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Opportunities for Carbon Dioxide Removal Within the United States Department of Agriculture

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Farming and ranching communities in the United States sit at the front lines of climate change impacts and responses. In particular, terrestrial atmospheric carbon dioxide removal (CDR) can reduce climate change impacts while increasing resilience to extreme weather. Currently, many CDR technologies and strategies are still under research and development (R&D), and lack sufficient federal support to reach widespread deployment. Here, we provide an assessment of the United States Department of Agriculture's (USDA) existing programs and organizational structure, its capacity to support research and demonstration of CDR, and recommendations for expansion of these capabilities. We summarize USDA's previous and current efforts to incorporate CDR R&D within their research, education, and economics mission, as well as opportunities to refocus and expand existing programs. Potential future actions to expand CDR R&D capabilities include: (1) the establishment of a new extramural research agency and an intramural technology commercialization program within USDA, (2) improved coordination between the Foundation for Food and Agriculture (FFAR) and USDA, (3) improved intra-agency and inter-agency coordination, and (4) congressional action to establish and fund new CDR programs within USDA. USDA can pursue multiple strategies to enhance CDR, driving development, demonstration, and deployment across the United States.

Keywords: carbon dioxide removal, climate policy, research and development, United States Department of Agriculture, Advanced Research Projects Agency

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INTRODUCTION

The United States Department of Agriculture (USDA) contains several offices and programs that provide limited support for research, development, and demonstration (RD&D) activities relevant to carbon dioxide removal (CDR) (Sanchez et al., 2018). The bulk of this research and development support is facilitated through Under Secretary of Research, Education, and Economics' (REE) agencies, which include the Agricultural Research Service (ARS), National Institute of Food and Agriculture (NIFA), the National Agricultural Statistics Service (NASS), and the Economic Research Service (ERS). Additionally, offices reporting to other Under Secretaries, such as the Forest Service, the Farm Service Agency (FSA), and the Natural Resources Conservation Service (NRCS), operate programs that perform both research and development functions relevant to CDR. While REE offices focus primarily on applied research, the Forest Service, FSA, and NRCS perform a variety of demonstration and deployment functions. With a collective operating budget of nearly $5 billion annually, collaborative efforts across these agencies have already yielded significant advancements in the research and development of climate change mitigation and adaptive land

management strategies and technologies. Below, **Table 1** summarizes the missions, jurisdictions, programmatic focuses, funding levels, and CDR relevant land management strategies of the Research, Education, and Economics offices, as well as the Natural Resources Conservation Offices and the United States Forest Service.

Given USDA's organizational structure, REE mission, and diverse set of expertise and programs, the Department and Congress are well-positioned to refocus and expand existing research programs relevant to carbon dioxide removal. REE's primary objectives of increasing economic opportunity and conserving natural resources through scientific and economic research and education could enable many existing programs to be refocused or modified without congressional action or expanded and augmented through changes in appropriation and authorization legislation to yield significant advancements in CDR RD&D.

We consider three main categories of CDR approaches in this paper: natural, technological and hybrid. Natural solutions include, but are not limited to, improved land management through reduced tillage, increased crop rotation, sowing of cover crops, and increases in forest biomass. CDR-relevant research that is not explicitly focused on CDR, but could provide important lessons for CDR includes carbon cycling in soils, forest management, conservation, and bioenergy crop production. Technological approaches include processes that capture carbon emissions and either reliably sequester them for extended periods or convert them into valuable products or commodities. Hybrid approaches include aspects both of natural and technological CDR, such as bioenergy with carbon capture and sequestration (BECCS). Although we assess how RD&D on all of these approaches could be incorporated within USDA's programs, we focus primarily on natural approaches or "land-use CDR."

This report summarizes USDA's existing program structure and funding mechanisms for research, development, and demonstration (RD&D) with potential applications to carbon dioxide removal, and offers suggestions to refocus or expand these efforts through congressional action, improved coordination, and new research offices. Section I describes the current state and structure of USDA's RD&D and REE initiatives, Section II analyzes past and current RD&D efforts relevant to CDR at USDA and other departments, and Section III provides suggestions on how to improve USDA's capacity for carbon dioxide removal RD&D.

SECTION I: RESEARCH, EDUCATION, AND ECONOMIC AND RELATED FUNCTIONS OF USDA

In the section below, we review the REE functions of USDA. Specifically, we highlight several important distinctions within these offices relevant to CDR RD&D, including: sources and types of funds, funders and performers, and intramural and extramural RD&D. The REE mission within the USDA serves many diverse functions and is detailed below in **Box 1**.

Section I: Preview

- Research, Education, and Economic priorities of USDA and their relevance to CDR
- Structure and process of funding for USDA agencies and offices
- Organizational structure of USDA offices, agencies, and leadership
- Comparative assessment of public and private funding for agricultural R&D
- Summary of intramural and extramural research institutions and agencies supported by USDA
- Summary of development, demonstration, and deployment activities funded and performed by USDA

Additionally, this section assesses how carbon dioxide removal (CDR) could be integrated into the REE functions of the USDA to advance the Chief Scientist's focus areas around renewable energy, natural resources, and environment; plant health and production; agricultural systems and technology; and agricultural economics and rural communities.

Funding for Research and Development

Currently, the two primary pieces of legislation authorizing and appropriating funds for USDA are the 2018 Agriculture Improvement Act—known colloquially as the 2018 Farm Bill—and the Agriculture, Rural Development, Food and Drug Administration, and Related Agencies Appropriations Act. Parallel to other federal departments, USDA receives funds through both the appropriations and authorization processes. Authorization laws establish, continue, or modify mandatory funds, whereas appropriations provide discretionary funding for programs that may or may not be authorized. In Sections I and II, we summarize the structure and funding of USDA agencies, as well as current and prior USDA, interagency, and related efforts to incorporate and enhance RD&D. In Section III, we consider opportunities to alter future appropriation and authorization legislation to provide additional support for RD&D relevant to CDR.

Together, the Farm Bill (**Box 2**) and the Agriculture, Rural Development, Food and Drug Administration, and Related Agencies Appropriations Act provide funds for the REE functions of USDA through intramural agencies, such as the Agricultural Research Service (ARS), the National Agricultural Statistics Service (NASS), and the Economic Research Service (ERS), which depend exclusively on federal funding. These offices carry out their RD&D functions internally through USDA staff and facilities. These two Acts also provide funding for the National Institute of Food and Agriculture (NIFA), an extramural office, which receives some additional funds from state and non-governmental institutions, but re-grants nearly all authorized and appropriated funds to institutions outside USDA to perform solicited RD&D activities, as explained below in **Box 3**. Additionally, the Under Secretary for Research, Education, and Economics, the Office of the Chief Scientist, and the Research, Education, and Economics Extension Office receive operational funding to oversee and orchestrate these offices and their programs, and ensure RD&D efforts are appropriately prioritized across the six components of the REE mission.

TABLE 1 | USDA Under Secretaries and their reporting offices, as well as their programmatic focus and funding.

Under Secretary	Agency or service	Total 2018 funding (in millions)	Science or management jurisdiction	Land use categories	Programmatic focus	Relevant CDR practices	Example programs
Under Secretary of Research, Education, and Economics	Agricultural Research Service (ARS)	$1,388	To research and deploy programs that reduce risks associated with agriculture	Cropland, pastureland, grassland, and aquaculture	Research that reduces economic and ecological risks associated with agricultural production	Agricultural soils Rangeland soils Improved wood utilization Land sparing and intensification (+BECCS/BEBCS) Improved forest management	Soil and Air Program, Sustainable Agricultural Systems Research Program, Grass, Forage, and Rangeland Agroecosystems Program
	Economic Research Service (ERS)	$87	To conduct objective economic research to inform and enhance public and private decision making	Cropland, aquaculture, and pastureland	Research that improves decision making capacity around economic issues associated with agricultural production	Land sparing and intensification Rangeland soils Agricultural soils	Resource and Rural Economics Program, Information Technology Services, and Agricultural Resource Management Survey
	National Institute of Food and Agriculture (NIFA)	$1,564	To provide leadership and funding for initiatives that ensure the long-term viability of agriculture	Cropland, grassland, and pastureland	Funding and programmatic support for research and education programs that enhance the sustainability of agriculture	Agricultural soils Land sparing and intensification Rangeland soils Improved forest management Improved wood utilization (+BECCS/BEBCS) Urban forestry and agriculture	Sustainable Agricultural Systems, Global Change and Climate Programs, and Agriculture and Food Research Initiative
	National Agricultural Statistics Service (NASS)	$191	To provide timely and accurate statistics and data sets on nearly every aspect of agriculture	All land use types	Research to develop objective and unbiased statistics on agriculture needed by people working in and depending upon U.S. agriculture	Land sparing and intensification Rangeland soils Agricultural soils	US Agricultural Census, Crops and Plants, Economics and Prices, and Research, Science and Technology
Under Secretary for Farm Production and Conservation	Natural Resources Conservation Service (NRCS)	$5,202	To provide farmers and ranchers with financial and technical assistance to voluntarily implement conservation practices	Cropland, rangeland, and pastureland	Financial and technical assistance to land managers implementing conservation practices, as well as decision assistance	Land sparing and intensification Rangeland soils Agricultural soils Aquatic ecosystems Improved forest management	Conservation Technical Assistance Program, Landscape Conservation Initiatives, Conservation Stewardship Program, and Environmental Quality Incentives Program
	Farm Service Agency (FSA)	$2,035	To equitably serve all farmers, ranchers, and agricultural partners through the delivery of effective, efficient agricultural programs for all Americans	Cropland, rangeland, and pastureland	Research and extension services with a diverse and multi-talented work force, dedicated to achieving an economically and environmentally sound future for American Agriculture.	Land sparing and intensification Rangeland soils Agricultural soils Improved wood utilization (+BECCS/BEBCS)	Conservation Reserve Program, Emergency Forest Restoration Program, Grassland Reserve Program, Biomass Crop Assistance Program
Under Secretary for Natural Resources and Environment	United States Forest Service (USFS)	$6,649	To sustain the health, diversity, and productivity of the nation's forests and grasslands	Forests and rangelands	Research and extension services that help to preserve the long-term viability of forestry and agriculture	Land sparing and intensification Rangeland soils Improved forest management Improved wood utilization (+BECCS/BEBCS) Urban forestry and agriculture	Forest Inventory and Analysis, Experimental Forests & Ranges, and National Forest System

We segregate land use types into crop (row-crop agriculture), pasture (seeded and heavily managed grazing lands), range (natural ecosystems in which the climax vegetation is primarily grasses), forests (ecosystems in which at least 10% of surface area is covered by trees), and aquaculture (natural or artificial). Authors' analysis, with 2018 Budget Summary data from USDA. BEBCS, Bioenergy with Biochar Systems; BECCS, Bioenergy with Carbon Capture and Storage.

Box 1 | Research, Education, and Economic priorities of the Chief Scientist.

As shown below in **Figure 1** the National Agricultural Statistics Service, the National Institute for Food and Agriculture, the Agricultural Research Service, and the Economic Research Service all report to the Chief Scientist. At USDA the Chief Scientist also serves the role of the Under Secretary for Research, Education, and Economics. The focus of the Chief Scientist is to align the research objectives and programmatic focuses of these four agencies across six focus areas within the REE mission: (1) renewable energy, natural resources, and environment; (2) food safety, nutrition, and health; (3) plant health and production; (4) animal health and production; (5) agricultural systems and technology; and (6) agricultural economics and rural communities.

Box 2 | The "Farm Bill."

The 2018 Agriculture Improvement Act, known commonly as the "2018 Farm Bill," is an omnibus bill composed of twelve titles, providing roughly half a trillion dollars in funding for various USDA functions over a period of 5 years. The titles include (1) Commodities, (2) Conservation, (3) Trade, (4) Nutrition, (5) Credit, (6) Rural Development, (7) Research and Extension, (8) Forestry, (9) Energy, (10) Horticulture, (11) Crop Insurance, and (12) Miscellaneous (Johnson and Monke, 2008; Chite, 2014). The bill is renewed roughly every 4 years and has gone by an array of different titles since its inception, but was originally established as the Agriculture Adjustment Act in 1933. While roughly 80% of the funds appropriated through the 2014 Farm Bill were allocated to Title IV: Nutrition, the Bill also provides billions of dollars in financial support to America's rural constituencies through crop insurance, conservation payments, and loan support (Monke, 2018).

Although Congress has updated research and development priorities through the Farm Bill in recent years, the annual appropriations process provides the most frequent opportunity to amend these priorities.

Structure of Research Offices

As shown in **Figure 1**, all USDA Offices, Assistant Secretaries, and Under Secretaries report directly to the Secretary. Within USDA, the most relevant Under Secretaries for CDR RD&D include the Under Secretaries for Natural Resources and the Environment, Farm Production and Conservation, and Research, Education, and Economics. Below in **Figure 1**, we highlight agencies within the Chief Scientist's REE authority, as well other agencies with related RD&D objectives, with the potential to support the advancement of CDR technologies and land management strategies.

Intramural and Extramural Funding

In 2018, REE programs received a total of $3.04 billion with $1,343.4 million to the ARS, $1,407.8 million to NIFA, $191.7 million to NASS, and $86.8 million to ERS (Monke, 2018). Intramural organizations are primarily supported through annual federal appropriations bills, which provide funding for staff salaries, facilities, and operating expenses (Monke, 2018). Conversely, offices that support extramural research, such as NIFA receive federal funding for a small group of staff that are responsible for distributing the majority of appropriated and authorized federal funds to Land Grant Universities and Colleges, non-profits, and for-profit corporations, through both formula funds and competitive grants.

Box 3 | Funding: competitive and formula, intramural and extramural, and mandatory and discretionary.

Within USDA, there are "funders," or offices without research capacities that re-grant nearly their entire budget to other institutions, and "performers," or offices that have the capacity to perform R&D activities internally. These performers can be either intramural, meaning they operate within a USDA office, or extramural, meaning the funds are transferred to external institutions or organizations that perform the research on behalf of USDA. These funds can be competitive, meaning all qualified institutions may submit proposals to perform the solicited work, or predetermined as "formula funds" through USDA's appropriations requests. Finally, funds provided to USDA are either mandatory or discretionary. Discretionary funds are revisited annually through the appropriations process, whereas mandatory funds are established in the Farm Bill and are fixed for the entire period of that bill. While there is significant overlap between mandatory and formula funds, some discretionary funding is disseminated through formula funds. For example, discretionary funding provided to NIFA supports formula funds to Land Grant Universities and Colleges. Conversely, some mandatory funds support competitive grant programs, such as NIFA's Biomass Research and Development Initiative.

Formula funds for extramural research, originally established and primarily authorized through the Hatch and the Smith-Lever Acts, provide a base level of support to Land Grant Universities and Colleges and their associated Cooperative Extension Services (Pearson and Atucha, 2015). These institutions are also provided an opportunity to submit proposals for competitive grants which are open to all qualified organizations identified in **Box 4**, and are funded through both discretionary and mandatory funds. While funding for intramural research at USDA agencies is exclusively federal, funding for Land Grant Universities and Colleges and State Agricultural Experiment Stations (SAES) is significantly more diverse. In addition to federal formula funds, Land Grant Institutions and SAES locations also receive support through research grants and contracts from private companies, research grants from trade groups, state governments, philanthropies, and individuals, and revenue and fees from the sale of products, services, and technology licenses.

To demonstrate the scale at which USDA both funds and performs applied research, we compare public and private investment in agricultural research to that of renewable energy. As shown in **Figure 2**, public investment in RD&D for renewable energy sources exceeded that of agriculture for the first time in recent history in 2013. While renewable energy RD&D receives roughly equal support from public and private sources, agricultural research has predominately been supported by the private sector. This is significant with respect to CDR as over half of private investment in RD&D is directed toward crop and seed biotechnology alone (Fuglie et al., 2018). Since the private sector invests almost no funds in research on climate mitigation or natural resource conservation for agriculture, much of this work has been taken up by REE offices, making the USDA an ideal actor to begin work on a variety of important research questions at the intersection of CDR and agriculture (Clancy

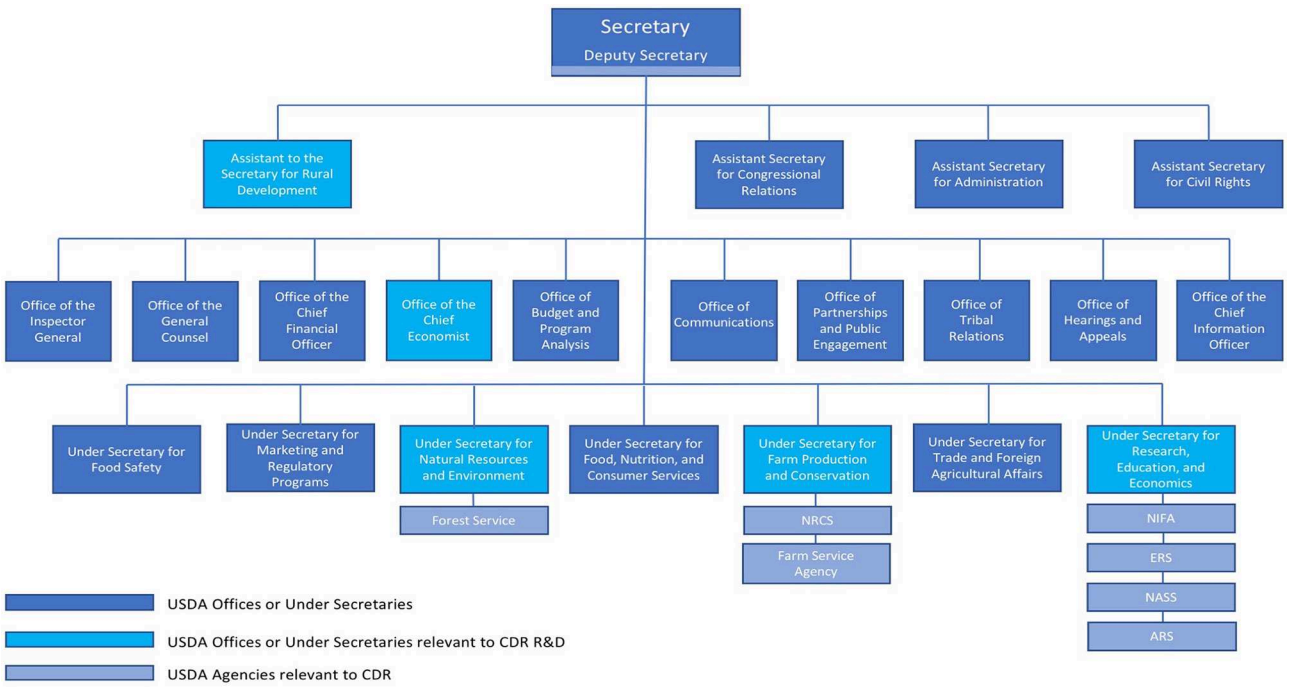

FIGURE 1 | Organizational structure of the United States Department of Agriculture, with focus on Offices and Under Secretaries with opportunities to support carbon dioxide removal (light blue), and the relevant agencies they oversee (gray-blue) (Authors' analysis of USDA Organizational Chart).

Box 4 | Eligibility for NIFA competitive grants.

Eligibility requirements for competitive grants through NIFA differ significantly across programs. The complete list of applicants eligible for at least one program includes (a) State Agricultural Experiment Station; (b) colleges and universities (including junior colleges offering associate degrees or higher); (c) university research foundations; (d) other research institutions and organizations; (e) Federal agencies; (f) national laboratories; (g) private organizations or corporations (including non-profit); (h) individuals who are U.S. citizens, nationals, or permanent residents; and (i) any group consisting of two or more entities identified in (a) through (h). Eligible institutions do not include foreign and international organizations. While not all of USDA's extramural grants have matching requirements, NIFA programs assessed in this report vary from 20 to 100% matching requirements. Notably, both Land Grant Institutions and non-Land Grant Agricultural Universities are exempt from matching requirements.

et al., 2016). Given the Under Secretary of REE's ongoing support for climate and CDR related agricultural RD&D and the private sector's minimal engagement on the topic, most agriculturally relevant CDR RD&D projects have been performed or funded within existing USDA climate and energy programs.

Despite a comparatively small budget with respect to the private sector, USDA is able to perform intramural research in addition to funding extramural research, thus leveraging additional private sector and NGO funds through matching requirements. Matching requirements for NIFA programs relevant to CDR RD&D range from 20 to 100%, and are often dependent on whether the project focuses on research, development, or demonstration. In 2009 the private sector provided 69% of all agricultural research funding, while federal and state funding contributed 21 and 10%, respectively. The utilization of these funds is relatively proportionate, with industry performing 62% of research, USDA performing 27%, and Land Grant Universities and Colleges and SAES performing 11% (Monke, 2018). Accordingly, USDA applies just over half of its REE funding to intramural research, and roughly 7% of private research funds[1] are provided to USDA intramural RD&D initiatives. In this regard, USDA is able to focus intramural efforts on research topics the private sector fails to address, while also enhancing the scale of extramural R&D through matching requirements that necessitate grantees to attract additional state, local, or private funds (Clancy et al., 2016; Fuglie et al., 2018).

Extramural and Intramural Institutions

Extramural institutions relevant to USDA's capacity to perform RD&D on CDR are the State Agricultural Experiment Sites and NIFA Land Grant Universities and Colleges (United States Department of Agriculture, 2016a). SAES sites were established through the Hatch Act in 1887, and require funds to be matched by state and local governments; however, states typically contribute several times the funds provided by USDA (Cash, 2001; Schimmelpfennig and Heisey, 2009). Federal funding for SAES locations is determined by a state's farming and rural population and funded research topics range widely

[1] These funds consist of (a) research grants and contracts from private companies, (b) research grants from trade groups, philanthropies, and individuals, and (c) revenue and fees from the sale of products, services, and technology licenses.

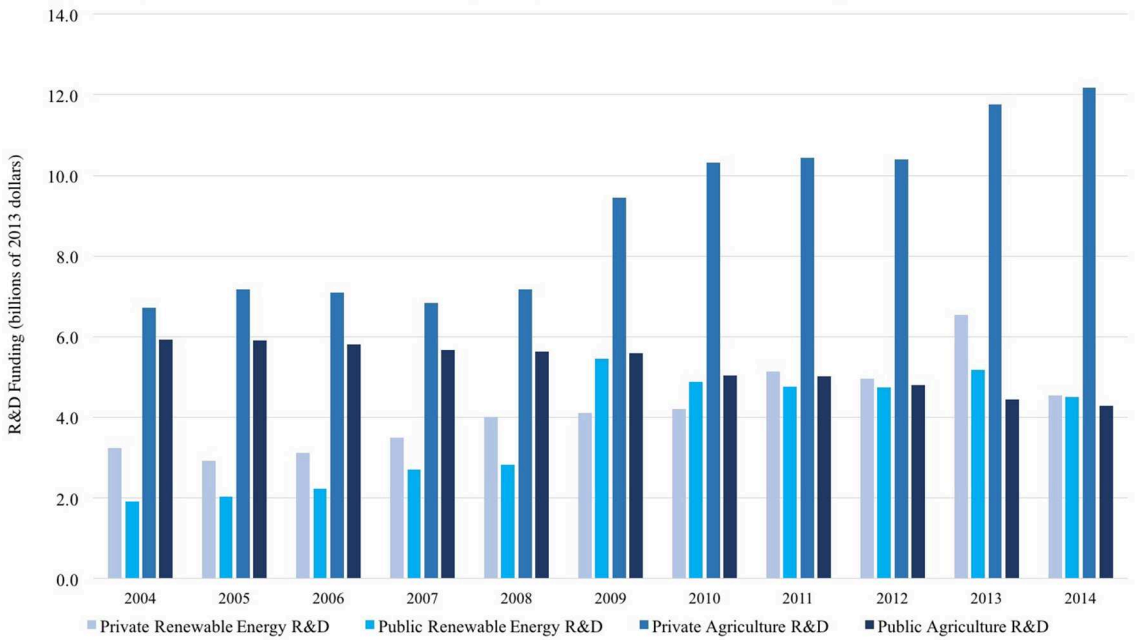

FIGURE 2 | Public and private research funding for agriculture and clean energy from 2004 to 2014 in billions of 2013 USD (Authors' analysis with data from the Economic Research Service and Bloomberg New Energy Finance).

from bioenergy crop genetics to basic carbon cycling science. Accordingly, NIFA's partnership with these localized research sites offers USDA access to and influence over roughly a hundred geographically diverse and cooperatively funded research stations.

With just over a hundred locations across the United States, Land Grant Universities and Colleges are typically paired with SAES and receive over 90% of USDA's extramural funding (King et al., 2012). The Land Grant Universities and Colleges were originally established through the Morrill Acts of 1862 and 1890, which granted federally controlled lands to states for the purpose of endowing and siting educational institutions. Since their inception, these institutions have performed research and outreach to improve the sustainability and efficiency of the agricultural sector, while also helping land manager overcome barriers to productivity.

Within the broader group of Land Grant Institutions, NIFA is also mandated through the 2014 Agriculture Improvement Act to designate Centers for Excellence[2] (COE), defined as institutions that have demonstrated exceptional efficacy at producing cost effective research, leveraging public-private partnerships, and disseminating findings to key stakeholders. Institutions identified as Centers of Excellence are provided priority when applying to funding through NIFA's competitive programs, including CDR-relevant programs, such as the Agriculture and Food Research Initiative, the Biomass Research and Development Initiative, and the Sustainable Agriculture Research and Education Program. Given the competitive nature of the funding and the wide pool of applicants, designation as a NIFA COE will be used as a tie breaker for similarly qualified applicants.

Agricultural Research Service offices, Forest Service offices, and designated USDA Climate Hubs similarly provide vital long-term scientific research in all states, however, they perform this work as intramural offices, funded directly though USDA formula funds. Particularly pertinent to CDR, the ten Forest Service and ARS offices are demarcated as USDA "Climate Hubs," intended specifically to research opportunities for agriculture and forestry operations to adapt to and mitigate the impacts of climate change. Located across the United States, USDA Climate Hubs are intra-agency ("within" agency) institutions, intended to combine expertise from ARS, USFS, and NRCS to provide regionally specific research to aid USDA technical assistance services in developing and implementing climate-informed decision-making frameworks (United States Department of Agriculture, 2016b). The Hubs are guided and overseen by an Executive Committee of senior officials within USDA, and are supported through the intramural funds provided to the associated agencies and extramural grants. These efforts are further bolstered by collaboration with the Department of Interior (DOI) and the National Oceanic and Atmospheric Administration (NOAA), making these Hubs a promising resource to harness the expertise, infrastructure, and ongoing research of multiple departments and USDA offices to research and develop opportunities to integrate CDR into agriculture and land management strategies. Given that many Climate Hubs already perform applied research on carbon sequestration in agricultural soils and vegetation, these locations could enhance and expand these efforts to develop a national network for land-use CDR.

[2]At the time of publication, NIFA had not yet announced research sites and institutions that would be designated as Centers of Excellence.

Development, Demonstration, and Deployment

Many USDA agencies focus explicitly on or perform demonstration and deployment functions alongside applied research. Offices working on demonstration and deployment initiatives include NRCS, the Forest Service, and the Cooperative Extension Service (**Box 5**).

Similar to funding for REE objectives, funds for demonstration and deployment are appropriated through the Agriculture, Rural Development, Food and Drug Administration, and Related Agencies Appropriations Act and serve to support field office operations and competitive grant programs. Additional support is also provided through the Farm Bill in order to facilitate technical assistance services, direct conservation payments, and cost-sharing programs for land managers. Funds to NRCS and the Forest Service to provide technical assistance for conservation, demonstration activities, and conservation payments to private land owners are provided through the Conservation (II) and Forestry (VI) Titles of the Farm Bill, while demonstration and deployment payments for bioenergy programs are facilitated through the Energy Title (IX) (United States Forest Service, 2017). Each of these programs has recently been, and could further be, tailored and focused to incentivize conservation and cultivation practices that sequester carbon in soils and biomass. The Forest Service and NRCS both carry out limited research activities; however, the focus of their agencies is to provide technical assistance, education, and demonstration resources to private land owners.

SECTION II: CURRENT AND PRIOR USDA TERRESTRIAL AND HYBRID CDR PROGRAMS

Below we summarize recent and current federal efforts to incorporate RD&D relevant to CDR within the programs of USDA and related departments. We focus on the recent efforts of prior administrations, led by the Office of Science and Technology Policy, DOE's Advanced Research Projects Agency-Energy (ARPA-E), and USDA's ARS and NIFA, as well as more recent legislative progress through the 2018 Farm Bill.

Box 5 | Cooperative extension service.

The Cooperative Extension Service (CES), established in 1914 through the Hatch Act, designates an obligation beyond the research and development functions of Land Grant Universities (LGU) to provide non-formal education services to empower farmers, ranchers, and communities to adapt to changing technology, prepare for and respond to emergencies, and protect the environment. As the federal partner of the Cooperative Extension System, NIFA guides and supports the development of educational priorities and curriculum through both formula and competitive funding. NIFA is responsible for leading and directing collaboration among regional offices and LGUs, in order to ensure findings from USDA research programs are disseminated to rural communities. The Service calls for leading academics at LGUs to translate scientific findings into clear language that county-level educators can teach through lessons in practical application. This work is distinct from NRCS's technical assistance function, which is intended to provide farmers and ranchers with individualized on-farm decision assistance specific to regional and practice-specific challenges.

Section I: Key findings

- The REE priorities of USDA are well-aligned with CDR RD&D
- Funding for REE agencies is roughly split between intramural and extramural research
- Private funding for agriculture RD&D has significantly exceed public funding in recent years
- USDA funds and operates hundreds of offices, institutions, and research sites across the U.S.
- Beyond research, USDA also funds and performs a variety of development, demonstration and deployment actives

Section II: Preview

- Existing interagency collaborations relevant to CDR RD&D
- Structure and function of federal initiatives outside of USDA relevant to CDR RD&D
- Prior administration efforts to research CDR opportunities in the agricultural sector
- Prior Department of Energy and the White House RD&D efforts relevant to CDR
- New programs or program updates supporting CDR RD&D in the 2018 Farm Bill

Interagency Collaboration

While USDA collaborations with other departments are currently limited, there are model programs that demonstrate the significant value and potential of interagency initiatives. The Biomass Research and Development Initiative (BRDI), originally established through the Biomass Research and Development Act in 2000, is an interagency collaboration between USDA and DOE, facilitated through NIFA. The program offers 3 years grants from $500,000 to $2,000,000 to eligible institutions for research on the production of biofuels, bioproducts, and biopower, and includes a Technical Advisory Committee that operates as an independent body to provide direction on the focus of the program. The program aims to advance the economic competitiveness of biofuels and biopower and funds projects at all levels of the supply chain (feedstock development, biomass processing, and fuel synthesis), with a focus on technologies at the research stage. Importantly for CDR RD&D, the 2018 Farm Bill revises the program to include bioproducts (chemicals or materials derived from renewable biomass) and specifies that there must be a member on the Technical Advisory Committee with expertise on technological carbon capture and utilization.

Similarly, NIFA's Agriculture and Food Research Initiative includes a partnership with DOE's Office of Biological and Environmental Research through the Plant Feedstock Genomics for Bioenergy Program. Specifically, the program aims to fund projects that research and develop techniques to better understand and improve biomass characteristics, yield, or sustainability, water and nitrogen use efficiency.

While applications are reviewed collaboratively, awards ranging from $200,000 to $400,000 are made independently by each department.

Both of these programs highlight the advantageous nature of collaborative initiatives between USDA and DOE, especially on the topics of bioenergy and carbon utilization, due to DOE's longstanding leadership on genome-scale technologies, biomass conversion, and carbon capture, and USDA's expertise on crop improvement. Moreover, ongoing partnerships between NIFA and various DOE programs demonstrate NIFA's capacity to spearhead interagency collaboration through leading extramural research programs for cross-cutting research topics like CDR. Still, interagency efforts between DOE and USDA with relevance to CDR are few and limited to NIFA completive grant programs.

As discussed previously, USDA Climate Hubs perform similar interagency research, development, and education functions, providing premier locations for high-level collaboration between USDA agencies and other departments. Populated by officials and experts from NOAA, DOI, the Cooperative Extension Service (CES), and USDA offices (including ARS, NRCS, and USFS), Climate Hubs serve as geographically diverse locations to coordinate programs across offices to ensure efforts are complementary (**Figure 3**). Operating as an amalgam of the research and outreach efforts performed across USDA offices, Climate Hubs focus on synthesizing the best available science into educational and technical assistance efforts that support land managers in adjusting their production strategies to sequester carbon and adapt to changes in climate.

Terrestrial CDR Research and Development Outside of USDA

Alongside support for many USDA offices and programs, the 2014 Farm Bill established the Foundation for Food and Agriculture (FFAR) as a non-governmental non-profit foundation. The intention of FFAR is to provide increased investment in innovative partnerships and applied RD&D critical to nourishing a growing global population. Relevant to CDR, the Foundation's charter dictates that grants be made to support plant health, production, and plant products, renewable energy, natural resources and the environment, agriculture systems and technology, and agriculture economics and rural communities. With an original endowment of $200 million, the Foundation operates across three primary programs; Fostering the Future, Challenge Areas, and Strategic Initiatives. While the Fostering the Future initiative aims to educate the agricultural researchers of the future, the Challenge Areas and Strategic Initiatives highlight specific research gaps and barriers in agriculture and fund eligible institutions to develop solutions.

Strategic Initiatives at FFAR relevant to CDR include grants to address the research challenges outlined in NASEM's *Science Breakthroughs to Advance Food and Agricultural Research by 2030* and an initiative to improve the productivity of photosynthesis. A notable success of this initiative is the recent demonstration by the Realizing Increased Photosynthetic Efficiency (RIPE) program, an FFAR grantee, of radically more efficient photosynthesis in engineered crops resulting in up to 40% increase in yield (South et al., 2019). Challenge Areas relevant to CDR include a Next Generation Crops Program and a Soil Health Program. Although the focus of these programs is increased agricultural production and resiliency, their findings could easily be applied to enhance and monitor carbon sequestration in biomass and soils.

In its brief existence, FFAR has yielded impactful advancements in a number of research topics relevant to CDR. However, the current structure and focus areas of FFAR do not effectively support CDR RD&D. For instance,

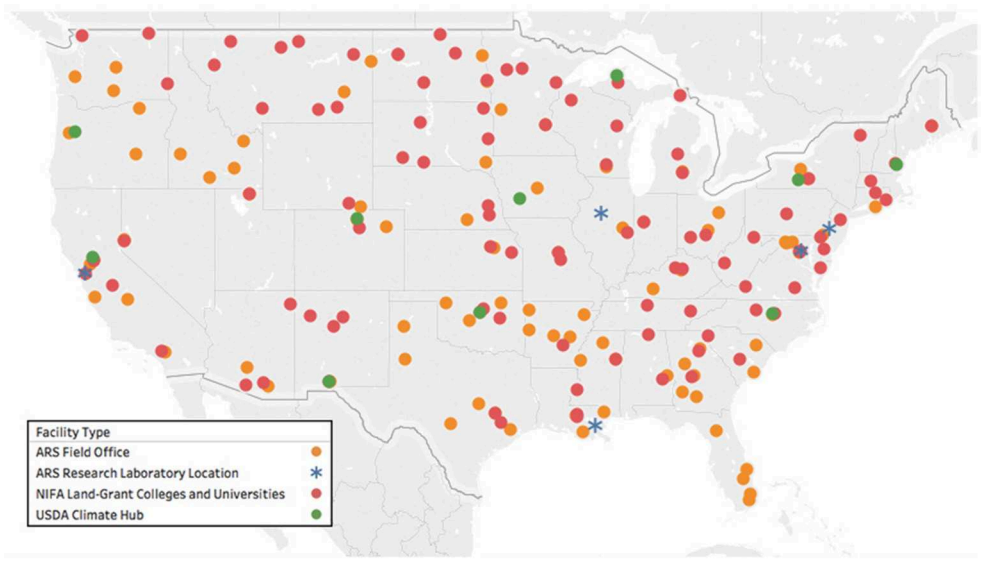

FIGURE 3 | Across the United States, USDA Climate Hubs, Land Grant Universities and Colleges, and Agricultural Research Service offices and laboratories serve as a geographically distributed network of research sites. Collectively, these facilities operate in every state, providing a diverse range of ecosystems, soil types, and climates.

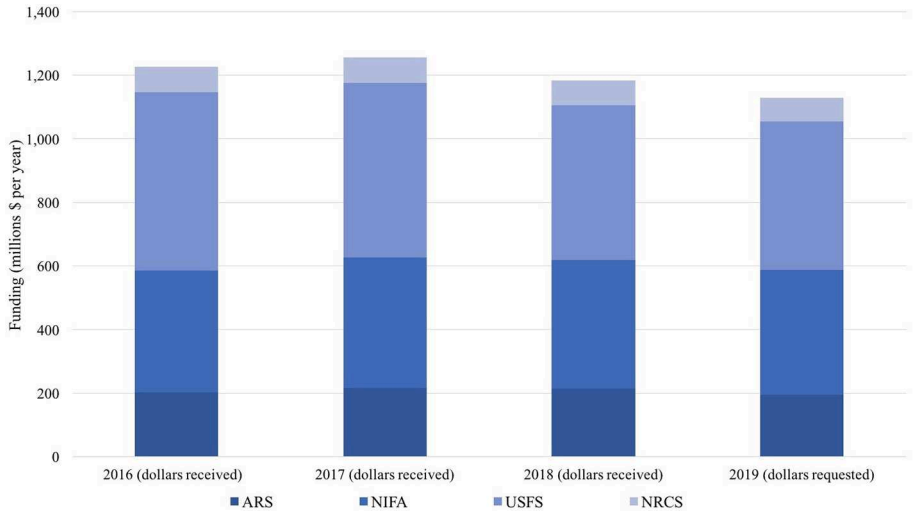

FIGURE 4 | Funding for climate and energy programs within USDA. NIFA funding includes the Agriculture and Food Research Initiative, the Sustainable Agriculture Research and Education Program, the Biomass Research and Developmental Initiative, the Biodiesel Fuel Education Program, and the Renewable Resources Extension Act. ARS funding includes the Environmental Stewardship Program. Forest Service funding includes the Forest and Rangeland R&D Program. NRCS funding includes the Soil Survey Program [Authors' analysis with data from United States Department of Agriculture (2018, 2019) Budget Justification Summaries].

FFAR has one-to-one grant matching requirements for most programs that make it difficult for applicants to qualify for funding. Additionally, as an independent foundation outside of federal jurisdiction, FFAR is not required or well-positioned to coordinate and collaborate with USDA agencies or offices, including the Office of Chief Scientist. As we discuss later in this document, FFAR's support and leadership could be augmented by DOE and USDA offices.

Similar to FFAR's strategy of supporting extramural research on topics too nascent for the private sector or intramural agencies, the DOE Advanced Research Projects Agency-Energy (ARPA-E) funds extramural research to advance high-potential, high-impact energy technologies that are too premature for private-sector investment. Although ARPA-E focuses primarily on energy technology, efforts like the Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS) program have clear applications to agriculture and land-use CDR. The ROOTS Program, housed within ARPA-E's Transportation Fuels category, provides grants for advanced phenotyping RD&D occurring at universities and national labs across the country (Advanced Research Projects Agency, 2016). Given the program's explicit goal of developing phenotypes with enhanced capacities to store carbon dioxide in soils, the program's results have clear applications to a variety of agricultural crops and conservation practices intended to sequester carbon dioxide. Specifically, the ROOTS program aims to develop crop varieties with enhanced root structures that sequester 50% more carbon in soils, while also reducing N_2O emissions. Similarly, ARPA-E's Transportation Energy Resources from Renewable Agriculture (TERRA) program is facilitating improvement of advanced biofuel crops, specifically energy sorghum, by developing and integrating remote sensing platforms, data analytics tools, and high-throughput plant breeding technologies.

Prior Administration Efforts: Climate-Smart Agriculture

During recent administrations, USDA has been empowered to develop programs that not only adapt to, but also mitigate the risks associated with climate change. No program is more noteworthy than USDA's initiative on Climate Smart Agriculture and Forestry, developed as a domestic contribution to FAO's international Global Alliance for Climate Smart Agriculture. The initiative, unveiled in 2014 by then-Secretary Tom Vilsack, sought to develop and deploy new technologies and data systems to support land managers in a rapidly changing climate, while also reducing carbon emissions from land use and agricultural production (Sanchez et al., 2018). In 2015, USDA's *Building Blocks for Climate Smart Agriculture and Forestry* set an aggressive objective of reducing agricultural emissions by 120 million metric tons of carbon dioxide per year by 2025 (United States Department of Agriculture, 2010). With regard to CDR, the program focuses on enhanced carbon sequestration in agricultural soils, grassland and pasture stewardship, promotion of hardwood products, and improved forest management.

Funding for programs focused on climate and energy have remained relatively constant (**Figure 4**). Beyond mere road-mapping, USDA had already begun work on many of the research gaps relevant to land-use CDR. In 2009, for instance, ARS began work on series of biochar[3] trials in an effort to evaluate the efficacy of the substance as a soil amendment and water purification substrate under the USDA-ARS Biochar and Pyrolysis Initiative. The Initiative included a 2007–2010 program intended to evaluate opportunities for carbon sequestration in

[3]Biochar is black carbon produced from biomass sources (i.e., wood chips, plant residues, manure, or other agricultural waste products) for the purpose of transforming the biomass carbon into a more stable form (carbon sequestration).

conventional and novel agricultural systems (funded at $11 million), and another ARS program from 2008 to 2011, to assess and quantify the capacity of biochar to sequester carbon and enhance crop yields (funded at $2.8 million) (United States Government Accountability Office, 2010). This work was expanded in the 2010 budget through an additional $9 million in funds to the Environmental Stewardship Program to perform research on commercially viable technologies to enhance and quantify carbon sequestration in agricultural lands (United States Department of Agriculture, 2015). Collectively, these piecemeal initiatives demonstrate progress, yet greater funding and a refocusing of programmatic structures and objectives within USDA will be required to advance these solutions toward commercial deployment.

Prior Administration Efforts: Other Programs

In recent years, the U.S. Department of Energy has also provided moderate yet meaningful levels of support for land-use CDR. For instance, in 2010, the DOE's National Energy Technology Lab (NETL) published *Best Practices for Terrestrial Sequestration of Carbon Dioxide* through the Regional Carbon Sequestration Partnership (RCSP), offering a research agenda and roadmap for improving carbon sequestration in agricultural soils, forests, and rangelands (National Energy Technology Laboratory, 2010). The report focuses on developing monitoring, verification, and accounting technologies and protocols for carbon sequestration in soils, forest biomass, and bio-based products. While the report and program were developed through DOE's RCSP, many of the technologies and protocols developed could effectively be implemented and deployed within existing USDA programs and improved through interagency efforts, such as the Biomass Research and Development Initiative (BRDI).

Similarly, DOE's Office of Science supports numerous scientific advances with application to terrestrial CDR, including Earth Systems Modeling and terrestrial ecosystem processes. In particular, Office of Science's Office of Biological and Environmental Research supports science and user facilities to achieve a predictive understanding of biological, earth, and environmental systems. The program seeks to understand the biological, biogeochemical, and physical processes that span from molecular scales to global scales that govern changes in watershed dynamics, climate, and the earth system. Yearly appropriations to the Office of Biological and Environmental Research are ∼$600 million.

In 2014, in response to the *Climate Action Plan–Strategy to Reduce Methane Emissions,* USDA, DOE, and the Environmental Protection Agency collaboratively produced the *Biogas Opportunities Roadmap*. The document outlined existing policies that could be modified to increase support for biogas production, as well as barriers to increased adoption of on-farm biogas systems. While the report aimed to highlight barriers and opportunities for biogas research and development at each of the departments, recent progress through the 2018 Farm Bill's Carbon Utilization and Biogas Education Program has put these learnings into practice. Specifically, the Biogas Education Program aims to educate agricultural producers on the energy, economic, and emissions benefits of implementing on-farm biogas systems.

In 2016, the White House Office of Science and Technology Policy (OSTP) produced a federal framework for soil science, developed in collaboration with more than a dozen other agencies. The release of OSTP's *The State and Future of U.S. Soils* for public comment began a process to established a framework to assesses and overcome three challenge and opportunity categories (land use and land cover change, unsustainable management practices, and climate change) and outlined opportunities for departments to expand or alter existing programs to overcome these challenges (White House Council on Environmental Quality, 2015). These findings helped to guide and motivate ARS to expand soil and climate research at long-term agricultural research sites, NIFA to establish new grant programs for soil health research, and the USFS to develop new models to assess and monitor carbon stocks in soils and biomass under a changing climate (White House, 2016).

Carbon Dioxide Removal in the 2018 Farm Bill

The 2018 Agriculture Improvement Act or "Farm Bill" establishes a variety of new research programs, funding opportunities, and task forces to aid the development and deployment of CDR land use strategies and technologies. Within the omnibus bill, modifications with applications to CDR fall into four main titles; Conservation (Title II), Research, Extension, and Related Matters (Title VII), Forestry (Title VIII), and Energy (Title IX). Within these new provisions, the 2018 Farm Bill supports and incentivizes research on a portfolio of CDR solutions, including land use (soils, forestry, and grazing management), hybrid (bioenergy and biogas/renewable natural gas), and technological (carbon utilization) carbon removal solutions (**Table 2**).

First, the Conservation Title makes extensive improvements to existing programs by incorporating soil carbon sequestration as an explicit criterion of assessment within subtitles, such as the Environmental Quality Incentives Program (EQIP) and the Conservation Stewardship Program (CSP). The Conservation Title, through the Soil Health Demonstration Trial Program, also mandates the quantification of soil carbon sequestration under various conservation and management practices across the country. This program also includes a demonstration component in order to educate land managers on these management and conservation practices, and reinforces the deployment incentives offered through CSP and EQIP with applied education and technical assistance.

These novel soil and conservation efforts are also well-complemented by technology focused programs in the Research and Extension Title (VII). Funded through the 2018 Farm Bill, the Agriculture Advanced Research and Development Authority (AGARDA) Pilot provides $50 million annually for grants to support the development of new technologies that help to enhance the resilience of agricultural systems in response to a changing climate and extreme weather events. The program is a component of the Office of the Chief Scientist, and is intended to be a collaborative effort between the USDA, other federal agencies, and FFAR. Six months from the enactment of

TABLE 2 | 2018 Farm Bill titles and subtitles relevant to CDR and new programs or updates to existing programs that directly support CDR RD&D (Authors' analysis of the 2018 Farm Bill Conference Report).

Title	Subtitles relevant to CDR	New CDR relevant programs or program updates
Title II Conservation	Subtitle B—Conservation Reserve Program Subtitle C—Environmental Quality Incentives Program & Conservation Stewardship Program Subtitle F—Agricultural Conservation Easement Program Subtitle G—Regional Conservation Partnership Program	On-farm conservation innovation trials for soil carbon EQIP and CSP incentives for practices that increase soil carbon Soil Health Demonstration Trial Program Advanced grazing management to increase soil carbon Soil Health and Income Protection Pilot Program
Title VII Research and Extension	Subtitle A—Agricultural Research, Extension, and Teaching Policy Act Subtitle B—Food, Agriculture, Conservation, and Trade Act of 1990 Subtitle D—Food, Conservation, and Energy Act of 2008 Subtitle F—Other Matters	Appropriate Technology Transfer for Rural Areas Program Research Equipment Grants for Land Grant Institutions Agriculture Advanced Research and Development Authority Pilot Sustainable Agriculture Technology Development and Transfer Algae Agriculture Research Program Biomass Research and Development Initiative's inclusion of Carbon Dioxide
Title VIII Forestry	Subtitle A—Cooperative Forestry Assistance Act of 1978 Subtitle B—Forest and Rangeland Renewable Resources Research Act Subtitle C—Global Climate Change Prevention Act of 1990 Subtitle D—Healthy Forests Restoration Act of 2003 Subtitle F—Forest Management	State and Private Forest Landscape Scale Restoration Program Healthy Forests Restoration Act: Carbon Sequestration Amendment Healthy Forest Reserve Program: Carbon Sequestration Amendment
Title IX Energy	Sec. 9002. Bio-based markets program Sec. 9004. Repowering assistance program Sec. 9005. Bioenergy program for advanced biofuels Sec. 9009. Feedstock flexibility Sec. 9010. Biomass Crop Assistance Program Sec. 9011. Carbon utilization and biogas education program	Carbon Utilization and Biogas Education Program

the 2018 Farm Bill, the Chief Scientist will select an AGARDA director that will be responsible for assembling a team to develop project solicitations as well as a strategic plan for the program. This work has the potential to fill many of the technology and knowledge gaps discussed in the Obama administration's *Building Blocks for Climate Smart Agriculture and Forestry* and the Regional Carbon Sequestration Partnership's *Best Practices for Terrestrial Sequestration of Carbon Dioxide.* The Research and Extension Title (VII) also makes important amendments to the Biomass Research and Development Initiative (BRDI), an interagency effort of USDA's NIFA and DOE's EERE. The initiative focuses on developing novel feedstocks as well as bio-products and biofuels, and through the 2018 Farm Bill, now offers funding opportunities for projects focused on the utilization or permanent sequestration of carbon dioxide. Specifically, the text authorizes BRDI to fund projects utilizing carbon dioxide that is byproduct of the production of bio-products or biofuels.

Within the Forestry Title (VII), the State and Private Forest Landscape Scale Restoration Program and the Healthy Forests Restoration and Reserve Programs now take an expansive and explicit focus on carbon sequestration, through both management and conservation practices. The modified Healthy Forests Restoration and Reserve Programs now require that funded forest management plans for land use change, vegetation treatment, or structural management include or evaluate the potential for implemented practices to impact or enhance carbon sequestration.

On the technology front, the Energy Title (IX) also makes important advancements through the Carbon Utilization and Biogas Education Program. The program authorizes $1 million per year for each of two subprograms; a program offering technical assistance and education on carbon dioxide utilization for rural communities with a focus on rural development and economic opportunity and another program offering technical assistance for the development of on-farm biogas systems. These funds will be deployed competitively to appropriate institutions that have demonstrated expertise and experience working on the technical and educational challenges surrounding these issues.

While all of these efforts are productive and praiseworthy, funding for conservation and land management programs within the Farm Bill compose a small percent of total funding, and an even smaller portion is dedicated to programs with potential applications to CDR. In the 2014 Farm Bill, the Conservation Title received 5.8% of funding ($28,165,000,000), the Research Title received 0.2% of funding ($800,000,000), the Energy Title received 0.2% of funding ($625,000,000), and the Rural Development ($218,000,000) and Forestry ($8,000,000) Titles received <0.1% of total funding (Monke, 2018). While the magnitude of these funds is significant, most of these funds have been authorized or appropriated for existing programs with little relevance to CDR. Accordingly, congressional action will likely be needed to develop new programs, or expand existing programs in order to incorporate and support CDR RD&D within USDA.

SECTION III: OPPORTUNITIES TO IMPROVE REE AT USDA

In this section, we provide recommendations to enhance USDA's capacity to perform RD&D on CDR

Section II: Key findings

- DOE and USDA currently lead multiple interagency research initiatives on CDR relevant topics
- FFAR and DOE's ARPA-E both lead initiatives dedicated to enhancing soil carbon sequestration
- Prior administration efforts to establish land-use CDR research have been largely discontinued
- OSTP and DOE established a number of CDR relevant initiatives that could be reinstated
- The 2018 Farm Bill establishes a variety of new RD&D programs and provisions for land-use and engineered CDR

Section III: Preview

- Strategies for USDA to lead inter-agency and intra-agency efforts for CDR RD&D
- A strategy for OSTP to reinitiate, coordinate, and expand its prior research efforts on CDR
- Recommendations to improve the alignment and coordination of FARR and USDA programs relevant to CDR
- Recommendations for an integrated technology incubator program across USDA agencies and Land Grant Universities and Colleges
- Opportunities for congressional action to implement the National Academies of Sciences, Engineering, and Medicine's recommended CDR RD&D research programs
- An outline for a new research agency within USDA using the Advanced Research Projects Agency (ARPA) model

through congressional action or improved inter-agency and intra-agency coordination. We offer recommendations for increased coordination within USDA through OCS, improved collaboration between FFAR and USDA on CDR, the establishment of a new research office and technology commercialization program at USDA, and additional programs that could be authorized through congressional action.

Agency-Led Efforts to Increase CDR RD&D

USDA possesses robust intra-agency ("within" agency) and inter-agency ("between" agencies) science coordination capabilities through its Office of Chief Scientist. Notably, OCS communicates with other science-performing agencies within the federal government, including the Department of Energy. We believe that OCS is a durable framework to promote intra- and interagency coordination on CDR RD&D at USDA.

Nevertheless, several actions could increase CDR RD&D efforts within USDA. First, USDA could empower its Science Council, which advises the Secretary and Chief Scientist, to study terrestrial CDR. For instance, it could establish a team or committee to advise on coordination efforts across USDA offices, including REE offices, Forest Service, NRCS, the Farm Service Agency, and the Office of the Chief Economist (OCE), as well as the Office of Energy and Environmental Policy within OCE. Second, OCS could prioritize inter-agency coordination activities focused on CDR, including diverse agencies like the Environmental Protection Agency, and the U.S. Department of Interior. This could build on the lessons from the Biomass Research and Development Initiative, which coordinates with DOE. Finally, CDR RD&D could benefit from Secretary-level engagement. Each of these actions could coincide with a funding increase or other legislative interventions to support CDR RD&D.

White House-Led Efforts to Increase CDR RD&D

As discussed in Section II, OSTP's *The State and Future of U.S. Soils* helped to guide and motivate ARS, NIFA, and USFS to expand their soil and climate research. While a draft of the report was circulated for public comment in 2016, a finalized version of the report has not been published. OSTP or USDA could revise the report to reflect public comments and publish a final draft of the report, solidifying a research agenda to guide the Office. The impact of OSTP's framework in motivating new research demonstrates the Office's unique capacity to orchestrate interagency RD&D efforts alongside public-private partnerships, largely through the expansion and modification of existing efforts and infrastructure. Previous scholarship has emphasized the role OSTP could play in catalyzing RD&D across CDR technologies (Sanchez et al., 2018). Notably, OSTP may be able to satisfy key criteria for efficient and effective CDR RD&D, including embracing technological diversity and administrative efficiency, fostering agency buy-in, and achieving commercial deployment. Undoubtedly, USDA would play a large role in any OSTP effort to coordinate or enhance CDR RD&D.

Improved Coordination Between FFAR and USDA

As discussed in Section II, a portion of FFAR grants are explicitly intended to address the breakthrough RD&D advancements identified by NASEM in the *Science Breakthroughs to Advance Food and Agricultural Research by 2030* (Breakthroughs 2030) report. The NASEM highlight five main focus areas: (1) microbe productivity in guts and soils, (2) advancements in genetic evaluation and engineering, (3) expanding and enhancing agricultural datasets, (4) developing and improving sensors and biosensors across agriculture, and (5) using transdisciplinary analysis to develop system-wide methods to increase production (National Academies of Sciences, Engineering, and Medicine, 2018a,b). As discussed below, each of these focus areas has the ability to catalyze CDR, either through increased carbon storage in land or land-sparing through increased productivity.

First, the Breakthroughs 2030 report makes recommendations for improved analysis of the role of the microbiome in cycling carbon among other nutrients within soils, and seeks to provide a better understanding of these processes in the broader context of animal and plant interactions. Results from this research could better inform best management practices for carbon sequestration, and biologically enhance the efficiency with which microbial communities cycle and store carbon in soils. Second, with regard to genetic evaluation and engineering, it is clear that advancements in this field could complement and inform the phenotyping efforts for bioenergy feedstocks currently occurring through AFRI and BRDI programs, resulting in more productive

TABLE 3 | To define core research topics, FFAR solicited NASEM to produce the *Science Breakthroughs to Advance Food and Agriculture by 2030* report.

Science breakthroughs to advance food and agricultural research by 2030 as adopted by FFAR	Related CDR research needs identified in negative emissions technologies and reliable sequestration
The potential of microbiomes—in the animal gut, in soil, and everywhere in between—to increase efficiency and overcome obstacles in production	Soil dynamics at depth
Advancements in genetic evaluation and editing, including making the most of CRISPR and other technologies to accelerate the evolution of food production	High carbon input crop phenotypes
Expanding and analyzing the many pools of data involved in growing and producing food	Monitoring of forest stock enhancement projects A National on Farm Monitoring System Data-model platform for predicting and quantifying agricultural soil carbon removal and storage
Developing and improving sensors and biosensors across all agricultural sectors to increase productivity and better target interventions	Soil dynamics at depth Monitoring of forest stock enhancement projects A National on Farm Monitoring System
Examining, through transdisciplinary collaborations, entire systems in food production and finding the keys to adapting and transforming them to overcome challenges and increase production	Experimental network improving agricultural soil carbon processes Biochar studies Scaling carbon sequestering agricultural activities

The focus areas identified in the report are aligned with related research topics also identified by NASEM the same year in their recent Negative Emissions Technologies and Reliable Sequestration report on CDR.

and efficient bioenergy feedstocks. Additionally, results in this focus area could also support the advanced phenotyping efforts occurring through the ROOTS program at ARPA-E, supporting and expediting the creation of crops with advanced carbon sequestering root networks.

While much work is required to enhance and standardize agricultural datasets, the development of sensors and these datasets in unison will be mutually beneficial, and could improve the accuracy and accessibility of carbon stock and flux datasets. Moreover, as demonstrated in **Figure 3**, the immense number of USDA agricultural research sites could easily facilitate data collection on carbon stocks and fluxes at high geographical and temporal resolution.

As discussed in Section I, FFAR is a non-governmental foundation and is not incentivized or required to coordinate with USDA or other federal departments. **Table 3** demonstrates the substantial overlap in the Breakthroughs 2030 NASEM report commissioned by FFAR and the more recent NASEM report on CDR. Given that many of FFAR's current research priorities overlap heavily with research needed to catalyze CDR, improved coordination between USDA and FFAR could allow many of FFAR's existing programs to support significant research on CDR. Through formal or informal alterations to FFAR's mission and charter, FFAR leadership could improve coordination among USDA and FFAR research objectives to resolve jurisdictional conflicts and duplicative efforts to strengthen the impact of both organizations' initiatives relevant to CDR. By aligning the focus of FFAR Challenge Areas and Strategic Initiatives with ongoing USDA research efforts at the executive level, staff at FFAR and USDA would be able to more effectively communicate and complement each other's work, resolving disputes that could arise around duplicity and dominion. Moreover, explicit direction for improved coordination through FFAR and USDA leadership could empower FFAR grantees both in and outside of USDA to more strategically access and align with the resources provided by REE agencies. Finally, informal convening among USDA and FFAR staff could help to develop and strengthen relationships and coordination between staff at both entities.

With greater cooperation between USDA and FFAR, FFAR could explicitly incorporate CDR research within relevant programs, or establish a new program exclusively dedicated to land-use CDR within its Challenge Areas. Additionally, FFAR could decrease or eliminate matching requirements for USDA agencies and institutions exempt from NIFA matching requirements to support projects unlikely to receive additional support from the private sector. Finally, through the USDA's network of technical (ARS, FSA, and USFS), social science (ERS and NASS), and transdisciplinary (NIFA and NRCS) agencies, USDA could offer substantial resources and expertise to FFAR in integrating CDR research within their existing programs. Accordingly, FFAR could also offer USDA greater financial support to pursue research topics related to CDR through its existing programs or a new program dedicated to CDR. Finally, through increased coordination among officials at USDA and FFAR, extramural research initiatives at the department and the foundation could be structured in a complementary and mutually beneficial manner.

Improving Commercialization Support Within USDA Agencies

In order to accelerate the commercialization of the technologies and processes needed to supplement and support the R&D efforts occurring at USDA agencies, additional entrepreneurial and tech-to-market support will likely be necessary. While ARS laboratories and FFAR and NIFA grant programs have effectively delivered impactful discoveries at the research stage, these processes and technologies must rapidly scale and mature beyond the laboratory in order provide benefits to land managers. In addition to the funding provided through USDA extramural grant programs, mentorship, market intelligence, facilities, and professional development trainings could all help to accelerate

the transition academic research projects into commercial technologies. In order to rapidly develop the research occurring at ARS laboratories and Land Grant Universities and Colleges into scalable technologies, researchers will need to acquire the skills necessary to secure private investment.

Specifically, proven curriculums from national lab and university technology incubator and accelerator programs could provide excellent models for the creation of a similar program embedded within REE agencies. Broadly, incubators and accelerators are structured programs intended support early stage companies and technologies in order to expedite the commercialization process. While the difference between accelerators and incubators is not well-established, incubators generally operate on an open timeline with less structured curriculum, whereas accelerators have a strict timeline and intensive curriculum (Kushner, 2018). With laboratories located across the US in close proximity to national laboratories, ARS could establish a federal technology incubator program to accelerate the maturation of promising research to commercialized technologies with the capacity for wide-spread deployment.

There is also clear precedent for the establishment of an incubator program within a federal department. DOE's Energy I-Corps, a specialized version of NSF I-Corps curriculum, pairs teams from national labs with industry mentors in order to teach researchers commercialization and business skills through condensed 2-months curriculum. The I-Corps program operates sites at dozens of universities and colleges throughout the US, providing facilities and expertise to researchers and engineers working to commercialize their technologies. An incubator positioned within USDA could offer similar opportunities through the ARS laboratories, research offices, Land Grant Universities and Colleges, and partnerships with national laboratories. Moreover, NIFA Centers of Excellence, having already demonstrated an exceptional capacity for commercialization, education and extension work, could provide valuable curriculum, expertise, and facilities for such a program. Finally, ARS laboratories could offer much needed facilities for entrepreneurs to quickly test and improve their technologies.

Several national laboratories already have incubator or accelerator programs, including Argonne National Laboratory, National Renewable Energy Laboratory, and Lawrence Berkeley National Laboratory. Notably, Cyclotron Road at Lawrence Berkeley Laboratory has demonstrated particularly strong results. Since 2015, the program has provided $15 million in financial support to 41 fellows who have gone on to attract over $80 million in support for their projects. Focused on electronics, clean power, and advanced manufacturing, the program provides entrepreneurial scientists with a 2-years fellowship that includes funding, mentorship, professional development and training, and access to university and national laboratory facilities. The Cyclotron Road model could allow ARS to recruit and mature nascent technologies crucial to measuring, increasing, and enhancing CDR deployment in agricultural, natural, and working lands in the US. A similar program within USDA could leverage a small amount funding to drastically expand the impact of ongoing intramural and extramural research occurring through the department's agencies.

Opportunities for Congressional Action on CDR RD&D

In 2018, the National Academies of Science, Engineering, and Medicine (NASEM) published *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda,* assessing key knowledge gaps in the field of carbon dioxide removal. The report evaluates these gaps and recommends research projects and appropriate funding levels sufficient to address these knowledge and technology gaps. **Table 4** aligns these projects and funding recommendations along the categories of research, development, demonstration and deployment, and makes suggestions for which offices and programs could best house this research, as well as the legislative actions(s) needed to facilitate these programs. Many agencies within USDA and DOE already operate programs similar to those recommended by the National Academies; however, additional funding at the magnitude identified in the report is crucial to unlocking these advancements in a meaningful timeframe.

With an upper bound of $1.35 billion in total additional funding over the next 20 years, USDA and DOE agencies could substantially improve the United States' capacities to research, develop, demonstrate, and deploy land-use and technological carbon dioxide removal. Below, **Table 4** designates appropriate legislative actions in the forms of additional funding, improved direction, and the authorization of new programs. In the case of many NASEM recommendations, existing programs are sufficient in scope and objective to begin research on the recommended topics, however, additional funding through the appropriations process would be needed to integrate the recommended projects. In other cases, existing funding levels and programs are sufficient, but the Appropriations Committee could add language to their report directing the scope, intention, or interagency collaboration of the research projects. Finally, some recommended research projects are entirely outside the scope of existing USDA R&D efforts and entirely new programs would need to be developed to support the recommended projects.

Funding With Offices and Legislative Actions

Some of the efforts recommended by NASEM are actionable through clear direction to agencies through appropriations report language, and in some cases, existing funding is sufficient to pursue these projects. In these instances, report language can be used to explicitly direct collaboration or coordination among agencies. Still, in many other cases, NASEM's recommendations are sufficiently novel that existing programs could not reasonably pursue this research, and the establishment of additional funding or a new program through congressional action will likely be necessary. In most cases, congressional action through the appropriations and authorizations processes will be necessary to establish and fund NASEM's recommended research programs, as existing programs are either not well-suited to

TABLE 4 | National Academies of Sciences, Engineering, and Medicine's recommended research programs and associated funding levels paired with the authors' recommendations for the best agencies to house these initiatives as well as the most effective legislative actions.

	Research focus	Funding	Time frame	Offices	Legislative action
Research	High carbon input crop phenotypes	$40–50M	20 years	DOE (EERE & APRA-E) and USDA (NIFA)	Additional funding and appropriations report language
	Soil dynamics at depth	$3–4M	5 years	USDA (ARS & NIFA)	New program, appropriations report language, and additional funding
	Harvested wood preservation	$2.4M	3 years	USDA (USFS)	Additional funding
	Biochar studies	$3M	5–10 years	USDA (ARS)	Additional funding
Development	Monitoring of forest stock enhancement projects	>$5M	≥3 years	USDA (USFS)	Additional funding
	A National on Farm Monitoring System	$5M	Ongoing	USDA (NRCS & FSA)	Additional funding and appropriations report language
	Data-model platform for predicting and quantifying agricultural soil carbon removal and storage	$5M	5 years	USDA (NASS & ERS)	Additional funding and appropriations report language
Demonstration	Forest demonstration projects: increasing collection, disposal, and preservation of harvested wood; and forest restoration	$4.5M	3 years	USDA (USFS & NRCS)	Appropriations report language
	Experimental network improving agricultural soil carbon processes	$6–9M	≥12	USDA (ARS)	New program and additional funding
	Social sciences research on improving landowner responses to incentives and equity among landowner classes	$1M	3 years	USDA (ERS)	Additional funding
Deployment	Scaling carbon sequestering agricultural activities	$2M	3 years	USDA (NRCS)	Additional funding

Recommendations for report language are included when multiple agencies or offices will require direction to coordinate on a single initiative (National Academies of Sciences, Engineering, and Medicine, 2018a,b with authors' analysis of relevant offices and legislative actions).

house this research or current funding is insufficient. **Table 5** summarizes the recommended increase in appropriations for USDA Agencies or Services based on National Academies of Sciences, Engineering, and Medicine's recommended research programs and associated funding levels paired with the authors' recommendations for the best agencies to house these initiatives.

New Research Offices

Finally, USDA can benefit from enhanced research capabilities that have proven successful in other portions of the federal government. For instance, USDA does not have many authorities granted to certain offices of the DOE and U.S. Department of Defense known as the "Advanced Research Projects Agency" (ARPA) model. These include organizational flexibility on an administrative level and significant authority given to program directors to design programs, select projects, and actively management projects (Azoulay et al., 2019). Some, but not all, of these authorities have been granted to the Advanced Agriculture Research and Development Authority (AGARDA) Pilot program in the 2018 Farm Bill, as described above. Moving forward, this Agency can evolve from the AGARDA Pilot.

Below, we propose an independent research office within USDA to focus on CDR and other climate-related research. We describe the goals, means, role of the director, personnel, and coordination authorities of a new research office, based largely off of legislation establishing ARPA-E within DOE (Gordon, 2007):

- **Goals**: The new office should focus on two primary goals: (1) to overcome the long-term and high-risk technological barriers in the development of agricultural and land management technologies related to climate change and CDR, and (2) to ensure that the United States maintains a technological lead in developing and deploying advanced agricultural and land management technologies that increase economic opportunities.
- **Means**: Much like ARPA-E, this new agency may (1) identify and promote revolutionary advances in fundamental sciences, (2) translate scientific discoveries and cutting-edge inventions into technological innovations, and (3) accelerate transformational technological advances in areas that, due to technical and financial uncertainty, industry is not likely to undertake without Federal assistance.
- **Director**: The Director should report to the Secretary and coordinate with the Chief Scientist to identify relevant scientific priorities and future trends relating to agricultural technologies. The responsibilities of the Director should include: (1) approving new programs, (2) developing funding criteria and assessing the success of programs, (3) administering funds, (4) terminating programs that are not achieving their goals, and (5) ensuring support for a diversity of agricultural practices.
- **Personnel**: Like ARPA-E, the Director should designate term-limited Program Managers. Responsibilities include: (1) establishing research and development goals for the program,

TABLE 5 | Recommended increase in appropriations for USDA Agencies or Services based on National Academies of Sciences, Engineering, and Medicine's recommended research programs and associated funding levels paired with the authors' recommendations for the best agencies to house these initiatives (Authors' analysis of USDA FY2020 Budget Summary).

Under Secretary	Agency or service	Total 2018 funding (in millions)	Relevant CDR practices	Relevant existing programs	Recommended increase in appropriations (in millions)
Under Secretary of Research, Education, and Economics	Agricultural Research Service (ARS)	$1,388	Agricultural soils Rangeland soils Improved wood utilization Land sparing and intensification (+BECCS/BEBCS) Improved forest management	Soil and Air Program, Sustainable Agricultural Systems Research Program, Grass, Forage, and Rangeland Agroecosystems Program	$14.0
	Economic Research Service (ERS)	$87	Land sparing and intensification Rangeland soils Agricultural soils	Resource and Rural Economics Program, Information Technology Services, and Agricultural Resource Management Survey	$3.5
	National Institute of Food and Agriculture (NIFA)	$1,564	Agricultural soils Land sparing and intensification Rangeland soils Improved forest management Improved wood utilization (+BECCS/BEBCS) Urban forestry and agriculture	Sustainable Agricultural Systems, Global Change and Climate Programs, Biomass, Research and Development Initiative, and Agriculture and Food Research Initiative	$27
	National Agricultural Statistics Service (NASS)	$191	Land sparing and intensification Rangeland soils Agricultural soils	US Agricultural Census, Crops and Plants, Economics and Prices, and Research, Science and Technology	$2.5
Under Secretary for Farm Production and Conservation	Natural Resources Conservation Service (NRCS)	$5,202	Land sparing and intensification Rangeland soils Agricultural soils Aquatic ecosystems Improved forest management	Conservation Technical Assistance Program, Landscape Conservation Initiatives, Conservation Stewardship Program, and Environmental Quality Incentives Program	$9.3
	Farm Service Agency (FSA)	$2,035	Land sparing and intensification Rangeland soils Agricultural soils Improved wood utilization (+BECCS/BEBCS)	Conservation Reserve Program, Emergency Forest Restoration Program, Grassland Reserve Program, Biomass Crop Assistance Program	$2.5
Under Secretary for Natural Resources and Environment	United States Forest Service (USFS)	$6,649	Land sparing and intensification Improved forest management Improved wood utilization (+BECCS/BEBCS) Urban forestry	Forest Inventory and Analysis, Experimental Forests & Ranges, and National Forest System	$12.3

Section III: Key findings

- The Office of the Chief Scientist and the Science Council could urge REE agencies to pursue CDR RD&D projects
- OSTP could catalyze and coordinate CDR RD&D across departments
- FFAR and USDA both currently fund RD&D on several topics relevant to CDR but lack coordination. Through improved communication and collaboration, the effectiveness of both entities' research efforts on CDR could be significantly improved
- USDA could leverage its facilities and technical expertise to establish a commercialization program to accelerate the development of early stage CDR technologies
- Current USDA funding is insufficient to pursue the CDR RD&D programs recommended by NASEM. Congressional action through the appropriations process could provide additional funds and direction to establish these programs within USDA agencies.
- Congress could establish a new independent research agency within USDA based on the ARPA model in order to support breakthrough research on climate and CDR

(2) soliciting applications for specific areas of particular promise, (3) building research collaborations for carrying out the program, (4) selecting projects on the basis of merit, (5) preparing technologies for an eventual transfer from lab to market, (6) monitoring the progress of projects supported under the program, (7) recommending program restructure or termination of research partnerships or whole projects.

- **Coordination**: the Agency should work with existing and new advisory committees, along with (1) the President's Council of Advisors on Science and Technology, (2) FFAR, (3) ARPA-E, (3) the Defense Advanced Research Projects Agency, and (4) other professional or scientific organizations with relevant expertise.

The authority and flexibility of this new Agency within USDA would greatly enhance REE efforts relevant to CDR RD&D within USDA.

CONCLUSION

Currently, there are a number of programs within USDA agencies performing and funding research with applications to CDR. Throughout the REE agencies (ERS, NASS, ARS, and NIFA), USFS, and NRCS, there are number of ongoing programs working to quantify, monitor, and enhance carbon storage in agricultural and working lands across the United States. However, we find that the funding for these programs is meaningfully less than the funding recommended by the National Academy of Sciences in their recent report *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Moreover, some of the agricultural and conservation RD&D programs recommended by the NASEM could not be reasonably incorporated within the scope of existing USDA programs.

Given array of ongoing research relevant to CDR occurring through USDA agencies, we conclude there are a number of strategies that could augment the department's capacity to fund and perform the RD&D projects recommended by NASEM. First, we find that there are number of efforts that could be led and coordinated through OCS and the associated Science Council to expand and enhance research on CDR. The OCS could request the Science Council to perform research on CDR and to coordinate this research across REE agencies, as well as the Forest Service and NRCS. The OCS could also coordinate interagency efforts among USDA agencies and external departments, such as DOI, DOE, and EPA.

There are also opportunities for the White House to lead efforts on CDR research at USDA, specifically through OSTP. We find that OSTP is well-positioned to help initiate and orchestrate interagency collaboration on CDR RD&D. OSTP could help agencies across USDA and related department to coordinate and collaborate on a number of key CDR RD&D projects identified by NASEM by using existing resources, such as the *State and Future of US Soils Report*.

Outside of USDA, we find significant overlap in the Strategic Initiatives and Challenge Areas funded by FFAR and the research needs for CDR identified by NASEM. Currently, FFAR's status as an independent foundation does not encourage collaboration between FFAR and USDA, however, through coordination by leadership of each organization, FFAR could more effectively fund USDA agencies and extramural institution to perform research on CDR. Voluntary engagement between executive leadership at USDA and FFAR could avoid duplicative efforts and could improve the effectiveness of both entities.

While greater interagency and intra-agency coordination could improve much of the ongoing RD&D relevant to CDR at USDA, still congressional action will be necessary to establish and fund many of the key CR RD&D projects identified by NASEM. We find that a number of these initiatives will require the establishment and funding of new research programs across USDA in order the make significant progress in actualizing CDR land management strategies. Through the appropriations and authorization processes, Congress can create new programs, provide additional funds to existing programs, and detail requests for collaboration or use funds through report language.

Finally, in the case of some nascent or high-risk CDR research projects, the establishment of a new office within USDA may be necessary. Given the success of the ARPA model, a similar program housed within USDA could support and help to commercialize long-term, high-risk research projects that could not otherwise be pursued by the public or private sectors. Beyond extramural funding, we also consider the potential benefits of an incubator or accelerator program housed within a USDA agency. Drawing inspiration from public programs like I-Corps and public-private partnerships like Cyclotron Road, we argue that a commercialization support program within USDA could help to accelerate the maturation of laboratory stage technologies toward deployment.

Notably, we do not recommend the establishment of a new research office or initiative exclusively for CDR. Instead, we argue CDR RD&D could more effectively be pursued at USDA by incorporating research into relevant existing programs, and adding additional programs within agencies with aligned expertise, missions, and facilities. USDA can pursue

multiple strategies for increasing coordination among both USDA agencies other departments, incorporating and funding new research programs within USDA agencies, adding new USDA offices, and improving USDA coordination with FFAR. Taken together, these efforts can catalyze CDR across USDA and the federal government, driving development, demonstration, and deployment across the United States.

AUTHOR CONTRIBUTIONS

DS designed the research. RJ and DS performed the research. RJ wrote the original manuscript and created figures. DS revised the manuscript.

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GLOSSARY

2018 Farm Bill—Agriculture Improvement Act of 2018
2014 Farm Bill—Agricultural Act of 2014
AFRI—Agriculture and Food Research Initiative
ARPA-E—Advanced Research Projects Agency-Energy
ARS—Agricultural Research Service
BRDI—Biomass Research and Development Initiative
CDR—Carbon Dioxide Removal
COE—Center of Excellence
DOE—United State Department of Energy
ERS—Economic Research Service
FAO—Food and Agriculture Organization of the United Nations
FFAR—Foundation for Food and Agricultural Research
FSA—Farm Service Agency
MVA—Monitoring, Verification, and Accounting
NASEM—National Academies of Sciences, Engineering, and Medicine
NASS—National Agricultural Statistics Service
NGO—Non-Governmental Organization
NIFA—National Institute of Food and Agriculture
NIH—National Institutes of Health
NRCS—Natural Resources Conservation Service
NSF—National Science Foundation
OSTP—Office of Science and Technology Policy
R&D—Research and Development
RD&D—Research, Development, and Demonstration
REE—Research, Education, and Economics
USFS—United States Forest Service