation for emission reductions already exists in policy frameworks. Rapid, direct-to-farmer payments are needed to build producers' confidence and encourage adoption and investment in low-carbon technologies and practices. In contrast, soil organic carbon is labile, and the challenge of permanence burdens the market and the producer with multiyear obligations that require discounted or delayed payment structures.

Mobilization of this innovation engine will clearly demonstrate the transformative impact of these payments (i.e., additionality).

At full adoption, a 71% reduction in farm emissions leaves an average of 725 kg CO_2e/ha in emissions. This is comfortably within the estimated range of incremental soil carbon sequestration that is achievable for this land-use category (8) and a significant portion of row-crop acres will achieve net negative emissions.

These innovations apply to crop production, and to fully decarbonize agriculture, animal production, which comprises 50% of agricultural emissions, must also be addressed. For animal production systems, grain/feed production is a significant source of total life cycle emissions (44). By sourcing carbon-negative grain, it is possible that the net impact of some of those systems can be carbon-negative. Other emissions, including methane production in ruminants, require an independent technical path to reduction.

Every sector will chart its own path to net negative emissions to address climate change. For agriculture to succeed, policy makers and emission credit buyers need to understand practical matters of markets and technology adoption to engage producers, attract investors, and inspire technology developers. Using a systems approach to technology optimization and fostering an innovation ecosystem that looks at a combination of technologies, agriculture can meet its critical societal function to provide food, feed, fiber, and fuel and support rural economics, all while generating significant environmental benefit for the public good.

Data Availability. All study data are included in the article and/or *SI Appendix*.

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