BREAKTHROUGH INSTITUTE

FROM LAB TO FARM

ASSESSING FEDERAL R&D FUNDING FOR AGRICULTURAL CLIMATE MITIGATION

EXECUTIVE SUMMARY

Agriculture is a substantial source of greenhouse gas (GHG) emissions, accounting for about 10% of the U.S. total. Farmers, ranchers, and other agricultural producers are also directly affected by rising temperatures, more frequent and intense heat waves, drought, and other extreme weather that result in part from increased GHG emissions.

Climate-smart agriculture is a set of approaches that aims to achieve three goals: producing more and better food, increasing agricultural systems' resilience to drought and other climate-related impacts, and reducing net GHG emissions.

Public agricultural research and development (R&D), and the innovation it supports, is key to advancing the goals of climate-smart agriculture. First, R&D drives increases in agricultural productivity and efficiency, thereby reducing land use, use of other inputs, and related GHG emissions. Second, the R&D of more drought-resilient crops, heat-tolerant animal breeds, and resource-efficient farming practices and technologies (e.g., precision irrigation systems) is critical to reducing farmers' vulnerability to extreme weather and climate-related impacts. Third, the development and adoption of farming methods that reduce agriculture's carbon footprint depend on such research and innovation. And even after development, many climate-smart farming practices and technologies, whether well-established or emerging, face barriers to widespread adoption that require further research to overcome.

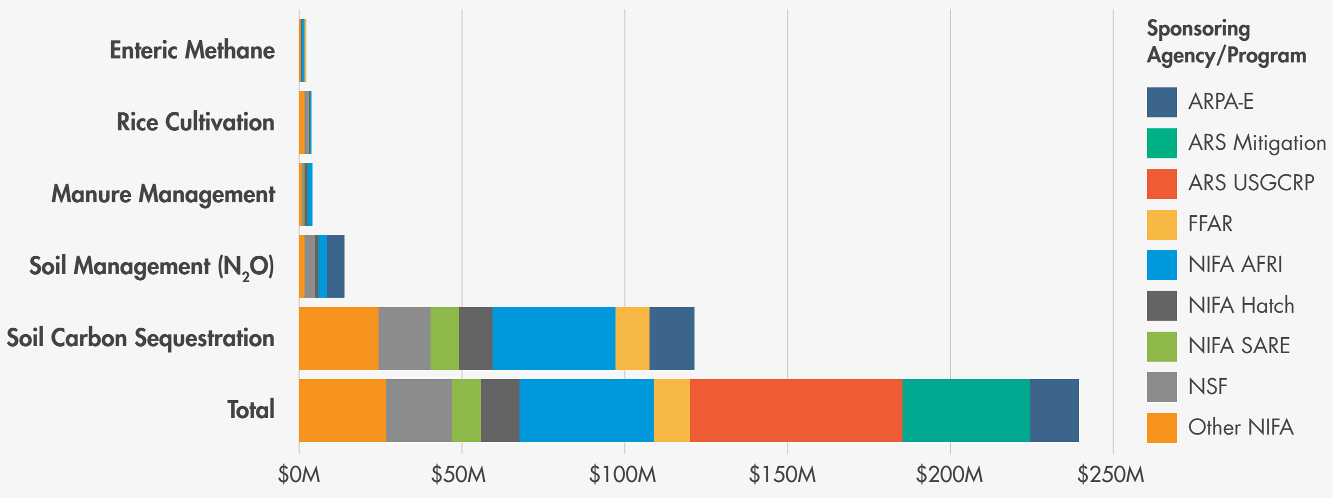
Despite being a critical mission, climate mitigation and adaptation is not a statutory priority of the U.S. Department of Agriculture (USDA), and there is no interagency body that specifically collects and disseminates data on how this mission is being addressed.

This report presents the first detailed and systematic analysis of funding from federal R&D agencies for agricultural climate mitigation. It includes analysis of tens of thousands of projects supported by the primary federal funders of agricultural research, including the USDA's National Institute of Food and Agriculture (NIFA) and Agricultural Research Service (ARS), the Foundation for Food & Agriculture Research (FFAR), the National Science Foundation (NSF), and the Department of Energy's Advanced Research Projects Agency—Energy (ARPA—E). This report presents estimates for all funding from R&D programs administered by the above agencies. This includes funding for basic, applied, and developmental research as well as for education and extension activities that are part of research projects and programs. It excludes funding for programs dedicated to education and extension, such as Smith—Lever Act funding for agricultural extension, as well as conservation programs such as the USDA's Environmental Quality Incentives Program or Conservation Reserve Program.

The federal R&D agencies and programs included in the analysis spent an estimated $241 million per year on agricultural climate mitigation from 2017 to 2021. This amount is roughly 35-fold less than that spent on U.S. clean energy innovation. Therefore, this report underscores the scale of climate mitigation potential represented by agricultural R&D.

Our analysis also reveals how the distribution of R&D funding aligns with the sources of agricultural GHG emissions and the potential to mitigate those emissions, enabling us to identify key funding gaps. While the majority of funding has been directed to projects related to soil carbon sequestration, several notable emissions sources have received relatively little funding (Figure ES-1). For example, projects related to enteric fermentation (part of the digestive process of cattle and other ruminants) received less than 2% of mitigation funding that could be categorized, even though methane from enteric fermentation accounts for over 28% of agricultural emissions.

Figure ES-1: Agricultural R&D Spending on Climate Mitigation (2017–2021 average)

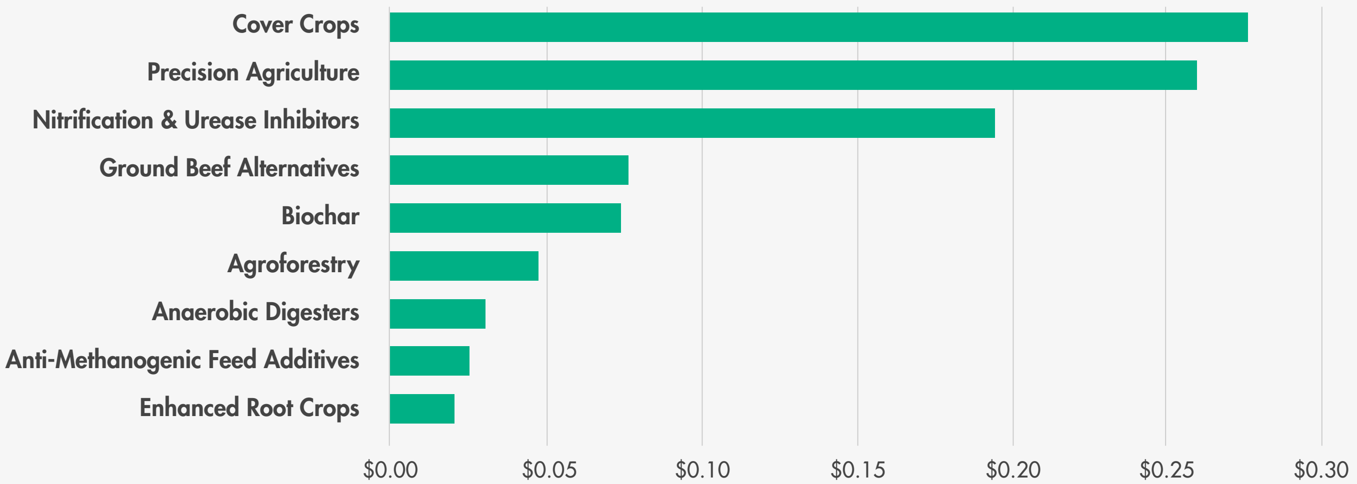


Notes: ARS mitigation and U.S. Global Change Research Program (USGCRP) reflect USDA estimates of enacted funding for FY21. ARS funding by mitigation area is not calculated owing to data limitations. Other funding is calculated based on analysis of project descriptions for 2017–2021. Columns do not sum to equal total because funding for projects can fall under multiple categories.

The USDA provides the majority of federal mitigation-related R&D funding for agriculture through ARS and NIFA. Within ARS, programs such as Soil and Air, Sustainable Agricultural Systems, and the Long-Term Agroecosystem Research (LTAR) Network support important mitigation efforts. Within NIFA, the Agricultural Food and Research Initiative (AFRI) funds the largest share of mitigation-related research, particularly through its Sustainable Agricultural Systems program and Bioenergy, Natural Resources, and Environment priority area. Outside of the USDA, the NSF, ARPA-E, and FFAR provide a significant amount of funding. Several other programs contribute smaller amounts, such as the USDA's Hatch funding for land-grant institutions and Sustainable Agriculture Research and Education (SARE) program.

The R&D programs identified in this report play a crucial role in developing the climate-smart solutions necessary to reduce U.S. GHG emissions while enhancing the resilience of our agricultural systems and rural economies. To maximize their beneficial outcomes, funding for these programs should be bolstered through the Farm Bill, annual appropriations, and other legislation. However, funding should also target the areas where it can have the greatest impact. This analysis finds that while substantial R&D funding is dedicated to projects involving cover crops, a wide range of practices and technologies receive little R&D funding relative to their potential to reduce the carbon footprint of U.S. agriculture (Figure ES-2). These underfunded opportunities include developing and testing methane-inhibiting feed additives (e.g., red seaweed) and drugs for cattle and breeding crops designed to sequester more carbon in the soil.

Figure ES-2: R&D Agency Funding for Mitigation Strategies per Metric Ton of U.S. Mitigation Potential (2017–2021 average)



Notes: Funding for ground-beef alternatives represents all federal alternative protein R&D from the Good Food Institute (GFI) grants tracker. All other funding values are calculated based on keyword analysis of NIFA, SARE, FFAR, and ARPA-E project descriptions from 2017 to 2021. Funding value for agroforestry is the sum of estimates for alley cropping, silvopasture, windbreaks, and riparian buffers.

Sources for mitigation potential: Cover crops: Fargione et al. (2018); precision agriculture: Eagle et al. (2022); nitrification & urease inhibitors: Kanter and Searchinger (2018); ground-beef alternatives: D'Croz et al. 2022; biochar: Fargione et al. (2018); agroforestry: Eagle et al. (2022); anaerobic digesters: Eagle et al. (2022); anti-methanogenic feed additives: Eagle et al. (2022); and enhanced root crops: Paustian et al. (2016). See Appendix Table A5 for details on mitigation funding estimates.

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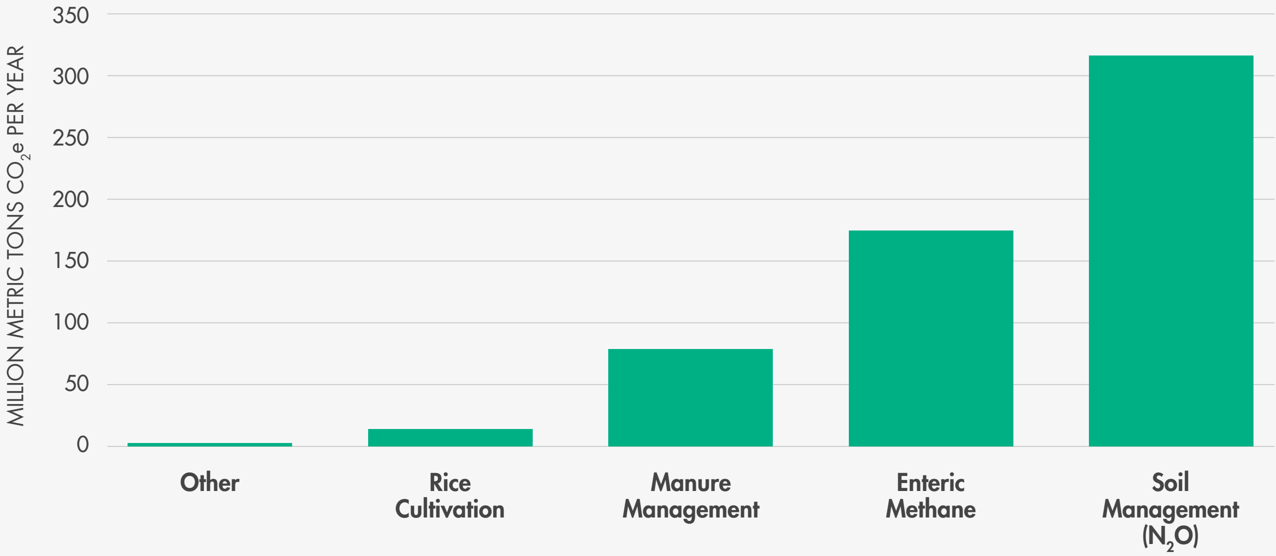
INTRODUCTION

Agriculture is a substantial source of greenhouse gas (GHG) emissions, accounting for approximately 10% of U.S. emissions according to the Environmental Protection Agency (EPA) when considering the global warming impact of gases over a 100-year period.[1,2] A breakdown of the main sources of U.S. agricultural GHG emissions in 2020 is presented in Figure 1. Soil management activities, including fertilizer application, account for over half of agricultural emissions. Application of nitrogen fertilizer and manure, deposition of manure from grazing animals, retention of crop residues, and other activities add mineral nitrogen to the soil, which microbes convert to nitrous oxide (N_2O), a potent GHG. Nearly 30% of emissions in the sector arise from enteric fermentation, the process in which microbes in the digestive tract of cattle and other ruminants decompose food, producing methane as a by-product.[3] Manure management—the storage, treatment, and transportation of livestock manure—also produces methane and N_2O emissions, accounting for about 13% of agricultural emissions. A small share of emissions also arises from other activities such as rice cultivation, field burning, and liming. Several activities related to agriculture are not included in the EPA's estimates of agriculture's carbon footprint, but also generate emissions. Although croplands and grasslands can sequester carbon in the soil, converting land to cropland and grassland generated 54 and 18 million metric tons (MMT) carbon dioxide-equivalent (CO_2e) in 2020, respectively, the equivalent of 12% of the EPA's estimate of total agricultural emissions. The production of ammonia, a key component of fertilizer, generated 12.7 MMT CO_2e, equivalent to 2% of agricultural emissions.

Figure 1: U.S. Agricultural GHG Emissions in 2020



Source: US EPA, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020," Figure 2-9.

Globally, farming, ranching, aquaculture, and other types of agricultural production, excluding emissions related to the supply chain or land use, account for roughly 15% of emissions.[4] Agriculture accounts for a larger share of emissions globally than in the United States, partially because global agricultural production is typically more GHG-intensive than in the U.S.[5] and because agriculture accounts for a greater share of economic activity in other countries than in the U.S.[6] Further, expansion of cropland and pasture contributes to global land-use change, accounting for at least three-quarters of deforestation.[7] Overall, including land use and land-use change as well as the supply chain and post-retail waste, food systems contribute as much as 34% of the world's emissions.[8]

Emissions of carbon dioxide, methane, nitrous oxide, and other GHGs block heat from escaping the Earth, contributing to changes in the climate such as warming temperatures, shifting precipitation patterns, and more frequent and intense drought, flood, and extreme weather. Since the late 1970s, the average surface temperature across the contiguous United States has risen by 0.32°F to 0.55°F per decade, warming a total of 2.6°F since 1970.[9,10] Nine of the top 10 warmest years have occurred since 1998.[11] While warming may benefit some crops and farmers, elevated growing-season temperatures are projected to reduce yields of major commodity crops and lead to substantial loss of livestock productivity.[12] Warming temperatures and heat waves, which are growing more frequent and intense,[13] have caused billions of dollars of crop losses across the United States.[14] Changing weather patterns influence precipitation, increasing rainfall in some areas while contributing to intensive and widespread droughts, such as in the Southwest, which directly impact crop production.[15] Evidence also shows that agricultural pests and diseases are increasing in some regions as they warm.[16]

Innovation is key to climate adaptation—reducing farmers' vulnerability to extreme weather, rising temperatures, and other impacts of climate change—as well as to climate mitigation, which includes reducing GHG emissions and removing carbon dioxide from the atmosphere. One of the most important mitigation and adaptation strategies is increasing farm yields, whether through crop and livestock breeding, more-efficient use of inputs, or other means. Expanding yields enables farmers to produce more with less land, resources, and emissions. For instance, efficiency improvements enabled the carbon footprint of a pound of beef, chicken, and milk to fall 34%, 51%, and 68%, respectively, since 1961.[17] A 2018 World Resources Institute report estimated that increasing global crop and livestock yields at the same rate they have historically risen would avoid more land-use change and GHG emissions by 2050 than all other plausible food system changes combined.[18] Federal and other government R&D, by funding fundamental research and other efforts the private sector lacks the incentive to support, enabled much of the historic growth in yields and will be needed to continue increasing yields.[19]

There is a wide variety of other mitigation and adaptation strategies. Many are somewhat established but face barriers to widespread adoption. These barriers may be at least partly addressed by research and innovation as well as incentives and farmer outreach. Such farming practices and technologies include, but are not limited to:

- **Cover crops:** Planting crops such as barley, alfalfa, or clover on cropland that would otherwise lay fallow can reduce soil erosion, increase soil carbon levels, reduce the impact of flooding and drought on crops,[20] and add nitrogen to the soil, reducing the need for fertilizer. Adding cover crops to the roughly 88 million hectares of primary cropland that do not already incorporate them would sequester about 103 MMT CO_2e/year.[21] However, the carbon sequestration is reversible, and adoption of cover crops on all remaining cropland is unlikely, especially in the near term. Although planting cover crops can be profitable, farmers have been slow to do so in part because of high up-front costs, low access to information about site-specific impacts, and challenges with incorporating them into current cropping systems.[22]

- **Precision agriculture:** Farm equipment such as soil nitrogen sensors, yield maps, and machinery that can vary fertilizer application rates across a farm based on nutrient levels can reduce overall fertilizer application rates, reduce nitrogen losses per unit of fertilizer applied, and increase yields.[23] Widespread adoption of such precision agriculture technology and other nitrogen management practices could reduce emissions by approximately 27 MMT CO_2e/year by 2030.[24] Although adoption of variable-rate fertilizer application equipment remains low, additional research and farmer outreach on its costs and benefits as well as development of lower-cost, improved equipment could spur greater usage.

- **Cattle feed optimization and productivity-enhancing technologies:** The amount of feed needed to produce one pound of beef or one gallon of milk has fallen over time, in part because of breeding and efforts to optimize cattle feed rations. However, further improvements in feed efficiency are possible. A 10% increase in feed efficiency during the feedlot stage of beef production could reduce beef's life-cycle carbon footprint by 1%–2%.[25] Likewise, combining existing technologies that increase cattle productivity, such as implants and ionophores, could reduce emissions by up to 7% according to one study.[26] If such changes occurred throughout the U.S. beef production system with the same level of mitigation, increased feed efficiency would reduce emissions approximately 2–4 MMT CO_2e/year, and productivity-enhancing technologies would reduce emissions approximately 15 MMT CO_2e/year. [27]

- **Enhanced-efficiency fertilizers:** Enhanced-efficiency fertilizers (EEFs) include slow- and controlled-release fertilizers and those containing nitrification or urease inhibitors. The latter reduce conversion of fertilizer nitrogen to forms that are easily lost to the environment. Nitrification inhibitors can reduce on-farm N_2O emissions by nearly 27% on average, according to recent modeling.[28] With adoption rates currently low, the technical mitigation potential of EEFs is likely large. However, little mitigation is currently possible at a low cost.[29] Thus, further research is needed to reduce costs, understand the environmental conditions that enhance or reduce EEFs' effectiveness, and identify and mitigate potential ecological impacts such as on aquatic ecosystems.[30]

Emerging, early-stage technologies also hold great mitigation and adaptation potential but will require substantial R&D and commercialization before they can be widely adopted. These include:

- **Meat alternatives:** Plant-based and cultivated (also referred to as cultured, cell-based, or lab-grown) meat generally has a smaller carbon and land footprint than animal-based meat, particularly compared with beef.[31] Survey research indicates that if the prices of beef alternatives fell to the same levels as conventional ground beef, then about 20%–30% of consumers would opt for them.[32,33] Recent modeling estimates that if meat alternatives achieved 30% or 60% of the U.S. beef market share (as some sources project is possible by 2040), emissions could fall by approximately 20 or 40 MMT CO_2e, respectively, compared with a 2018 baseline.[34] Despite this potential, current prices for meat substitutes are substantially higher, consumers prefer the taste of beef, and high-quality alternatives to many meat products do not exist.[35,36] Further research is needed to address these challenges and may include efforts to develop better ingredient processing and manufacturing equipment.[37]

- **Enhanced root crops:** Greater root depth, size, and distribution increase crops' soil carbon sequestration potential. Scientists are researching the genetic traits that control these root characteristics with the goal of breeding crops with enhanced roots. The development and widespread adoption of crops with enhanced roots could potentially sequester as much as 746 MMT CO_2/year in U.S. soils. However, this estimate is highly speculative and optimistic, assuming a doubling of root carbon inputs and an extreme downward shift in annual crops' root distribution.[38] The ARPA-E ROOTS (Rhizosphere Observations Optimizing Terrestrial Sequestration) program has provided a total of $35 million to 10 multiyear projects related to enhancing crop roots. These include a project at Penn State University that discovered a previously unknown trait in corn that increases root biomass and depth.[39,40] However, research remains at an early stage. A 2019 National Academies of Sciences, Engineering and Medicine report estimated that enhanced root crop research would require $40–$50 million in annual funding for a period of 20 years.[41]

- **Feed additives, vaccines, drugs, and genetics:** A suite of agricultural innovations is emerging with the potential to reduce enteric methane emissions. For example, vaccines could be developed to target the microorganisms responsible for enteric fermentation, and cattle could be selectively bred to have lower emissions. Both of these innovations are in early stages and require substantial research to be developed, tested, and widely adopted. One of the more developed approaches consists of giving cattle feed additives that are shown to reduce methane emissions. Testing, regulatory approval, and adoption by all producers of the most widely researched additive, 3-nitrooxypropanol (3-NOP), could reduce enteric methane emissions from dairy and beef production by as much as 20% (34 MMT CO_2e/year) below 2018 levels.[42] Further development and adoption of additives in earlier stages of research, such as red seaweed, could potentially reduce emissions even more—by as much as 57 MMT CO_2e/year from beef production—if effective formulations were developed that could be administered to grazing cattle.[43] However, these additives require long-term feeding trials and safety assessments to meet U.S. Food and Drug Administration (FDA) requirements. Farm-based trials can cost over $1 million, depending on the number of animals needed for testing.[44] Research is also needed on how to produce additives, such as red seaweed, with minimal ecological and environmental impact. Further study is also essential to learn how to better deliver additives to cattle while they are grazing, which is when the majority of emissions are produced.

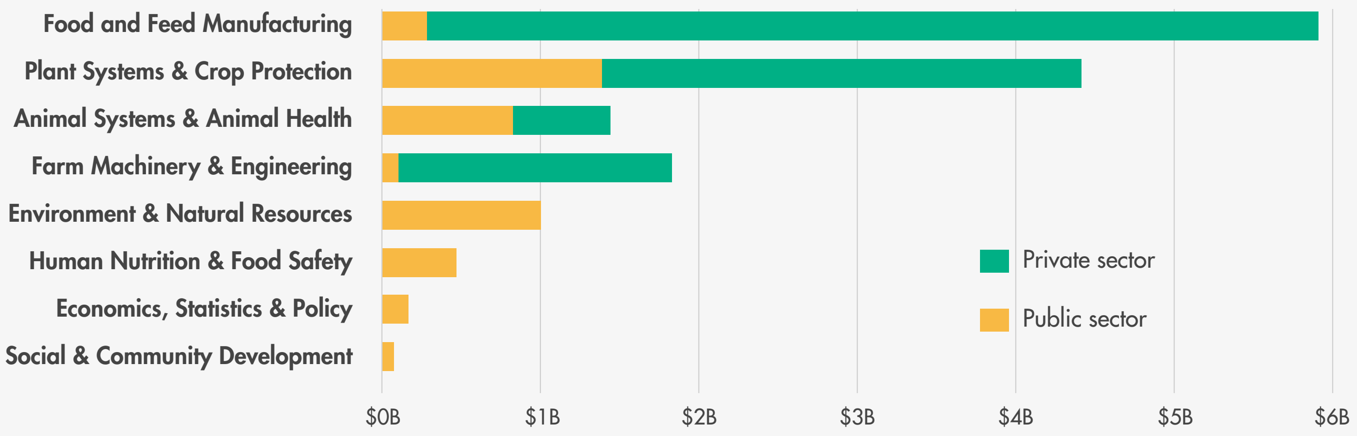
- **Biochar:** Converting crop residue and other waste biomass into a form of charcoal designed to be incorporated into soils, referred to as "biochar," and applying it to agricultural soils can sequester carbon and increase crop yields in some environments.[45] If all dry biomass from crop residues that aren't already harvested (e.g., for forage) were used for biochar and applied to farmland, it could sequester as much as 95 MMT CO_2/year.[46] However, a high level of scientific uncertainty exists as to biochar's net mitigation potential. The science must account for emissions from transporting and processing biomass, biochar's potential impact on emissions of nitrous oxide and methane from the soil, and other factors. More research is needed to understand its life-cycle environmental impacts as well as to identify conditions in which biochar can best increase yields. The National Academies of Sciences has estimated that $3 million per year in research funding would be needed for 5–10 years to address these barriers.[47]

Several established and emerging practices are also often claimed to have great mitigation potential, but scientists generally acknowledge they have limited potential or require additional research before their climate impact can be well understood. For instance, shifting from conventional tillage to no-till or reduced-till farming is often claimed to sequester carbon. But recent research indicates that, although no-till farming increases carbon levels at the soil surface by reducing soil disturbance, it reduces levels deeper in the soil profile, resulting in little to no net sequestration.[48,49] These recent assessments rely on more accurate soil collection methods that account for sample depth and soil mass among other factors. Likewise, although a variety of grazing practices and regimes, often referred to as "regenerative," has been observed to increase soil carbon in specific locations, great scientific uncertainty remains about the national-scale mitigation potential of these methods.[50] These examples illustrate the need to better measure, model, report, and verify the mitigation impact of many agricultural practices.

In short, increasing crop and livestock productivity, reducing the carbon footprint of production, and adapting to the threats climate change poses are critical and interlinked priorities for U.S. agriculture. Efforts to address these three goals are often referred to as "climate-smart agriculture."[51]

Public R&D is central to climate-smart agricultural innovation. Public R&D funds the basic and applied research underpinning many productivity-enhancing innovations that the private sector further develops and commercializes. Public R&D also generates and preserves open-access data that benefit all researchers. In addition, public R&D supports far more research focused on environmental stewardship and outcomes than does private R&D, as Figure 2 illustrates.

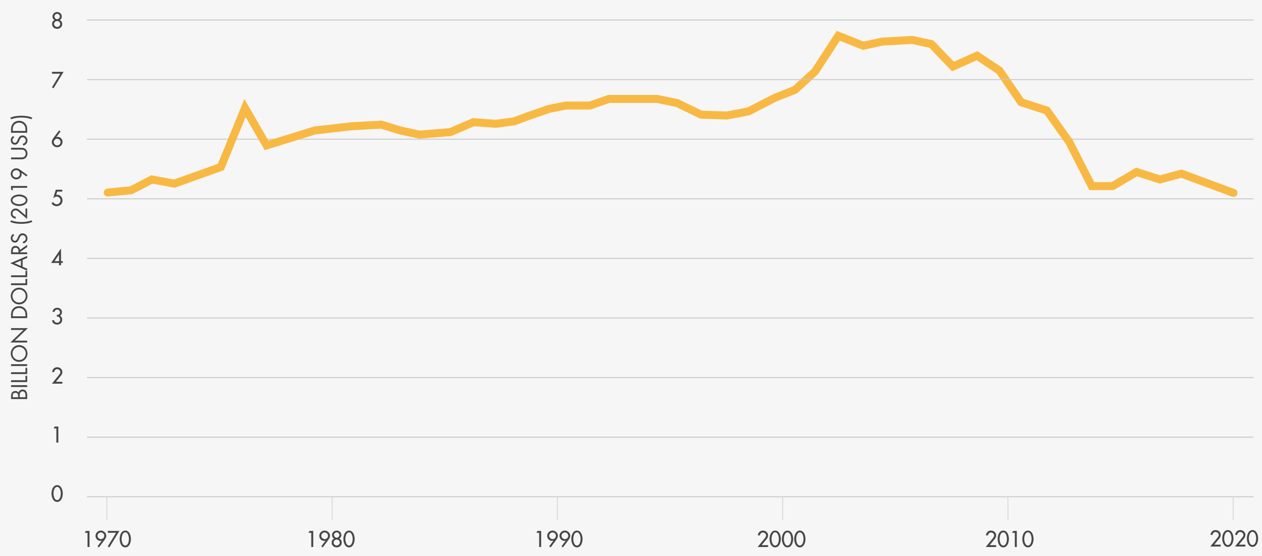
Figure 2: Public Agricultural R&D Efforts Focus More on the Environment than Private R&D Efforts Do



Source: Matthew Clancy, Keith Fuglie, and Paul Heisey, "U.S. Agricultural R&D in an Era of Falling Public Funding," USDA ERS, https://ers.usda.gov/amber-waves/2016/november/us-agricultural-r-d-in-an-era-of-falling-public-funding/.

Despite its many potential benefits, overall federal R&D funding has decreased over the past decades, as Figure 3 shows. From its peak in 2002 at $7.64 billion, U.S. public spending on agricultural R&D (adjusted for inflation) fell by about one-third to $5.16 billion in 2019 (the last year for which complete statistics are available), similar to the level of spending last seen in the 1970s.

Figure 3: Public Spending on Agricultural R&D Has Fallen by One-Third Since 2002



Notes: Spending on public agriculture R&D includes federal, state, and nongovernment funds used for food, agriculture, and forestry research by the USDA, land-grant universities, and other cooperating institutions. Spending is in 2019 dollars adjusted for inflation using the National Institutes of Health Biomedical Research and Development Price Index. The spike in R&D spending in 1976 was the result of an adjustment in the federal fiscal year, in which 1979 included five quarters of spending.

Source: Nelson and Fuglie, "Investment in U.S. Public Agricultural Research and Development."

This report focuses on addressing another challenge to sufficiently funding climate-smart agricultural R&D: the lack of public data on how much federal R&D funding is going toward different areas of climate-smart agriculture. The U.S. Department of Agriculture (USDA) has, on occasion, provided estimates of total funding for climate mitigation and adaptation, but these data are not required by law and have not, in the past, included funding for specific research areas within these broad categories. This omission is not unique to the USDA; other federal agencies also fund agriculture-related research, though it is rarely reported as helping advance climate-smart agriculture. This lack of data transparency prevents policymakers and other stakeholders from evaluating previous and current research directions as well as identifying which areas require more research funding and which are well covered.

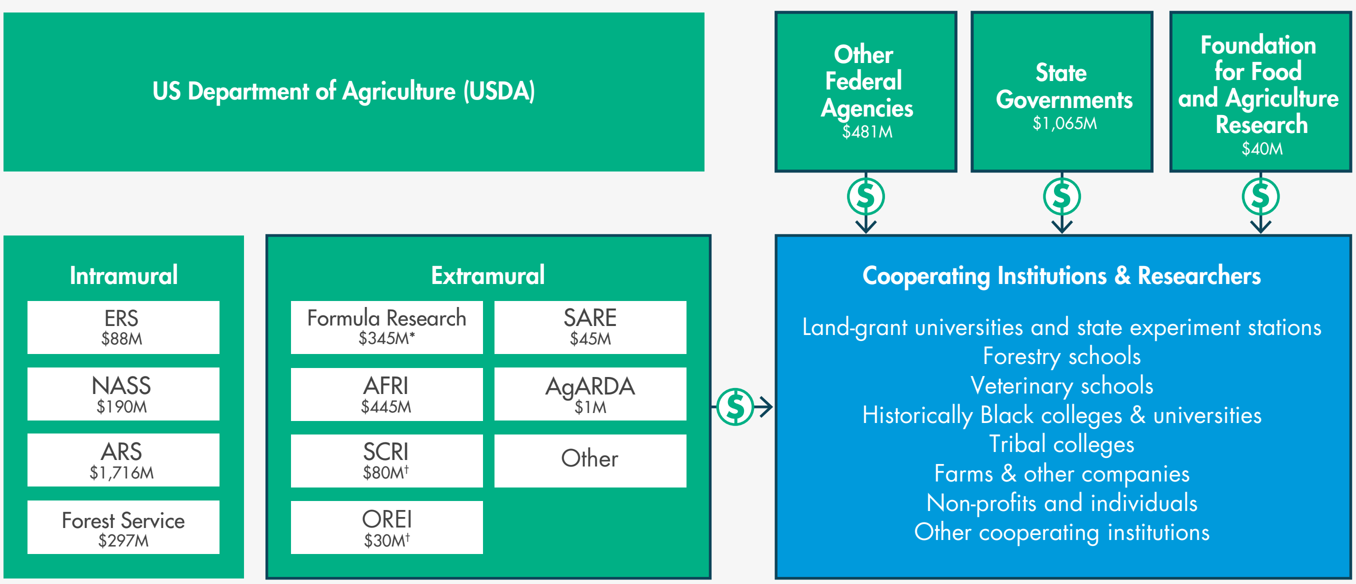
This report presents the first detailed and systematic analysis of funding from federal R&D agencies for climate-smart agriculture, with an emphasis on climate mitigation. The next section, "Federal Agricultural R&D Programs," describes the current structure of federal agricultural R&D funding, agencies, and programs. Section 3, "Aggregate R&D Funding for Climate-Smart Agriculture," presents estimates of aggregate funding from R&D agencies for climate mitigation, adaptation, and productivity growth. Section 4, "Detailed R&D Funding for Climate Mitigation," presents more-detailed estimates of R&D agency funding for climate mitigation and specific emissions sources and sinks. Section 5, "Comparing R&D funding for Practices with Their Mitigation Potential," presents funding estimates for select mitigation practices and technologies and compares their funding levels to their mitigation potential. The final section, "Policy Implications," discusses options for Congress and agencies to better support climate-smart agricultural R&D, including the Farm Bill and the annual appropriations process.

FEDERAL AGRICULTURAL R&D PROGRAMS

The federal government is the largest funder of U.S. public agricultural research, as illustrated in Figure 4. In 2019, the federal government funded 64%, or $3.24 billion, of the total $5.04 billion allocated to agricultural R&D. State governments are the next largest funder, providing $1.06 billion, followed by nongovernment sources at $741 million.[52]

In 2019, the USDA accounted for 85% of federal agricultural R&D funding. Within the USDA, funds were equally distributed between intramural and extramural research.[53] Intramural research is performed at USDA agencies such as the Agricultural Research Service (ARS), while extramural research consists of research grants to universities, nonprofits, companies, and other institutions. Other agencies, such as the National Science Foundation (NSF) and the National Institutes of Health (NIH), provided the remaining 15% of federal funding for agricultural R&D. These agencies fund agriculture primarily through grants to university colleges and schools of agriculture, forestry, and veterinary medicine.

Figure 4: Structure of U.S. Public Agricultural R&D



Notes: USDA values represent agency/program funding in the Consolidated Appropriations Act, 2022. Values for other federal agencies and state governments represent funding for agricultural research in 2019 according to Nelson and Fuglie (2022). Foundation for Food & Agriculture Research value represents federal funding for the program in 2019, according to their 2019 Impact Report. Owing to the use of different data sources for USDA funding, the sum of all figures does not equal the $5.04 billion total reported in the text. Intramural funding supports research conducted by federal personnel. Extramural funding supports activities conducted by nonfederal personnel.

*Hatch, Evans–Allen, 1994 Research. †Mandatory funding.

USDA Intramural Research

The USDA conducts intramural research mainly through two agencies: the ARS and the R&D arm of the US Forest Service. Other agencies the USDA funds include the Economic Research Service (ERS) and the National Agricultural Statistics Service (NASS).[54]

The ARS is the USDA's chief scientific in-house research agency and is one of the four agencies in the USDA's Research, Education, and Economics Mission Area. ARS research focuses on providing scientific tools and innovative solutions for American farmers, producers, industry, and communities. The research aims to sustain America's agro-ecosystems and natural resources as well as ensure agricultural economic competitiveness and excellence. The ARS has a roughly $1.6 billion FY22 budget for staff and research expenses, and a $128 million budget for facility maintenance and construction.[55] It employs roughly 2,000 scientists and postdocs, along with 6,000 other employees, who work on 660 research projects within 15 National Programs.[56]

The R&D arm of the US Forest Service informs management actions taken by the Forest Service, States, Tribes, and other land managers to sustain the health, diversity, and productivity of forests and grasslands. The Forest Service's R&D division also produces a number of products, such as datasets, tools, web-based content, and digital media to make the science available and accessible to natural resource managers, policymakers, and the public.[57]

The USDA's ERS conducts high-quality and objective economic research on trends and emerging issues in agriculture, food, the environment, and rural America. This information is used by public and private sector decision makers to ensure efficient stewardship of agricultural resources and economic prosperity of the agricultural sector. Closely watched products from the ERS include annual 10-year projections for the farm sector, estimates of U.S. agricultural productivity, and state fact sheets.[58]

The USDA's NASS provides accurate, timely, and comparable statistics covering virtually all aspects of U.S. agriculture, down to the local level. This is achieved by conducting hundreds of surveys every year and preparing reports. For instance, the NASS conducts the Census of Agriculture every five years, which provides detailed agricultural data for every county in America.[59]

USDA Extramural Research

The USDA extramural research funds are administered mostly by the USDA's National Institute of Food and Agriculture (NIFA). In 2019, NIFA allocated around $1.1 billion for research: 26% through "capacity grants," 38% through competitive grants, and 36% through directed special grant programs.[60]

NIFA distributes capacity grants to state and territorial institutions on a formula basis and requires state institutions to match the federal grant. Examples of capacity grants include Hatch funds (for state agricultural experiment stations at land-grant universities), Evans–Allen funds (for colleges of agriculture at historically Black colleges and universities), and Animal Health and Disease Research Capacity Program funds.[61] Hatch funding was established by the Hatch Act of 1887, to conduct agricultural research programs that establish and maintain a permanent and effective agricultural industry in the United States. Funding is provided to State Agricultural Experiment Stations (SAES), departments established by colleges and universities (primarily land-grant institutions) across the 50 states, the District of Columbia, and the insular areas (e.g., Puerto Rico and the US Virgin Islands). Hatch activities include research on all aspects of agriculture, such as sustainable agriculture, aquaculture, nutrition, and safety.[62] At least 25% of Hatch funding is reserved for projects in which an SAES collaborates with another SAES, ARS, or college or university to solve problems concerning more than one state. Hatch funding in FY22 totaled $260 million.[63]

Evans–Allen capacity grants support agricultural research at the 1890 land-grant institutions that conduct agricultural research activities. Recipients also need to provide a 100% match from non-federal sources. 1890 land-grant institutions are historically Black land-grant universities established under the Second Morrill Act of 1890.[64] The program had a $80 million budget in FY22.[65] NIFA also funds smaller R&D programs on a formula basis, such as the $4 million Animal Health and Disease Capacity Program and the $36 million McIntire–Stennis Capacity Grant Program, which supports forestry research and operates a variety of extension programs, which had a $551 FY22 budget.[66]

NIFA also administers competitive grants, largely through the Agriculture and Food Research Initiative (AFRI). In FY22, NIFA allocated $445 million to competitive grants through AFRI. AFRI was established in the 2008 Farm Bill as the largest federal program providing competitive grants for research, extension, and education related to food and agriculture sciences. The largest share of funding is administered through the Foundational and Applied Science (AFRI-FAS) program (Table 1), which provides funding to a wide range of institutions including universities and colleges, for-profit businesses, and nonprofits such as the Two Blades Foundation in Illinois and the Stroud Water Research Center in Pennsylvania.[67] The goal of the program is broad: "to invest in agricultural production research, education, and extension projects for more sustainable, productive, and economically viable plant and animal production systems."[68] As such, it funds projects in six priority areas: (1) Plant health and production and plant products; (2) Animal health and production and animal products; (3) Food safety, nutrition, and health; (4) Bioenergy, natural resources, and environment; (5) Agriculture systems and technology; and (6) Agriculture economics and rural communities.[69]

Grants have funded a variety of research efforts that advance climate mitigation and improve farmers' global competitiveness, including projects on precision farming, soil health, and designing incentives to promote resource conservation and sustainability. The AFRI Sustainable Agricultural Systems (AFRI-SAS) program provides competitive grants to long-term projects that aim to minimize environmental impacts, adapt to climate change, improve rural prosperity, and enhance the quality of life of those involved in food and agriculture value chains. Between 2018 (when NIFA first announced the program) and 2021, NIFA has allocated about $87 million to the program annually and can fund about 15% of project applications.[70,71,72] The program seeks to fund visionary, transdisciplinary projects—integrating multiple disciplines like genomics and artificial intelligence—that take a systems approach to solving challenges. The program also has a strong focus on climate-smart agriculture; its 2022 request for applications listed "Climate-Smart Agriculture and Forestry" as one of three goals that projects must address. Unlike the AFRI-FAS program, funding is limited mainly to colleges and universities.[73]

AFRI's Education and Workforce Development program focuses on cultivating the next generation of research, education, and extension professionals in the food and agricultural sciences. As such, it funds primarily professional development opportunities for educational professionals, workforce training, fellowships for pre- and postdoctoral researchers, and other efforts that prioritize education and extension beyond AFRI's other programs.

Table 1: AFRI Funding Allocations ($ millions)

AFRI Program Area	2017	2018	2019	2020	2021	2022
Sustainable Agricultural Systems	—	86	98	87	78	80
Foundational and Applied Science	210	231	273	280	299	300
Education and Workforce Development	21	27	43	58	58	68
Other (e.g., Sustainable Bioenergy Challenge Area)	144	57	—	—	—	—
Total	375	400	415	425	435	445

Notes: Enacted funding for each fiscal year. Estimated funding for 2022. Values may not sum to total due to rounding and the use of different sources for program funding and total funding for 2022. Most recent values are used when values differ between explanatory notes.

Sources of data: USDA NIFA, "2023 USDA Budget Explanatory Notes – National Institute of Food and Agriculture" and USDA NIFA, "Request for Applications: Agriculture and Food Research Initiative," for estimated FY22 program funding.

NIFA also administers more than 40 non-AFRI competitive grant programs.[74] Of these, the programs with the most funding dedicated to climate mitigation (see next section for details) include the Sustainable Agriculture Research and Education (SARE) program, Organic Agriculture Research and Extension Initiative (OREI), and Specialty Crop Research Initiative (SCRI).

SARE provides competitive grants for farmer-driven research that advances sustainable agriculture and conducts extension/outreach programs and education to increase the adoption of sustainable farming practices. SARE was authorized by Congress in 1990 for no less than $60 million per year, though annual appropriations have never reached this level. In FY22, Congress provided $45 million in appropriations.[75] Between 1988 and 2017, SARE granted over $251 million: nearly $77 million to projects addressing soil health, about $41 million to projects addressing grazing, and $45 million to projects addressing issues related to water. About two-thirds of total funding was directed to research and education, with the remainder going to farmer/rancher, professional development, graduate student, and other projects.[76]

OREI provides competitive grants that support the research, education, and extension activities specific to organically grown and processed commodities. OREI was established in 2002 and secured permanent mandatory funding through the 2018 Farm Bill. FY22 funding is $30 million, with the total permanent baseline funding for FY23 set to increase to $50 million.[77] NIFA estimates that 26% of OREI applications are funded.[78]

SCRI provides grants to support research and extension projects addressing key challenges in the specialty crop industry. A specialty crop is defined in the Farm Bill as "fruits and vegetables, tree nuts, dried fruits, horticulture, and nursery crops (including floriculture)."[79] SCRI was authorized by the 2008 Farm Bill, and its FY22 funding levels are roughly $80 million.[80] NIFA estimates that 20% of applications are funded.[81]

Non-USDA Agricultural R&D Funding

Other federal agencies funded about 15% of federal agricultural R&D, $481 million in 2019.[82] These agencies include the Foundation for Food & Agriculture Research (FFAR), NSF, and the Department of Energy's Advanced Research Projects Agency—Energy (ARPA-E), among others.

The FFAR is an independent nonprofit research corporation, established by the 2014 Farm Bill, that partners with the private sector in order to address critical agricultural research gaps. The FFAR develops collaborative research efforts that match federal funding at least one-for-one with nonfederal support, such as from industry, foundations, and academic institutions. To date, the FFAR has secured $1.40 in nonfederal funding for every dollar of federal funding. The FFAR's priorities include soil health, sustainable water management, next-generation crops, advanced animal systems, urban food systems, and the health–agriculture nexus. Congress provided the agency with a total of $200 million in mandatory funding in the 2014 Farm Bill and $185 million in the 2018 Farm Bill.[83]

The NSF is an independent federal agency created in 1950 that relies on Congress's annual budgeting and appropriations process for program funding each year. In FY2021, the NSF received $8.5 billion, 94% of which goes toward research and education activities.[84] The NSF supports agricultural research across a number of branches, such as the Directorate for Biological Sciences (BIO), the Directorate for Geosciences (GEO), and the Office of Integrative Activities (OIA). For example, NSF BIO allocated approximately $818 million in funding in FY21 for research that advances the understanding of living systems, some of which was related to agricultural systems.[85]

ARPA-E was established within the U.S. Department of Energy to support the development of long-term, high-risk energy technologies to maintain U.S. advantages in science and technology. In 2007, ARPA-E was created through the America COMPETES Act, and in 2009, received $400 million in appropriations. Since then, ARPA-E has supported more than 400 energy technology research projects.[86] ARPA-E houses programs that specifically fund agricultural R&D, such as ROOTS and SMARTFARM (Systems for Monitoring and Analytics for Renewable Transportation Fuels from Agricultural Resources and Management). In FY17, ROOTS announced $35 million in funding for projects that aim to produce crops that increase soil carbon accumulation, reduce nitrous oxide emissions, and improve agricultural productivity, such as by developing deeper roots.[87] In FY20, SMARTFARM announced $16.5 million in funding for projects that reliably, accurately, and cost-effectively quantify biofuel feedstock production life-cycle emissions at the field level.[88] These projects could ultimately develop measurement and precision agriculture technologies that could be used for a variety of crops and operations.

In addition to the FFAR, NSF, and ARPA-E, other agencies that provide funding for food and agriculture research include the EPA, U.S. Agency for International Development (USAID), and Department of Defense (DOD).

The EPA funds various agricultural research initiatives to manage environmental pollutants and inform the public to protect the environment and human health. For example, in 2021, the EPA provided $11 million in funding for 11 "Farmer to Farmer" projects to improve water quality and environmental education.[89] In 2020, the agency awarded around $5 million for new research to understand and manage the impacts of per- and polyfluoroalkyl substances (PFAS) on water quality and availability in rural communities and agricultural operations across the United States.[90]

USAID, through its "Feed the Future Innovation Labs" program, funds agricultural research led by top U.S. universities in partnership with institutions in developing countries. The 21 innovation labs, each specializing in an area such as animal health or legume systems, aim to develop and scale up science-based solutions to reduce global hunger, poverty, and undernutrition. USAID historically has also been the primary funder for CGIAR (formerly the Consultative Group for International Agricultural Research), a global network of agricultural research institutions. USAID has donated an average of $122 million annually to CGIAR over the past 10 years, although this funding has fallen by about 60% since 2016, to $89 million in 2021.[91]

The DOD funds agriculture and food R&D programs that support the prevention, surveillance, and detection of biological threats. For instance, the DOD gave about $3 million to support the Food, Agriculture and Veterinary Defense (FAV-D) project. This will strengthen the defense of U.S. agricultural infrastructure by ensuring that the USDA and other first responders have countermeasures to respond to foreign animal disease outbreaks.[92]

Although federal R&D agencies and programs generally do not focus exclusively on climate-smart agriculture, many of them fund substantial amounts of relevant research, as the next three sections detail.

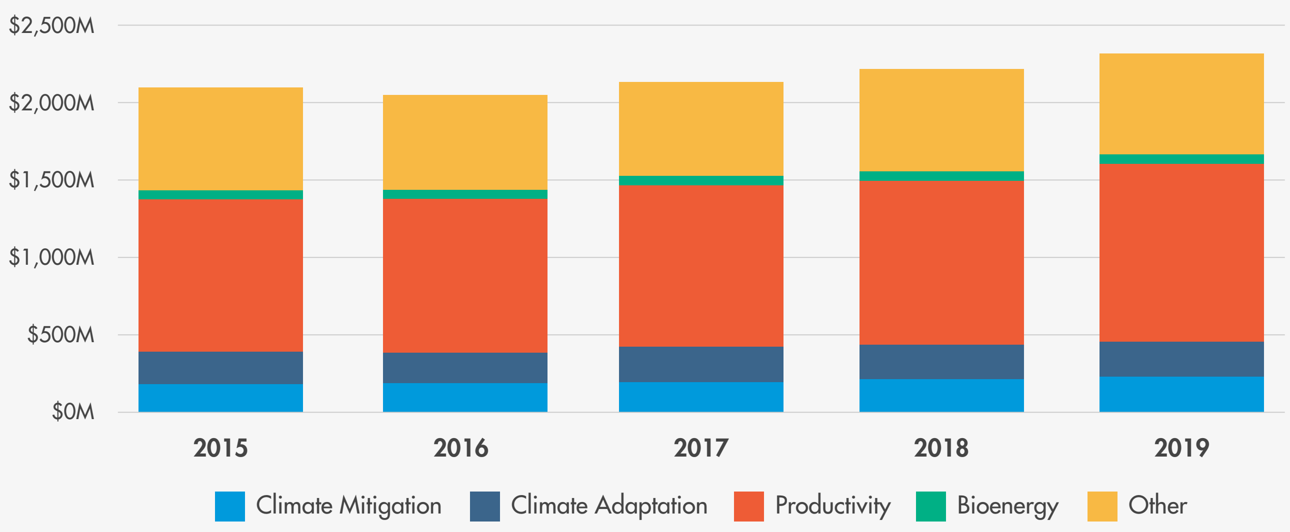
AGGREGATE R&D FUNDING FOR CLIMATE-SMART AGRICULTURE

To estimate aggregate levels of support from USDA R&D agencies for climate-smart agriculture, we mapped the 61 "knowledge areas" for which NIFA and ARS report spending totals into five categories related to climate-smart agriculture: productivity, mitigation, adaptation, bioenergy,[93] and other (see Appendix A for details). Even though this approach omits funding from the USDA's ERS and NASS, these agencies comprise only 9% of total USDA R&D spending; further, the USDA estimates they had only about $6 million in climate-related funding in FY21.[94,95]

Productivity Receives the Largest Share of USDA Climate-Smart R&D Funding

The largest share of NIFA and ARS spending focuses on R&D to increase production and productivity, generally through improving crop and livestock yields and reducing losses to pests, disease, and other threats (Figure 5). For instance, NIFA proposed directing 48% of AFRI's budget in FY21 to its plant and animal health and production priority areas.[96] Likewise, ARS's crop and livestock production and protection program areas had a budget of $776 million—56% of total research program funding.[97]

Figure 5: Greatest Share of USDA ARS and NIFA Funding Related to Productivity Growth



Note: Values shown are ARS and NIFA expenditures, categorized based on knowledge areas that ARS and NIFA report. Values include all ARS and NIFA expenses, including for R&D, extension, education, and administration. See Appendix A for the crosswalk showing how knowledge areas were categorized.

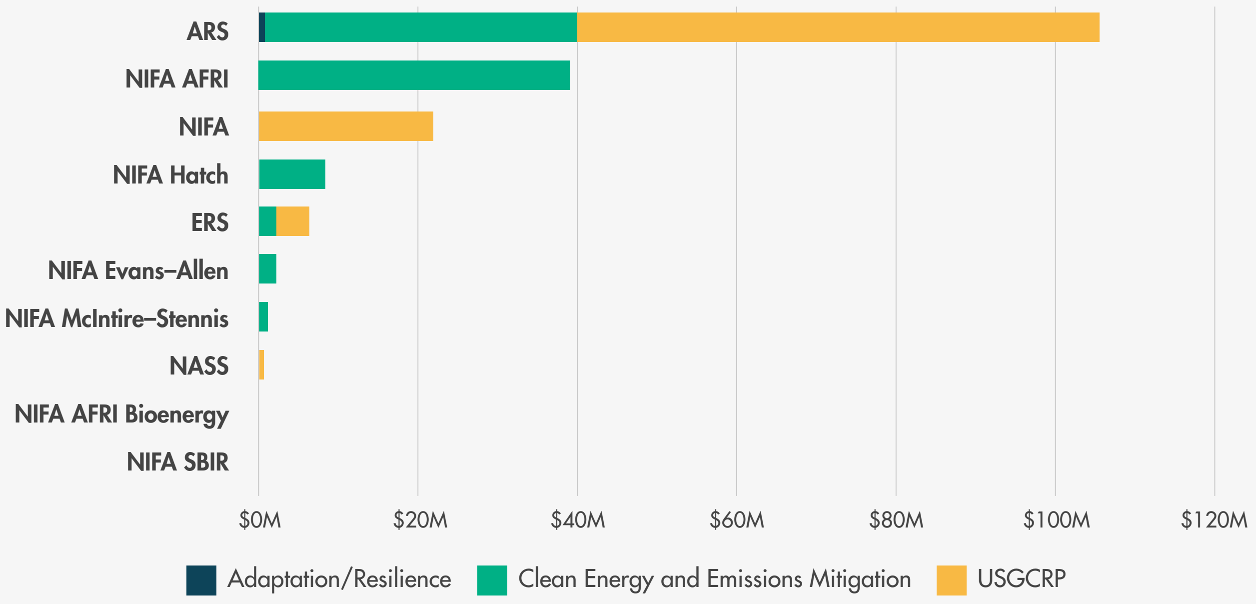
R&D that increases yields and other forms of productivity is key to both climate mitigation and adaptation. Simply put, improvements in total factor productivity—defined as an increase in output relative to all inputs used—can enable farmers to produce more with less land, resources, and emissions. Innovations and research that help farmers maintain or increase yields under current or future conditions (e.g., under water stress or high temperatures) also inherently contribute to climate adaptation. For instance, early-stage research efforts led by the University of Illinois to develop crops with more-efficient photosynthesis could enable farmers to increase yields even under adverse or less predictable weather and climate conditions.[98]

Estimated Climate-Related Funding Is Larger than the USDA Reports

Within the USDA, a growing but still relatively small amount of funding supports projects directly related to climate mitigation and adaptation (Figure 5). Based on analysis of total funding by knowledge area, we estimate that in FY19, NIFA allocated approximately $117 million to climate mitigation and $86 million to adaptation and related climate science, the most recent year for which data were available. Based on an analysis of ARS's reported funding by knowledge area, we estimate that the agency allocated $107 and $143 million to climate mitigation and adaptation, respectively, in FY19. In total, NIFA and ARS spent as much as $453 million on projects related to mitigation and adaptation, or 20% of their total funding.[99]

Our figures differ greatly from the USDA's own most recent estimates of climate-related expenditures. By contrast, the USDA estimates that its research agencies (ARS, NIFA, ERS, and NASS) devoted only $184 million in FY21 funding for activities related to clean energy, climate mitigation, and climate adaptation/resilience (Figure 6). They include in this total $90 million from agencies the USDA has identified as supporting the U.S. Global Change Research Program (USGCRP), an interagency initiative to coordinate research on global environmental change and its implications.[100]

Figure 6: USDA Research Agency Funding Related to Climate (FY21 enacted)



Source of data: Special tabulation request from USDA Office of Budget & Program Analysis (OBPA) to Dan Blaustein-Rejto, July 1, 2022.

Note: ARS = Agricultural Research Service, NIFA = National Institute of Food and Agriculture, AFRI = Agriculture and Food Research Initiative, ERS = Economic Research Service, NASS = National Agricultural Statistics Service, SBIR = Small Business Innovation Research program, USGCRP = U.S. Global Change Research Program.

The estimates for NIFA and ARS[101] are less than half as large as ours, highlighting several limitations of both figures:

1) The USDA's estimates are not publicly available, nor is any documentation about how the funding amounts were calculated. The USDA's Office of Budget & Program Analysis (OBPA) shared the estimates with the authors upon request.

2) Our estimates rely on spending data aggregated at the level of knowledge areas. However, this method prevents precise analysis. Some knowledge areas that we consider climate-related, such as "Pollution Prevention and Mitigation" and "Conservation of Biological Diversity," include climate-related projects but also unrelated projects.

3) The USDA's estimates omit funding for areas that arguably contribute to climate adaptation. The agency reports that AFRI, for instance, did not fund any projects related to adaptation. However, some projects that the agency lists as related to "Abiotic Stresses Affecting Plants" and "Environmental Stress in Animals" explicitly aim to help farmers

adapt to climate change. For example, a University of Colorado project is studying how weather variability affects dairy cow productivity, welfare, and enteric methane emissions, and how the dairy sector could adapt to future weather conditions.[102]

4) The USDA's estimates of climate-related funding appear to leave out substantial allocations for projects related to mitigation. The agency reports that AFRI's only climate-related funding in FY21 was related to bioenergy and industrial efficiency.[103] However, NIFA also funded many other projects related to mitigation, such as projects on cover crops, carbon sequestration, reducing fertilizer loss, and lowering enteric methane emissions, as the following section details.

DETAILED R&D FUNDING FOR CLIMATE MITIGATION

To estimate more-detailed funding trends and address the limitations of our aggregate analysis, we conducted a text analysis of projects funded by NIFA, FFAR, ARPA-E, and NSF. We report funding for the largest agricultural GHG sources that the EPA reports: agricultural soil management, enteric fermentation, manure management, and rice cultivation as well as soil carbon sequestration. However, the text analysis does not address all the limitations described above. In addition, detailed project-level funding or expense data are not available for ARS. Therefore, although we include ARS in our estimates of total R&D funding for climate mitigation, we do not further disaggregate funding or directly compare funding from ARS and other agencies.

R&D Funding for Agricultural Mitigation is 35 Times Lower than for Clean Energy

We estimate that NIFA, FFAR, ARPA-E, and NSF provided $134 million in funding per year, on average, for agricultural climate mitigation from fiscal year 2017 to 2021.[104] As Figure 6 shows, the USDA reports that ARS funded an additional $39 million in FY21 related to emissions mitigation and up to $104 million if USGCRP funding is also included. We estimate that funding could have been as high as $107 million in 2019.[105] Including this range of estimates of ARS funding, we estimate that recent funding from R&D agencies for agricultural climate mitigation has totaled $173–$241 million per year.

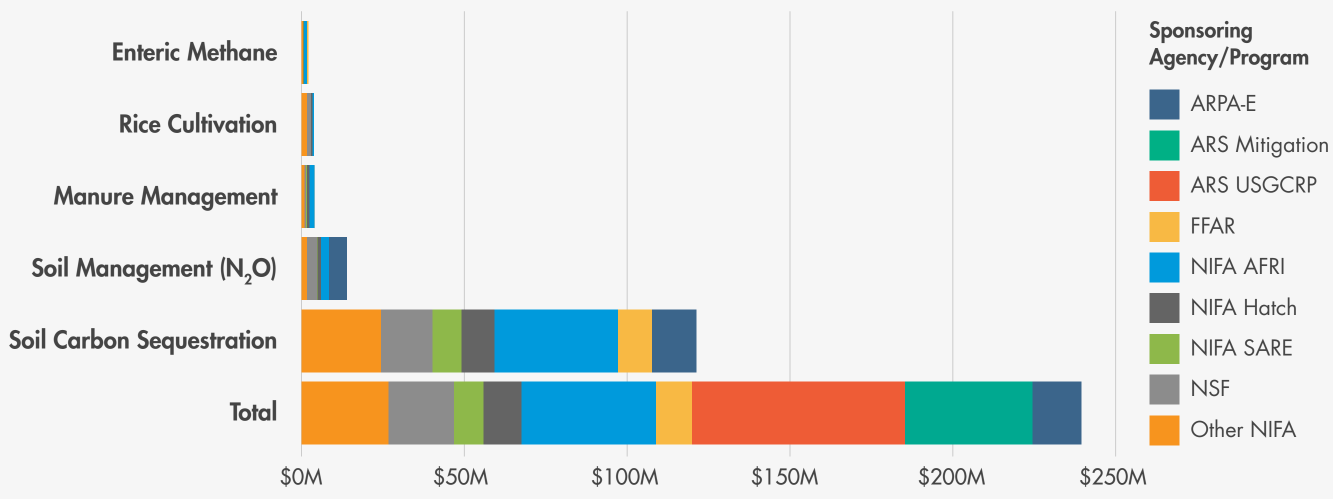
As in the aggregate analysis in the previous section, we find there is more USDA R&D funding for mitigation projects than the agency itself estimates. For example, we estimate that NIFA spent approximately $143 million on mitigation-related projects in FY21—almost three times larger than USDA's figure of $51 million.

Regardless of which estimate is considered, federal R&D funding for agricultural climate mitigation is substantially smaller than for clean energy, even accounting for agriculture's smaller share of national emissions. In 2020, energy (e.g., electricity, transportation, heating, and cooling) accounted for eight times more GHG emissions than agriculture.[106] However, the U.S. government spent about 35–49 times more on clean energy innovation in 2020 (~$8.4 billion) than R&D agencies spent on climate mitigation in agriculture.[107] This shows that climate-smart agricultural innovation as a whole is being seriously underfunded relative to climate-related innovation in other sectors and underscores the significant mitigation potential of the agricultural sector.

Greatest Funding for Soil Carbon Sequestration; Least for Enteric Methane

During 2017–2021, the majority of mitigation funding was allocated to projects related to soil carbon sequestration, on average $121 million per year (Figure 7). Projects include those seeking to understand or enhance soil health, soil carbon, or soil organic matter. For example, AFRI funded a $10 million multiyear project led by North Carolina State University to create tools that help farmers adopt and manage cover crops. Project activities include evaluation of cover-crop performance at 200 locations, development of processes to estimate performance using remote sensing imagery, and creation of calculators that enable farmers to assess their fields' nutrient needs when using cover crops.[108]

Figure 7: Agricultural R&D Spending on Climate Mitigation (2017–2021 Average)



Notes: ARS mitigation and USGCRP reflect USDA estimates of enacted funding for FY21. Funding by mitigation area is not calculated owing to data limitations. Other funding is calculated based on analysis of project descriptions for 2017–2021. Columns do not sum to equal total because funding for projects can fall under multiple categories.

The second largest share of mitigation funding from R&D agencies, an average of $14 million per year, was directed to agricultural soil management, the largest source of U.S. agricultural emissions (Figure 7). Soil management projects include those aiming to improve the efficiency with which crops use nitrogen, better understand or improve crops' ability to fix nitrogen from the air, and otherwise reduce nitrous oxide emissions from fertilizer application and biological sources of nitrogen.

As with other areas of climate-smart R&D, funding to reduce emissions from enteric fermentation was disproportionately low relative to its climate impact. Since 2017, enteric fermentation (part of the digestive process of cattle and other ruminants) accounted for more than 25% of total anthropogenic U.S. methane emissions and 28% of total U.S. agricultural emissions.[109] Further, reducing methane emissions also has near-term benefits (see Box 1). However, projects to understand, measure, monitor, and reduce enteric methane emissions received only $2 million per year from 2017 to 2021 (Figure 7). Although this amount does not include research conducted by ARS, owing to data limitations, it is nevertheless a relatively small portion of overall funding. Funding for enteric methane accounted for less than 2% of non-ARS funding for agricultural climate mitigation and 9% of funding for emissions reductions (excluding soil carbon sequestration). This suggests a significant opportunity for increased investment.

Despite being underfunded to date, R&D funding for projects related to enteric methane is rising. For example, congressional spending bills from FY19 to FY21 have included at least $1 million for the ARS Livestock Nutrient Management Research Unit to study the potential of Bromoform, a compound produced by red seaweed, to reduce enteric methane emissions.[110] And in 2022, the FFAR announced it would match industry contributions up to $2.5 million for the Greener Cattle Initiative, a five-year effort to reduce enteric methane emissions.[111] Further, AFRI's Sustainable Agriculture Systems (SAS) program announced a $10 million grant in 2021 to Colby College for a five-year study of the efficacy, safety, feasibility, and consumer perception of seaweed-based feed additives for U.S. dairy cattle.[112] Yet even considering these efforts, funding remains lower than for many other climate mitigation strategies and lower than study groups recommend. For instance, leading researchers from Princeton University, Cornell University, and other institutions have called for a $100 million global initiative just to run multiyear tests of feed additives.[113]

Although the discrepancy is less stark than for enteric methane, funding for research on manure management is also low relative to these activities' contributions to total agricultural emissions. Manure management received $4 million per year, or 3% of the $134 million total mitigation funding, but accounted for about 13% of emissions. Conversely, nearly $4 million per year, about 3% of total mitigation funding (excluding ARS), was allocated to reducing methane emissions from rice cultivation, which was responsible for only 2.4% of US agricultural emissions.

Box 1: The Importance of Reducing Methane in the Agriculture Sector

Although the largest share of U.S. GHG emissions derives from carbon dioxide (CO_2),[114] the agriculture sector's pronounced methane (CH_4) emissions provide important opportunities to reduce climate impacts. This is because of (1) methane's high global warming potential compared with carbon dioxide and (2) the near-term benefits of reducing methane emissions related to its shorter lifetime in the atmosphere. Although methane remains in the atmosphere for only 10 years or so, it plays an outsized role in near-term warming. This is because methane can trap about 80 times more heat than carbon dioxide does over a 20-year period for equal initial emissions.[115]

Thus, methane's short-lived but potent impact has made it a major contributor to the warming that the planet has experienced to date: The latest scientific findings suggest that methane emissions from human activities account for at least 25% of warming.[116] This also means that rapidly reducing the rate of anthropogenic emissions will both slow the rate of atmospheric warming and help limit peak warming.[117] Even so, the concentration of methane in the atmosphere is more than 2.5 times preindustrial levels and continues to rise.[118]

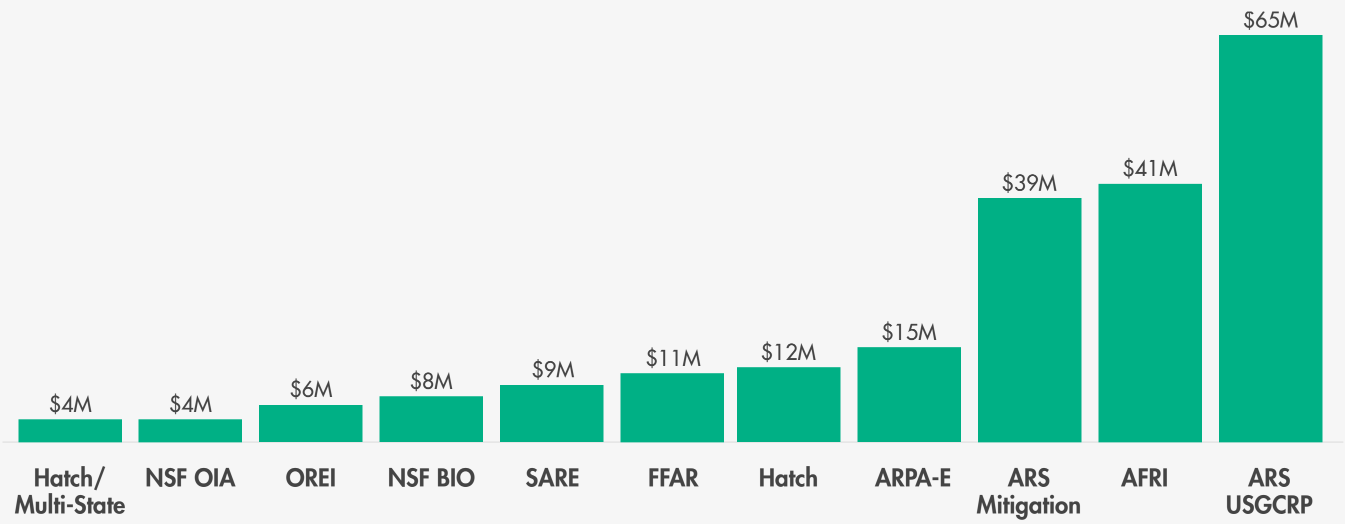
Enteric fermentation from livestock is the largest source of methane emissions in the United States, accounting for about 25% of the nation's total methane emissions in 2020. Manure management accounted for 9% of total methane emissions and rice cultivation for 2%.[119] Thus, reducing methane emissions per pound of beef or dairy has great potential to reduce emissions without significantly disrupting food systems or dietary habits.

Reducing agricultural methane emissions can play a powerful role in meeting U.S. commitments under the 2015 Paris Agreement[120] and is a critical part of avoiding the worst consequences of climate change. A growing literature describes the many long-term benefits of methane mitigation as well as the importance of early action.[121,122,123,124]

ARS and AFRI Provide the Most Mitigation Funding

From 2017 to 2021, the majority of funding for climate mitigation activities originated from ARS, AFRI, ARPA-E, Hatch capacity grants for land-grant universities, FFAR, and SARE. Additional substantial funding came from several of NSF's directorates, such as Biological Sciences (BIO) and the OIA (Figure 8).

Figure 8: Annual R&D Program Funding for Agricultural Climate Mitigation (2017–2021 average)



Notes: ARS mitigation and USGCRP reflect USDA estimates of enacted funding for FY21. Funding by mitigation area is not calculated owing to data limitations. Other funding is calculated based on analysis of project descriptions over 2017–2021.

Within ARS, several programs and research centers (also known as research units) support particularly important mitigation research. For instance, the Soil and Air program within the Environmental Stewardship Program Area aims to understand the effects that climate change has on agriculture and methods through which agriculture can adapt to climate change, among other topics.[125] For example, a research project in Arkansas is working on several goals, including linking precision agriculture and digital soil mapping technologies in order to optimize on-farm profitability and sustainability.[126] Another environmental program, Sustainable Agricultural Systems, supports producers in developing integrated information and technologies to solve problems related to productivity, profitability, energy efficiency, and natural resource stewardship.[127] One research project in Missouri seeks to improve traditional soil carbon modeling approaches by using measurements from multiple soil sensors and machine learning techniques.[128]

ARS's Long-Term Agroecosystem Research (LTAR) Network also supports mitigation by linking ARS's experimental research sites that collect long-term data on agricultural sustainability, climate change, ecosystem services, and natural resource conservation with partner sites operated by research institutions, such as universities.[129] LTAR sites often conduct research related to climate mitigation (see Box 2). ARS has also supported research on enteric methane, among many other areas, at research centers in University Park, Pennsylvania; Madison, Wisconsin; Bushland, Texas; and Beltsville, Maryland, among other sites. Although the lack of project-level funding or expense data for ARS prevents us from analyzing how much funding these programs or centers provide for mitigation, funding for the Environmental Stewardship Program has been gradually rising, though at a slower pace than total ARS program funding (Table 2).

Table 2: ARS Salaries and Expenses by Program ($ millions)

AFRI Program Area	2017	2018	2019	2020	2021	2022
New Product Quality/Value Added	102	101	102	117	121	121
Livestock Production	89	92	103	114	124	124
Crop Production	226	242	258	283	301	301
Food Safety	112	112	114	114	116	116
Livestock Protection	94	95	102	117	127	127
Crop Protection	198	202	207	217	223	223
Human Nutrition	87	88	91	92	99	99
Environmental Stewardship	217	219	225	232	252	252

Notes: Actual discretionary budget authority for each fiscal year; estimated discretionary budget authority for FY22. Values may not sum to total ARS funding due to rounding and because additional funds are allocated to other items such as repair and maintenance.

Sources of data: USDA FY19–23 Budget Summaries Explanatory Notes – Agricultural Research Service, www.usda.gov/sites/default/files/documents/fy19-budget-summary.pdf, 64; www.usda.gov/sites/default/files/documents/fy2020-budget-summary.pdf, 67; www.usda.gov/sites/default/files/documents/usda-fy2021-budget-summary.pdf, 75; www.usda.gov/sites/default/files/documents/2022-budget-summary.pdf, 100; www.usda.gov/sites/default/files/documents/2023-usda-budget-summary.pdf, 86-87.

Within AFRI, most mitigation-related funding falls under the SAS program, which has awarded about $80 million in competitive grants annually to long-term projects since 2019. About 30% of the SAS program's total funding has been directed to mitigation-related projects, accounting for 57% of AFRI's mitigation-related funding since 2019. AFRI also provides substantial mitigation funding (an estimated $11 million per year for 2017–2021) under its "Bioenergy, Natural Resources, and Environment" priority area. This priority area, one of six, supports projects to "promote, improve, and maintain healthy agroecosystems and the natural resources that are essential to the sustained long-term production of agricultural goods and services."[130] In FY21, this area awarded about $33 million to projects,[131] including about $13 million to projects evaluating the effect of farming practices on soil dynamics and developing innovative approaches to better understand and manage soil health and agricultural sustainability. Significant (though smaller) amounts of funding for mitigation projects stem from other priority areas such as "Plant Health and Production and Plant Products." See Box 3 for sample AFRI projects.

Box 2: ARS LTAR—Archbold Buck Island Ranch

Archbold Biological Station, in partnership with University of Florida, is one of 18 sites around the United States that are part of the USDA ARS Long-Term Agroecosystem Research (LTAR) network. Much of the station's research is conducted on Archbold's Buck Island Ranch, a 10,500-acre working cow–calf operation with 3,000 head of cattle, which serves as a living laboratory for long-term ecological research. Studies on the ranch have found that grazed semi-native pastures on the site are a net sink of CO_2, absorbing more through photosynthesis than they release and have a smaller climate impact even after accounting for methane generated by the cattle. A separate study found that grazed pasture stored more carbon than ungrazed pasture, having a smaller climate impact even after accounting for methane generated by the cattle. Archbold researchers continue to study GHG emissions from grasslands and grazing operations and how to reduce them, including by giving cattle feed supplements.[132]

Archbold Biological Station staff maintaining one of the eddy covariance systems to monitor GHG cycles in an improved pasture at Archbold's Buck Island Ranch. *Credit: Carlton Ward.*

Box 3: Select AFRI Projects

Nitrous oxide (N_2O) is a potent greenhouse gas with 298 times the warming potential of CO_2 over 100 years. Agricultural soils are currently the primary anthropogenic source of N_2O, the result of applying nitrogen fertilizers and manure.[133]

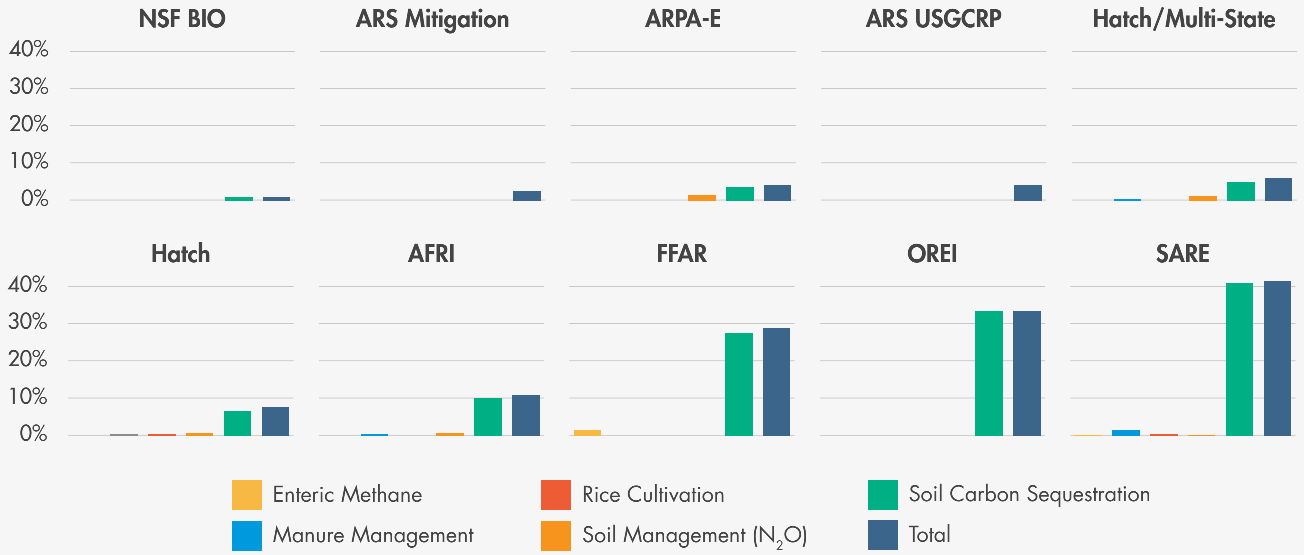
Pennsylvania State University was awarded a $288,500 AFRI grant in 2018 to research the impacts of various soil management practices (i.e., reduced tillage, cover cropping, and manure application) on soil nitrogen emission. It did so by studying soil microbes that prevent nitrogen from being released into the atmosphere.[134] The soil samples the study analyzed came from research plots established and supported by two other USDA programs: Northeast Sustainable Agricultural Research and Education (SARE) and USDA ARS's Long-Term Agroecosystem Research (LTAR) Network. AFRI grants have also supported a Penn State effort that led to the discovery of a gene in crops that increases nitrogen uptake ability and regulates the angle of root growth. The lack of this gene allows roots to grow at steeper angles, which in turn helps the roots grow more deeply into the soil.[135] This discovery may help breed crops that reduce groundwater pollution and N_2O emissions.

Lehigh University (Bethlehem, Pennsylvania) was awarded a $434,809 AFRI grant in 2020 to develop, synthesize, and test a novel fertilizer that uses rocks, minerals, and drywall gypsum waste as nutrient sources. This approach could reduce N_2O emissions and nitrogen runoff while increasing the availability of macronutrients (Ca, Mg, and S) and micronutrients (Zn and Cu) in the soil for crops.[136]

Three Large Agencies and Programs Devote More than 25% of Funds to Mitigation

For every dollar in funding, SARE, OREI, and FFAR provide more money for projects directly related to climate mitigation than other R&D agencies and programs that have at least $4 million in mitigation-related funding per year (Figure 9). The three agencies' funding supports predominantly soil carbon sequestration efforts. Projects related to soil carbon accounted for approximately 41%, 34%, and 28% of their respective spending from 2017 to 2021.

Figure 9: Percentage of Funding Supporting Climate Mitigation (2017–2021)



Notes: Only top-10 programs/agencies by percentage of funding supporting mitigation, and with >$4 million/year for mitigation are shown. ARS mitigation and USGCRP reflect USDA estimates of enacted funding for FY21. ARS funding by mitigation area is not calculated owing to data limitations. Other funding is calculated based on analysis of project descriptions over 2017–2021. Sum of individual categories does not equal "Total" because some projects fall under multiple climate mitigation categories.

Although we do not present funding levels by mitigation area for ARS owing to data limitations, the agency appears to provide substantial funding for projects related to manure management and agricultural soil management, relative to other agencies. Out of approximately 690 total research projects, ARS has over 80 projects related to manure and over 130 related to fertilizer.[137] For example, ARS's Central Great Plains Resources Management site in Akron, Colorado, is studying the long-term effects of manure on soil carbon and crop yields.[138] In Kimberly, Idaho, ARS researchers are studying how long-term use of manure, reduced tillage, and cover crops affect nitrous oxide emissions and crop yields.[139] And ARS has a multisite effort to assess the ability of innovative fertilizer technologies such as EEFs, precision fertilizer application systems, and biochar to reduce nutrient losses and improve efficiency.[140] However, without ARS reporting project-level funding, the agency's funding for mitigation areas cannot be compared with that of other agencies. More-detailed reporting from ARS on project-level funding or funding for different areas of climate mitigation would enable better evaluation and comparison.

The FFAR awards about 29% of funds to mitigation projects, much of it to projects related to soil carbon sequestration, and a greater share of its total funding (1.4%) to enteric methane than other agencies and programs allocate. The FFAR supports and operates several long-term, large-scale mitigation efforts. The FFAR, U.S. Farmers & Ranchers in Action, and the World Farmers Organisation have leveraged at least $15 million in funding from PepsiCo, McDonald's, The Nature Conservancy, and other organizations to form AgMission, a global initiative to achieve net-negative agricultural GHG emissions. The initiative comprises a wide variety of projects, including testing incentives for farmers to adopt soil health practices, developing reviews and meta-analyses on climate-smart research, and developing a comprehensive and interoperable data framework for climate mitigation and adaptation.[141] In addition, the FFAR funds research projects, consortia, and programs that aim to improve soil health—one of the foundation's six research priority areas. For example, in 2019, FFAR awarded about $746,000 (matched by an equal amount of nonfederal funds) to Iowa State University to study how prairie strips could best be integrated into corn and soybean fields to improve soil health, erosion, and farm profitability.[142] In 2021, FFAR announced a $5 million award, matched by Stonyfield Organic and the Stonyfield Foundation, to Wolfe's Neck Center in Freeport, Maine, to develop OpenTEAM. This platform provides farmers with better access to existing and new tools for soil carbon measurement, record-keeping, analytics, and other activities related to soil management while reducing farmer data entry.[143]

Box 4: Example FFAR Project on Enteric Methane

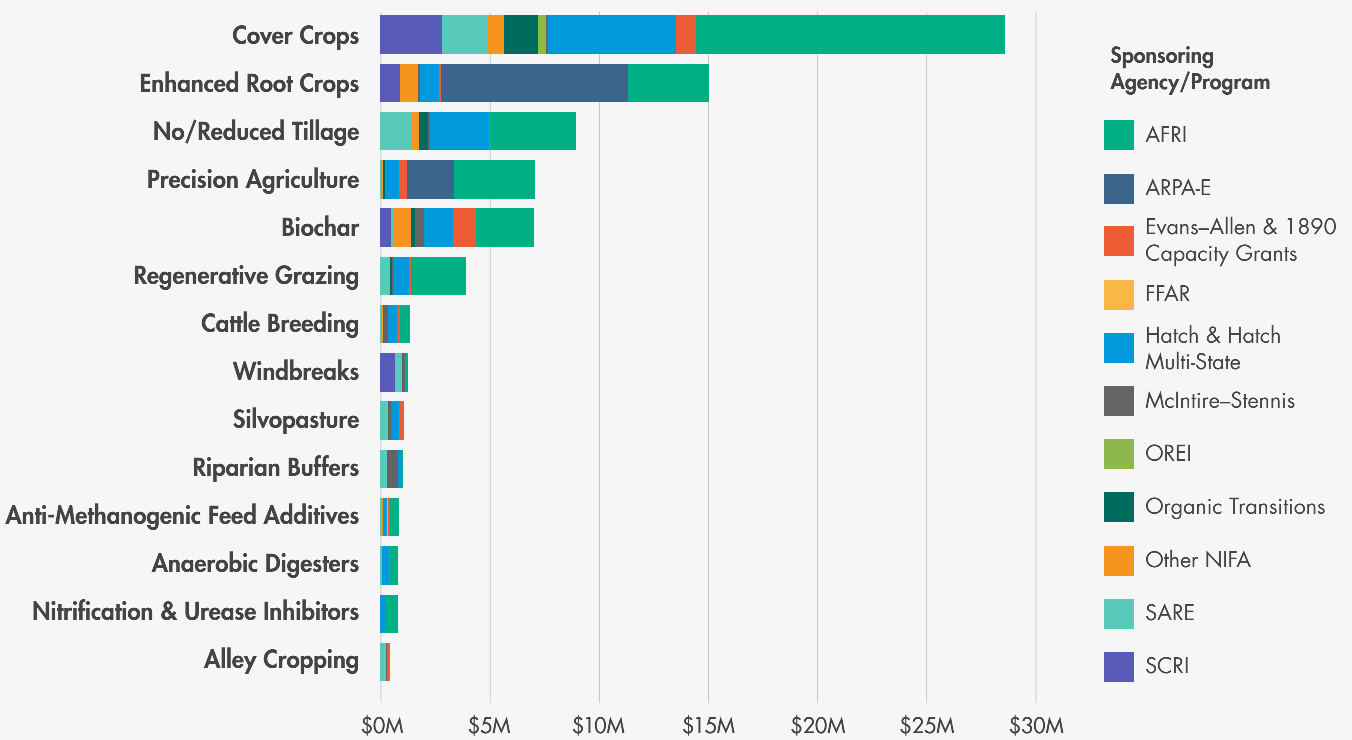
In 2018, the FFAR awarded a $50,000 grant to Elm Innovations and the University of California, Davis, to study the potential for red seaweed, *Asparagopsis armata*, to reduce methane emissions from dairy cattle when added to their diets. The research, with over $350,000 in matching funds and other contributions, was the first of its kind in the United States.[144] It ultimately found that feeding red seaweed to dairy cows reduced their enteric methane emissions by over 50%.[145] Since the project concluded, Elm Innovations (now Blue Ocean Barns) has raised nearly $27 million in funding.[146] In 2022, the California Department of Food and Agriculture approved its dried seaweed product as Generally Regarded As Safe for use as a digestive aid, and the company entered into partnerships with companies such as Ben and Jerry's, illustrating the near-term benefits FFAR's funding can have.[147]

COMPARING R&D FUNDING FOR PRACTICES WITH THEIR MITIGATION POTENTIAL

To further identify potential gaps in R&D funding, we also compared levels of funding that farming practices and technologies received from NIFA's programs, FFAR, and ARPA-E with their climate mitigation potential. We estimated annual funding levels, averaged over 2017–2021 and disaggregated by the source of funding, using text analysis of project titles and descriptions. We omitted NSF owing to data limitations. See Appendix A for details on the keywords used to categorize projects.

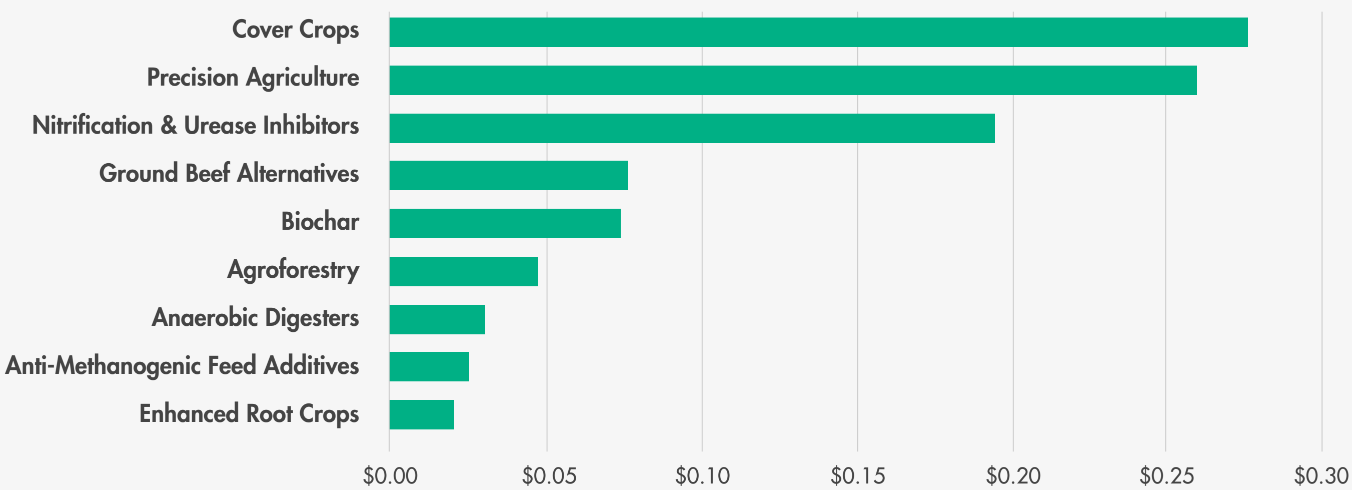
As Figure 10 shows, the greatest amount of funding, about $28 million annually, was devoted to cover crops. We estimate that NIFA, FFAR, and ARPA-E provided a total of $15 million, $9 million, $7 million, and $7 million to projects on enhanced root crops, no/reduced tillage, precision agriculture, and biochar, respectively. All other technologies and practices related to climate mitigation that we assessed received less than $4 million per year. These include technologies that require substantial basic and applied research to be scaled up, such as feed additives or nitrification and urease inhibitors. According to a separate analysis from The Breakthrough Institute and Good Food Institute, NIFA and FFAR have also provided about $3 million per year in grants for projects related to novel meat alternatives and other alternative proteins.[148]

Figure 10: NIFA, FFAR and ARPA-E Spending on Select Mitigation Practices (2017–2021 average)



In this area also, not all technologies and practices received a similar amount of funding from NIFA, FFAR, and ARPA-E relative to their climate mitigation potential. Figure 11 shows the amount of funding per metric ton of mitigation potential, based on estimates of technical mitigation potential in the United States from various sources. Our analysis should not be interpreted to suggest that any particular practice or technology has received too much or enough funding. Rather, it shows that a particularly large R&D funding gap remains for a few key areas, such as enhanced root crops and methane-reducing feed additives.

Figure 11: R&D Agency Funding for Select Mitigation Strategies per Metric Ton of U.S. Mitigation Potential (2017–2021 average)



Notes: Funding for ground-beef alternatives represents all federal alternative protein R&D from the GFI grants tracker. All other funding values are calculated based on keyword analysis of NIFA, SARE, FFAR, and ARPA-E project descriptions from 2017–2021. Funding value for agroforestry is the sum of estimates for alley cropping, silvopasture, windbreaks, and riparian buffers.

Sources for mitigation potential: Cover crops: Fargione et al. (2018); precision agriculture: Eagle et al. (2022); nitrification & urease inhibitors: Kanter and Searchinger (2018); ground-beef alternatives: D'Croz et al. 2022; biochar: Fargione et al. (2018); agroforestry: Eagle et al. (2022); anaerobic digesters: Eagle et al. (2022); anti-methanogenic feed additives: Eagle et al. (2022); and enhanced root crops: Paustian et al. (2016). See Appendix Table A5 for details on mitigation estimates.

Estimates of mitigation potential are taken from several sources, detailed in Appendix B. These estimates all reflect maximum or upper-level estimates of technical mitigation potential in the United States. As such, they don't account for how potential costs (e.g., the cost of implementing agroforestry practices like alley cropping) may limit adoption. These sources use different methods and assumptions to estimate mitigation potential over different time frames. Therefore, the values shown in Figure 11 should be viewed as approximations and compared with one another carefully. In addition, R&D related to each practice or technology may have a different impact on farmers' adoption of it, both in the United States and globally, and thus on climate mitigation. For example, although agroforestry receives less R&D funding than do nitrification inhibitors relative to its mitigation potential, an additional $1 million in spending directed toward research on agroforestry instead of nitrification inhibitors would not necessarily have a larger climate benefit.

Several practices are omitted from Figure 11, as their mitigation potential is poorly understood or highly uncertain. For instance, we are not aware of any robust, nationally representative estimates of the mitigation potential of regenerative grazing. We also omit no-till and reduced-till farming, given that recent assessments of these practices on mitigation potential either assume no net GHG mitigation or conclude that no-till cannot be guaranteed to draw down atmospheric CO_2.[149,150]

In addition, the list of practices analyzed and shown in Figures 10 and 11 is not comprehensive. For example, funding for research projects focused on measuring soil carbon, modeling soil carbon sequestration under different environments, or understanding the dynamics of nitrogen fixation are not included. These research areas are relevant and important. However, the wide range of projects that fall under these areas and their overlap with research on specific farm practices (e.g., no-till or cover crops) prevents us from estimating funding using text analysis. Therefore, total funding for all practices is not equivalent to the total level of funding for climate mitigation presented in the above sections.

POLICY IMPLICATIONS

Federal R&D agencies and programs provide critical support for basic and applied research needed to advance climate mitigation and adaptation in agriculture. Yet total agricultural R&D funding levels have stagnated, funding for productivity-focused research has declined, and several areas of climate mitigation (notably enteric methane) receive particularly low R&D funding relative to their mitigation potential. Many options are available for bolstering R&D programs to address these gaps.

The Farm Bill, set to be renewed in 2023, determines mandatory funding levels for several research programs. It historically has provided mandatory funding for FFAR and OREI. The 2018 Farm Bill provided OREI with mandatory funding, increasing it to $50 million in FY23. It also added it to the permanent baseline, effectively including it by default in future Farm Bills and providing researchers with greater funding predictability and assurance. The 2018 bill also provided $185 million in mandatory funding for FFAR, although it did not add it to the baseline.

Beyond the Farm Bill, additional opportunities to enhance climate-smart agriculture innovation can be found in the appropriations process and in standalone legislation. The annual appropriations cycle provides an opportunity for policymakers to fund climate-smart agricultural R&D and to direct additional funding to underfunded areas. Moreover, Congress has previously proposed standalone legislation to bolster agricultural R&D. For instance, in 2021, Senators Dick Durbin (D-Ill.) and Jerry Moran (R-Kan.) introduced the America Grows Act in the Senate, as did Representatives Cheri Bustos (D-Ill.-17), Jimmy Panetta (D-Calif.-20), and Kim Schrier (D-Wash.-8) in the House. The bill proposed increasing funding for the USDA's agricultural research agencies by 5% annually on an inflation-adjusted basis. The bill was modeled after the 21st Century Cures Act, which when it passed in 2016, increased funding for the NIH. Passing this or a similar bill would go a long way toward expanding R&D capacity to better address the myriad challenges the agricultural system faces.

In addition, several administrative changes could advance climate-smart R&D. Besides directing funding to neglected research areas, the USDA should improve the level of detail and transparency of the data it provides on agricultural R&D projects. A centralized, searchable database of R&D spending across agencies and programs (including grants as well as intramural research) would provide more accessibility and transparency. This would not only facilitate analyses such as those presented above, but could also aid researchers and program administrators, who must coordinate their work with that of other research programs. As part of this goal, the USDA should aim to make data on how ARS spends its budget more transparent. Without project-level funding or spending data, it is not possible to accurately estimate ARS spending on climate mitigation or other areas. In addition, R&D agencies should categorize intramural and extramural funding in more detail; for instance, they could establish consistent keywords across agencies and programs used to denote whether a project is related to climate mitigation, climate adaptation, productivity growth, or other issues.

Congress and the USDA have recently expanded support for the adoption of climate-smart farming practices. The Inflation Reduction Act provided approximately $20 billion in funding for conservation programs that provide farmers with financial and technical assistance to adopt environmentally beneficial practices and technologies.[151] The USDA also announced $2.8 billion in grants for Partnerships for Climate-Smart Commodities—70 projects that aim to expand markets for climate-smart commodities produced in the United States. These efforts should increase the adoption of existing climate-smart practices and lead to better quantification of their climate impacts.[152]

Despite these efforts, neither the Inflation Reduction Act nor the Partnerships for Climate-Smart Commodities provide substantial funding for critical R&D activities. The research funded by agencies such as NIFA, ARS, and FFAR underpins the United States' ability to decarbonize agriculture. Without it, agricultural producers will not have access to new and improved tools, technologies, and practices needed to minimize their carbon footprint. Ultimately, a robust federal agricultural R&D system is needed to support climate-smart innovation.

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APPENDIX A: METHODS

Our estimates of NIFA and ARS's climate-related funding, presented in section 3 and including values shown in Figure 5, are based on analysis of NIFA and ARS's reported expenditures by "knowledge area." We categorized if and how knowledge areas are related to climate-smart agriculture (CSA) using the crosswalk in Table A1 and aggregated by CSA category. For knowledge areas considered to contribute to both climate mitigation and adaptation, we allocated 50% of the funding to mitigation and 50% to adaptation.

Table A1: Crosswalk between NIFA and ARS Knowledge Areas and Climate Categories

Knowledge Area	CSA Category
001: Administration	Admin
101: Appraisal of Soil Resources	Climate Mitigation
102: Soil, Plant, Water, Nutrient Relationships	Climate Mitigation
103: Management of Saline and Sodic Soils and Salinity	Unrelated to CSA
104: Protect Soil from Harmful Effects of Natural Elements	Climate Mitigation and Adaptation
111: Conservation and Efficient Use of Water	Climate Adaptation
112: Watershed Protection and Management	Climate Adaptation
121: Management of Range Resources	Climate Adaptation
122: Management and Control of Forest and Range Fires	Climate Adaptation
123: Management and Sustainability of Forest Resources	Unrelated to CSA
124: Urban Forestry	Unrelated to CSA
125: Agroforestry	Climate Mitigation
131: Alternative Uses of Land	Unrelated to CSA
132: Weather and Climate	Climate Adaptation
133: Pollution Prevention and Mitigation	Climate Mitigation
134: Outdoor Recreation	Unrelated to CSA
135: Aquatic and Terrestrial Wildlife	Unrelated to CSA
136: Conservation of Biological Diversity	Unrelated to CSA

Table A1(Continued)

Knowledge Area	CSA Category
141: Air Resource Protection and Management	Climate Mitigation
201: Plant Genome, Genetics, and Genetic Mechanisms	Productivity
202: Plant Genetic Resources	Productivity
203: Plant Biological Efficiency and Abiotic Stresses Affecting Plants	Climate Adaptation
204: Plant Product Quality and Utility (Preharvest)	Productivity
205: Plant Management Systems	Productivity
206: Basic Plant Biology	Productivity
211: Insects, Mites, and Other Arthropods Affecting Plants	Productivity
212: Diseases and Nematodes Affecting Plants	Productivity
213: Weeds Affecting Plants	Productivity
214: Vertebrates, Mollusks, and Other Pests Affecting Plants	Productivity
215: Biological Control of Pests Affecting Plants	Productivity
216: Integrated Pest Management Systems	Productivity
301: Reproductive Performance of Animals	Productivity
302: Nutrient Utilization in Animals	Productivity
303: Genetic Improvement of Animals	Productivity
304: Animal Genome	Productivity
305: Animal Physiological Processes	Productivity
306: Environmental Stress in Animals	Climate Adaptation
307: Animal Management Systems	Productivity
308: Improved Animal Products (Before Harvest)	Productivity
311: Animal Diseases	Productivity
312: External Parasites and Pests of Animals	Productivity
313: Internal Parasites in Animals	Productivity
314: Toxic Chemicals, Poisonous Plants, Naturally Occurring Toxins, and Other Hazards Affecting Animals	Productivity
315: Animal Welfare/Well-Being and Protection	Unrelated to CSA

Table A1(Continued)

Knowledge Area	CSA Category
401: Structures, Facilities, and General Purpose Farm Supplies	Unrelated to CSA
402: Engineering Systems and Equipment	Productivity
403: Waste Disposal, Recycling, and Reuse	Climate Mitigation
404: Instrumentation and Control Systems	Productivity
405: Drainage and Irrigation Systems and Facilities	Climate Mitigation
501: New and Improved Food Processing Technologies	Unrelated to CSA
502: New and Improved Food Products	Unrelated to CSA
503: Quality Maintenance in Storing and Marketing Food Products	Unrelated to CSA
504: Home and Commercial Food Service	Unrelated to CSA
511: New and Improved Non-Food Products and Processes	Bioenergy
512: Quality Maintenance in Storing and Marketing Non-Food Products	Bioenergy
601: Economics of Agricultural Production and Farm Management	Unrelated to CSA
602: Business Management, Finance, and Taxation	Unrelated to CSA
603: Market Economics	Unrelated to CSA
604: Marketing and Distribution Practices	Unrelated to CSA
605: Natural Resource and Environmental Economics	Climate Mitigation and Adaptation
606: International Trade and Development Economics	Unrelated to CSA
607: Consumer Economics	Unrelated to CSA
608: Community Resource Planning and Development	Unrelated to CSA
609: Economic Theory and Methods	Unrelated to CSA
610: Domestic Policy Analysis	Unrelated to CSA
611: Foreign Policy and Programs	Unrelated to CSA
701: Nutrient Composition of Food	Unrelated to CSA
702: Requirements and Function of Nutrients and Other Food Components	Unrelated to CSA
703: Nutrition Education and Behavior	Unrelated to CSA
704: Nutrition and Hunger in the Population	Unrelated to CSA

Table A1(Continued)

Knowledge Area	CSA Category
711: Ensure Food Products Free of Harmful Chemicals, Including Residues from Agricultural and Other Sources	Unrelated to CSA
712: Protect Food from Contamination by Pathogenic Microorganisms, Parasites, and Naturally Occurring Toxins	Unrelated to CSA
721: Insects and Other Pests Affecting Humans	Unrelated to CSA
722: Zoonotic Diseases and Parasites Affecting Humans	Unrelated to CSA
723: Hazards to Human Health and Safety	Unrelated to CSA
724: Healthy Lifestyle	Unrelated to CSA
801: Individual and Family Resource Management	Unrelated to CSA
802: Human Development and Family Well-Being	Unrelated to CSA
803: Sociological and Technological Change Affecting Individuals, Families, and Communities	Unrelated to CSA
804: Human Environmental Issues Concerning Apparel, Textiles, and Residential and Commercial Structures	Unrelated to CSA
805: Community Institutions and Social Services	Unrelated to CSA
806: Youth Development	Unrelated to CSA
807: Disaster Preparedness, Mitigation, Response, and Recovery	Unrelated to CSA
901: Program and Project Design, and Statistics	Admin
902: Administration of Projects and Programs	Admin
903: Communication, Education, and Information Delivery	Unrelated to CSA
990: Unclassified	Unrelated to CSA

Table A2: Keywords for Text Analysis by EPA Emissions Source/Sink

Category	Title, Summary, Abstract, Keywords, or Objectives Include
Agricultural soil management	NIFA, SARE, and FFAR: (nitrous oxide OR N2O) NOT manure NSF: (fertilizer OR crop OR agriculture OR farming) AND (nitrous oxide) NOT manure
Enteric fermentation	(enteric OR feed additive OR asparagopsis OR burp) AND (methane or CH4) NOT enteric agar
Manure management	manure AND (methane OR nitrous oxide OR carbon dioxide OR CH4 OR N2O OR CO2)
Rice cultivation	rice AND (methane OR nitrous oxide OR carbon dioxide OR CH4 OR N2O OR CO2)
Soil carbon sequestration	NIFA, SARE, and FFAR: soil carbon OR soil health OR soil organic matter OR carbon sequestration OR carbon in soil OR carbon in the soil NSF: (soil carbon OR soil health OR soil organic matter OR carbon sequestration OR carbon in soil OR carbon in the soil) AND (agriculture OR agricultural OR farm OR crop OR livestock OR food)

Table A3: Keywords for Text Analysis by Practice/Technology

Practice/Technology	Title, Summary, Abstract, Methods, Keywords, or Objectives Include
Cover crop	cover crop AND climate keywords
Reduced tillage	(no-till OR no till OR reduced-till OR strip till OR strip-till OR residue and tillage management) AND climate keywords
Biochar	biochar AND climate keywords
Enhanced root crops	(enhanced roots OR deeper roots OR suberin OR root architecture OR rooting depth OR root depth OR root system) AND climate keywords
Alley cropping	alley cropping AND climate keywords
Silvopasture	silvopasture AND climate keywords
Riparian buffer	(riparian buffer OR riparian forest buffer OR forest buffer) AND climate keywords
Windbreak	(windbreak OR shelterbelt OR hedgerow OR snow fence OR living fence) AND climate keywords
Precision agriculture	(precision farming OR precision agriculture OR variable rate OR variable-rate OR VRT OR soil monitor OR soil map OR nitrogen test OR nitrogen sensor) AND climate keywords
Nitrification & urease inhibitors	(nitrification inhibitor OR urease inhibitor OR dicyandiamide OR nitrapyrin OR pronitradine OR dimethylpyrazole phosphate OR thiophosphoric triamide) AND climate keywords
Anaerobic digesters	(anaerobic digester OR biodigester OR manure digester) AND climate keywords
Regenerative grazing	(prescribed grazing OR managed grazing OR adaptive multi OR adaptive grazing OR mob grazing OR rotational grazing OR regenerative grazing OR pasture rotation) AND climate keywords
Feed additives	(feed additive OR feed supplement OR asparagopsis OR red seaweed OR 3-NOP OR 3-Nitrooxypropanol) AND climate keywords
Cattle breeding for methane intensity	NIFA & FFAR: (cattle OR cow) AND (breeding) AND climate keywords SARE: (cattle OR cow) AND (bovine) AND (livestock breeding) AND climate keywords

Note: Climate keywords are (greenhouse gas OR GHG OR climate mitigation OR carbon OR methane OR nitrous oxide OR CH4 OR N2O OR CO2).

Data sources

- NIFA project-level data were downloaded from the NIFA Data Gateway[153] on July 15, 2022.
- NIFA and ARS expenditures by knowledge area, shown in Figure 5, were downloaded from USDA REEIS[154] on March 6, 2022.
- ARPA-E data were downloaded from the agency web portal[155] on February 8, 2022.
- FFAR grant data were provided by FFAR on March 29, 2022.
- SARE data were downloaded from the agency web portal[156] on October 10, 2022.
- NSF data were downloaded from the agency web portal[157] on October 10, 2022.

NIFA

Project and financial details data from the NIFA Data Gateway include only award amounts for non-formula programs. Financial details data include each recipient's expenditures. According to NIFA staff, "This is typically close to the award amount, but not as accurate." We therefore used the latest award amounts for non-formula programs, and expenditure amounts for formula programs. The data do not include funding and expenses for Smith–Lever 3b and 3c programs or 1890 Extension programs. However, the data and values we used do include extension, education, and other activities within other programs. All data are reported by fiscal year. Titles, nontechnical summaries, keywords, and objectives were analyzed using the keywords in Tables A2 and A3.

ARPA-E

We manually categorized programs and projects based on whether their research objectives are to develop knowledge or technologies that would contribute to climate mitigation outside of biofuel production. Besides ROOTS and SMARTFARM, we included Special Projects related to SMARTFARM and Open 2018 projects related to precision agriculture. We excluded projects and programs that focus on decarbonizing energy or transportation, such as through ammonia synthesis or biofuels (e.g., the ECOSynBio program). The values used reflect award amounts per fiscal year.

FFAR

FFAR values reflect award amounts per fiscal year, excluding any matching funding. Fiscal year was calculated based on the award date provided. Titles and short summaries provided by FFAR were analyzed using the keywords in Table A2 and A3.

SARE

For results presented in section 4, we searched SARE "project reports" for the keywords in Table A2. The reports include a proposal summary/abstract and project objectives as well as a summary of materials, methods, results, outreach, and outcomes for finished projects. Values reflect award amounts per year. For results presented in section 5, we searched SARE project overviews, including proposal practices, summaries, abstracts, and objectives for the keywords in Table A3.

NSF

For results presented in section 4, we used NSF's advanced project search feature to search project titles and abstracts for the keywords in Table A2. To calculate the percent of directorate funding allocated to climate mitigation, we used total funding levels by directorate from NSF budget requests. Values reflect award amounts per fiscal year.

APPENDIX B: DATA TABLES

Table A4: Funding by Emissions Source/Sink

Agency/ Program	Agricultural Soil Management	Enteric Methane	Manure Management	Rice Cultivation	Soil Carbon	Total Climate Mitigation
ARPA-E	$5,465,887	$0	$0	$0	$13,622,062	$15,004,477
ARS Mitigation	NA	NA	NA	NA	NA	$39,000,000
ARS USGCRP	NA	NA	NA	NA	NA	$65,000,000
FFAR	$0	$540,000	$0	$0	$10,469,058	$11,009,058
NIFA AFRI	$2,454,983	$782,258	$1,572,128	$379,902	$37,704,394	$41,128,397
NIFA Hatch	$1,066,150	$158,276	$782,212	$407,892	$10,084,009	$11,699,832
NIFA SARE	$91,975	$114,944	$343,887	$117,910	$8,793,347	$8,928,574
NSF	$3,082,635	$151,200	$473,065	$1,154,365	$15,889,414	$20,086,819
Other NIFA	$1,663,846	$329,024	$808,271	$1,654,596	$24,192,273	$26,523,257

Note: ARS mitigation and ARS USGCRP reflect USDA estimates of enacted funding for FY21. ARS funding by mitigation area is not calculated owing to data limitations. Other funding is calculated based on analysis of project descriptions for 2017–2021. Columns do not sum to equal total because funding for projects can fall under multiple categories.

Table A5: Funding by Practice/Technology

Practice/ Technology	AFRI	ARPA-E	Evans–Allen and 1890 Capacity Grants	FFAR	Hatch and Hatch Multi-State Grants	McIntire-Stennis	OREI	Organic Transitions	Other NIFA	SARE	SCRI	Total
Alley Cropping	$0	$0	$134,042	$0	$16,042	$71,036	$0	$0	$0	$235,550	$0	$456,670
Anaerobic Digesters	$368,497	$0	$20,000	$0	$360,706	$0	$0	$0	$49,994	$5,986	$0	$805,183
Anti-Methanogenic Feed Additives	$383,500	$0	$115,439	$50,000	$169,902	$0	$0	$0	$79,786	$35,070	$0	$833,697
Biochar	$2,680,982	$0	$1,002,083	$16,300	$1,338,458	$378,132	$0	$191,946	$845,473	$55,710	$498,987	$7,008,071
Cattle Breeding	$452,449	$0	$135,039	$0	$396,526	$223,750	$9,999	$0	$72,216	$42,532	$0	$1,332,511
Cover Crops	$14,072,785	$0	$904,635	$0	$5,847,357	$47,890	$406,763	$1,505,322	$745,760	$2,092,722	$2,805,418	$28,428,652
Enhanced Root Crops	$3,689,390	$8,508,605	$59,544	$0	$873,787	$83,821	$0	$0	$830,282	$17,432	$880,207	$14,943,068
Nitrification & Urease Inhibitors	$569,625	$0	$0	$0	$205,021	$0	$0	$0	$0	$0	$0	$774,646
No/Reduced Tillage	$3,901,657	$0	$49,978	$0	$2,693,066	$66,529	$0	$423,216	$348,469	$1,413,677	$0	$8,896,592
Precision Agriculture	$3,669,028	$2,136,565	$378,805	$0	$606,071	$19,849	$0	$94,774	$111,246	$6,610	$0	$7,022,948
Regenerative Grazing	$2,522,516	$0	$63,105	$0	$753,546	$26,867	$0	$99,985	$60,000	$369,693	$0	$3,895,712
Riparian Buffers	$92,000	$0	$0	$0	$149,633	$490,521	$0	$0	$0	$311,494	$0	$1,043,648
Silvopasture	$0	$0	$216,057	$0	$338,845	$165,155	$0	$0	$0	$333,236	$0	$1,053,293
Windbreaks	$92,000	$0	$8,296	$0	$0	$159,698	$0	$0	$0	$313,826	$655,985	$1,229,805

Table A6: Estimates of Mitigation Potential

Practice/ Technology	Mitigation Potential (MMT CO_2e/year)	Notes and Sources
Enhanced Root Crops	746	Estimate of average annual soil carbon accrual over a 30-year period, reported in Paustian et al. (2016), assuming 100% adoption of improved phenotypes for the most optimistic scenario of a doubling of root C inputs and an extreme downward shift in root distributions, equivalent of an average rate of increase of almost 1.8 Mg C ha^{-1} yr^{-1}, and accounting for increased N_2O emissions from increased nitrogen inputs.
Cover Crops	103	Estimate of maximum 2025 mitigation potential, compared with business-as-usual 2025 emissions, assuming cover crops added to the roughly 88 million hectares of primary cropland that do not already incorporate them (Fargione et al. 2018).
Biochar	95	Estimate of maximum 2025 mitigation potential, compared with business-as-usual 2025 emissions, assuming biochar produced only with crop residues not already harvested. Estimate accounts only for the effects on soil carbon, not life-cycle emissions from producing, transporting, or applying biochar; effects of biochar on methane or N_2O; or effects on soil organic matter and crop yields (Fargione et al. 2018).
Anti-Methanogenic Feed Additives	34	High estimate of feasible 2030 emissions-reduction potential compared with 2018 baseline (Eagle et al. 2022).
Ground-Beef Alternatives	40	High estimate of feasible 2040 emissions reduction, compared with 2018 baseline, assuming that meat alternatives achieve the industry-based projection of 60% market share by 2040 (D'Croz et al. 2022).
Precision Agriculture	27	Estimate of feasible 2030 emissions-reduction potential for "nitrogen management" compared with 2018 baseline (Eagle et al. 2022). This is an upper estimate as" nitrogen management" includes precision agriculture as well as reduced nitrogen demand resulting from conservation agriculture; improvements in the source, rate, timing, and placement of fertilizer application; and EEFs.
Anaerobic Digesters	27	Estimate of feasible 2030 emissions-reduction potential compared with 2018 baseline (Eagle et al. 2022), assuming that 91% of mitigation potential is accounted for by digesters, including cover and capture of manure storage, as estimated in Pape et al. (2016).
Nitrification and Urease Inhibitors	4	Estimated mitigation potential of adopting EEFs over all ~12.79 million hectares of U.S. corn cropland projected to exceed a criterion rate for nitrogen use efficiency in 2030, assuming an average reduction in N_2O emissions of 29% (Kanter and Searchinger 2018).[158]
Agroforestry	80	Estimate of feasible 2030 emissions-reduction potential, assuming agroforestry practices (e.g., alley cropping, riparian buffers, silvopasture, and windbreaks) are installed on the equivalent of ≤10% of U.S. cropland area (Eagle et al. 2022).

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