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Federal research, development, and demonstration priorities for carbon dioxide removal in the United States

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Abstract

Atmospheric carbon dioxide removal (CDR) technologies may be critical to achieving deep decarbonization. Yet a lack of technical and commercial maturity of CDR technologies hinders potential deployment. Needs for commercialization span research, development, and demonstration (RD&D) activities, including development of new materials, reactors, and processes, and rigorous monitoring of a portfolio of demonstration projects. As a world leader in supporting science and engineering, the United States (US) can play an important role in reducing costs and clarifying the sustainable scale of CDR. To date, federal agencies have focused on voluntary or piecemeal CDR programs.

Here, we present a synthesis of research and developement needs, relevant agency authority, barriers to coordination, and interventions to enhance RD&D across the federal government of the US. On the basis of agency authority and expertise, the Department of Energy, Department of Agriculture, Department of the Interior, National Oceanic and Atmospheric Administration, and National Science Foundation are most central to conducting research, funding projects, monitoring effects, and promulgating regulations. Key enablers for successful programs include embracing technological diversity and administrative efficiency, fostering agency buy-in, and achieving commercial deployment. Based on these criteria, the executive branch could effectively coordinate RD&D strategy through two complementary pathways: (1) renewing intra-agency commitment to CDR in five primary agencies, including both research and demonstration, and (2) coordinating research prioritization and outcomes across agencies, led by the Office of Science and Technology Policy and loosely based on the National Nanotechnology Initiative. Both pathways can be stimulated by executive order or Congressional mandate. Executive branch implementation can begin at any time; future Farm and Energy Bills provide legislative vehicles for enhancing programs.

1. Introduction

1.1. Necessity and current state of CDR technology

Carbon dioxide removal (CDR) technologies, also known as negative-emissions technologies, will likely be critical to achieving deep decarbonization consistent with the Paris Agreement (Sanderson *et al* 2016). Yet CDR technologies are characterized by different levels of technology readiness, and are not yet deployed at commercial scale (Lomax *et al* 2015, Fuss *et al* 2014, Sanchez and Kammen 2016). Ability to limit warming to 2 °C, pursuing 1.5 °C, would be advanced by publicly-funded research to develop and ultimately deploy carbon removal solutions that are sustainable and cost-effective (Rogelj *et al* 2015, Edmonds *et al* 2013). For example, 87% of IPCC modeling scenarios consistent with 2 °C warming involve large-scale deployment of carbon removal, while median removal in 2 °C scenarios exceeds 10 $GtCO_2\ yr^{-1}$ by 2100 (Anderson and Peters 2016, Center for Carbon Removal 2015). In many of these scenarios, large-scale CDR deployment occurs within 1–2 decades: RCP2.6, a representative IPCC scenario limiting likely warming to 2 °C, involves new capacity additions of negative-emission power plants on the order of 25 gigawatts (GW) (equivalent to about 50 average-sized coal power

plants) annually as early as 2040, despite the fact that no such negative-emission power plants are operational today (Sanchez and Kammen 2016).

CDR technologies lack both technical and commercial maturity (Lomax *et al* 2015). According to the IPCC, 'the availability and scale of [CDR] technologies and methods are uncertain and CDR technologies and methods are, to varying degrees, associated with challenges and risks (high confidence)' (IPCC 2014). Research and development (R&D) to address such challenges and risks has been endorsed by a number of prominent organizations, including the US National Academy of Sciences in 2015 (National Academy of Sciences 2015). At the same time, a number of private companies are developing CDR technologies (Holmes and Keith 2012, Choi *et al* 2011).

No country has yet implemented a CDR R&D program, despite the large gap between envisioned scales of deployment and current technological readiness. With the exception of efforts to enhance carbon stocks in forests and soils, CDR technologies are absent from the Nationally Determined Contributions (NDCs) submitted in support of the Paris Agreement, while carbon capture and sequestration (CCS)—an enabling technology for CDR—is only mentioned as a priority area in three submissions (Fuss *et al* 2016). Small levels of explicit CDR research funding—on the order of tens of millions—have been awarded by the US, United Kingdom, and Germany over the past several years (National Energy Technology Laboratory 2015, Natural Environment Research Council 2016, German Research Foundation 2013).

The United States, in particular, has capabilities that could enable it to take a leadership role in developing CDR technologies. It has particular strength in science and engineering, as well as suitable geography for demonstration and early deployment. The US federal government financed approximately $140 billion of total R&D activity in 2013, including research at more than 80 federal laboratories (Atkinson 2014). It also has a large, diverse land base capable of increased CO_2 storage, and suitable CO_2 geologic storage capacity (Follett and Kimble 2000, Birdsey *et al* 2006, Carr *et al* 2009). The Obama Administration also indicated an interest in CDR techniques. Recently, the White House Mid-Century Strategy for Deep Decarbonization affirmed the role that CDR can play in US mitigation efforts through 2050 (The White House 2016). Notably, the strategy considers bioenergy with carbon capture and sequestration (BECCS), a prominent CDR technology, in its benchmark scenario, and includes a chapter on storing carbon and reducing emissions on US lands. It also calls for increased RD&D investment in a portfolio of CDR to identify opportunities and provide an 'insurance policy' for emissions reduction strategies.

Yet harnessing the US's potential strengths for CDR RD&D requires long-term prioritization, coordination, and strategic investment. R&D agendas are still being defined, while multiple federal agencies have missions and capabilities relevant to CDR technology development. Land-use research, in particular, is decentralized and geographically varied, encompassing numerous federal agencies, as well as state-level and industry-funded research (Mowery *et al* 2010). These characteristics motivate coordination activities at the federal level. The diversity of CDR technologies, and their varying degree of commercial status, further motivate prioritization and coordination efforts.

This article presents a synthesis of CDR R&D needs, relevant agency authority, barriers to coordination, and interventions to enhance RD&D coordination across the US federal government. This synthesis complements other technical analyses of CDR RD&D needs. The approaches we consider draw upon the historical strengths of multiple agencies and harness existing coordination mechanisms, consistent with recommendations by the National Academy (National Academy of Sciences 2015). In doing so, this article integrates knowledge from the fields of science, engineering, public management, and public policy to design federal RD&D that is adaptable and strategic, yet lays the basis for sustained innovation. We expect this synthesis to be relevant for civil society in designing effective CDR RD&D programs, as well as the research and policy community developing CDR technologies. More broadly, this synthesis is relevant to policy and decision-making around R&D program design, and technology governance in the United States and beyond.

1.2. Overview of RD&D needs

Several RD&D needs arise in the context of US federal government strategy. In the supplementary text (SI text) available at stacks.iop.org/ERL/13/015005/mmedia, we describe RD&D actions that can reduce costs and clarify the sustainable scale of CDR. This description, while not comprehensive, illustrates the range of science and engineering needs for CDR, as well as the range of technical and commercial maturity of such approaches (SI text). Future efforts, including by the National Academy, will develop more detailed R&D roadmaps for program managers, which complement this letter's focus on public administration and policy (National Academy of Sciences 2016). This discussion is summarized in figure 1.

2. Role of the US in CDR RD&D

2.1. Current efforts

To date, US federal agencies have focused on voluntary or piecemeal CDR programs. Nevertheless, the US has taken several actions to develop and demonstrate CDR technologies. Here, we attempt to describe, both quantitatively and qualitatively, current federal efforts to advance CDR and related pathway technologies. Given the broad scope of basic and applied science applicable to biological and engineered CDR pathways,

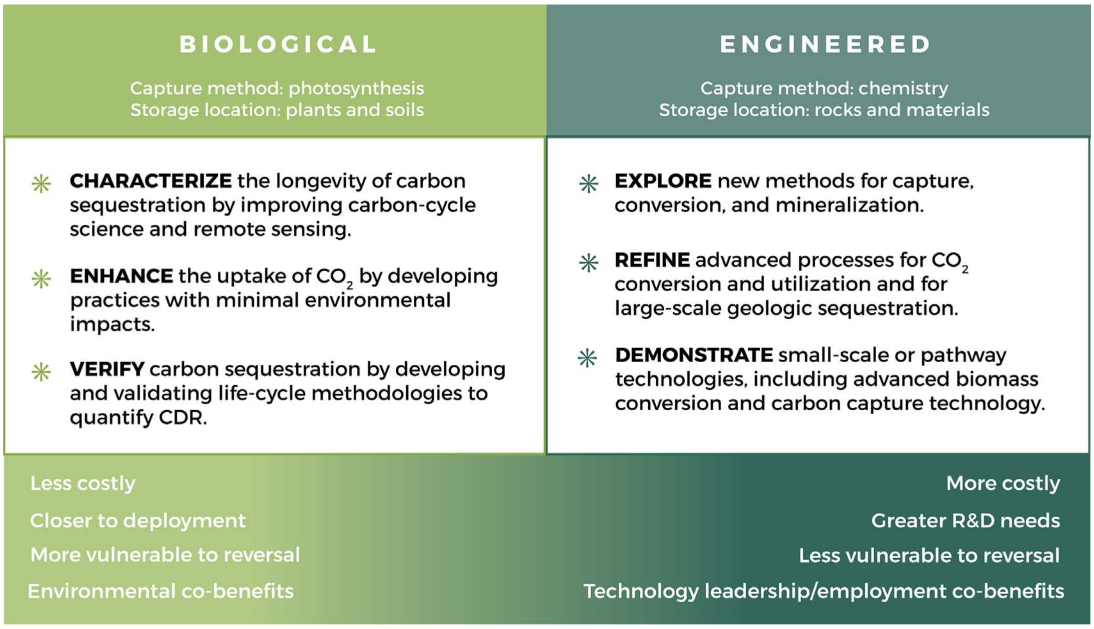

Figure 1. RD&D needs and attributes for biological and engineered CDR approaches (SI text).

we do not claim to be comprehensive. Nevertheless, we highlight a sample that represents the range of RD&D efforts across agencies.

There is no current quantification of the level of research dollars dedicated to CDR. The most recent approximation of federal R&D activity was performed in 2010 by the US Government Accountability Office (United States Government Accountability Office 2010). The report found \$767 000 between 2009–2010 going directly to three research activities specifically dedicated to CDR, with additional funding for the basic science and mitigation research with a direct connection to CDR. Below, we describe relevant agency efforts, before quantifying cumulative RD&D funding across agencies.

The Department of Energy's (DOE) Office of Fossil Energy (FE) has sponsored research and demonstration of CDR and other mitigation technologies that directly apply to CDR, including CCS. Two existing programs illustrate DOE's potential approach to CDR commercialization. First, DOE's Industrial Carbon Capture and Storage program has funded demonstration of CO_2 capture and storage from biofuels production (table 1) (US Department of Energy 2015a). Once fully implemented, the project will capture 1 million tons of biogenic CO_2 annually from corn ethanol fermentation for sequestration in the Mt. Simon Sandstone, a saline aquifer (Finley 2014). Second, DOE has devoted \$3 million in funding for applied research on dilute CO_2 capture (National Energy Technology Laboratory 2015), which can inform direct air capture approaches. Other mitigation-related research from the DOE is likely relevant to CDR technologies, including fossil CO_2 capture, storage, and utilization research funded through FE, the Office of Science, and the Advanced Manufacturing Office, and a CO_2 to liquid fuels program under the Advanced Research Projects Agency-Energy (ARPA-E) (Advanced Research Projects Agency-Energy 2016).

The DOE also has a long-standing commitment to support pathway technologies, such as CO_2 conversion and geological CO_2 sequestration. Congress has appropriated more than \$7 billion to CCS since 2008, including \$3.4 billion through the American Recovery and Reinvestment Act of 2009 (Folger 2016). This amount includes basic science, technology development, and large-scale demonstration. For instance, DOE has funded an energy innovation hub focused on 'solar fuels,' including those made by CO_2 reduction, since 2010 and has committed funding through 2020 (Weiner 2015). Similarly, FE continues to fund efforts to develop new CO_2 capture and compression technologies, primarily for coal-fired power plants (US Department of Energy 2015b).

The DOE also supports research for biological CDR, through both FE and ARPA-E. FE has prioritized land-use CDR in a select number of their Regional Carbon Sequestration Partnerships, which develop technology and infrastructure for large-scale CO_2 storage in soils and forests (National Energy Technology Laboratory 2017). In 2011, a lab operated by FE released a report detailing *Best Practices for Terrestrial Sequestration of Carbon Dioxide* (National Energy Technology Laboratory 2010). ARPA-E is also developing crops that will increase carbon uptake in soils through its ROOTS program (Advanced Research Projects Agency-Energy 2016).

The US Department of Agriculture (USDA) has also made efforts to support biological CDR. In

Table 1. Cumulative direct funding for CDR RD&D in the US. Data based on authors' assessment and United States Government Accountability Office (2010). Data do not include RD&D funding for pathway technologies, which is more significant.

Project description	Technology	Agency	Office/Division	Research or demonstration	Amount (nearest thousand)	Year awarded
Illinois Basin Decatur Project	BECCS	DOE	Office of Fossil Energy	Demonstration	66 700 000	2007
Illinois Industrial Carbon Capture and Storage Project	BECCS	DOE	Office of Fossil Energy	Demonstration	141 406 000	2010
Low-concentration CO_2 capture technology development	Direct air capture	DOE	Office of Fossil Energy	Research	3 000 000	2015
Improved crops for soil carbon sequestration	Carbon farming	DOE	Advanced Research Projects Agency-Energy	Research	35 000 000	2016
Impacts of biochar soil amendments	Biochar	USDA	Agricultural Research Service	Research	2 800 000	2009
Direct air capture systems analysis	Direct air capture	DOE	Office of Fossil Energy	Research	243 000	2009
Direct air capture analysis	Direct air capture	DOE	Office of Fossil Energy	Research	50 000	2009
Environmental impacts of ocean iron fertilization	Ocean iron fertilization	NSF	Directorate of Geosciences	Research	474 000	2010
National assessment of biological sequestration resources	All biological approaches	DOI	United States Geologic Survey	Research	5 000 000	2010
Evaluation of agricultural soil carbon sequestration	Carbon farming	USDA	Agricultural Research Service	Research	11 100 000	2010
Advanced biofuels with CCS	BECCS	NSF	Office of Integrative Activities	Research	6 000 000	2016
Design and impact of negative CO_2 emissions policies	All approaches	NSF	Office of Integrative Activities	Research	6 000 000	2016

2015, the USDA explicitly prioritized CDR through its *Building Blocks for Climate Smart Agriculture and Forestry* initiative (US Department of Agriculture 2016). Their Agricultural Research Service (ARS) also managed a number of biochar pilot projects in 2009 (Agricultural Research Service 2008).

During the Obama Administration, the White House began to coordinate land management through a climate lens. The Council on Environmental Quality (CEQ) published two related reports: *Priority Agenda for Enhancing the Climate Resilience of America's Natural Resources* and the 2015 *Progress Report on Climate Change and the Land Sector* (White House Council on Climate Preparedness and Resilience Climate and Natural Resources Working Group 2014, White House Council on Environmental Quality 2015). Additionally, in 2016, the Office of Science and Technology Policy (OSTP) convened an inter-agency working group with the goal to create a federal framework for soil science that included research priorities for soil carbon sequestration (White House Office of Science and Technology Policy 2016). These efforts have been voluntary, or focused on data collection and measurement. There have also been early discussions of CDR approaches within OSTP. For example, the US Global Change Research Program (USGCRP)—which is guided by OSTP—proposed it coordinate research focusing on the possibilities, limitations, and side effects of CDR approaches in a 2017 planning document (US Global Change Research Program 2017).

We estimate that cumulative direct CDR RD&D funds in the US total \$310 million, three quarters of which have gone towards CCS demonstration at biorefineries (table 1). DOE, USDA, DOI, and NSF have funded CDR projects directly, alongside pathway technologies. As US R&D expenditures total roughly \$140 billion each year, CDR RD&D represents a very small portion of US technology development efforts. Instead, these RD&D efforts are fragmented, uncoordinated, and nascent.

2.2. Agency relevance and authority

Federal agencies can perform five main functions related to RD&D: conducting research, facilitating information exchange, funding projects, monitoring projects/effects, and promulgating regulations (table 2) (Bracmort *et al* 2010). In the SI text, we discuss the role of the most relevant agencies in implementing

Table 2. Relevant agencies and authority for RD&D functions. NASA, USGCRP and EPA are omitted. This conceptualization is based on Bracmort *et al* (2010). For a more detailed discussion in the context of both CDR and solar radiation management techniques, see Gordon (2010).

Federal Agency	Conduct Research	Exchange Information	Fund Projects	Monitor Projects	Promulgate Regulations
Department of Energy (DOE)	Strong (engineered)	Yes	Strong	Limited	None
Department of Agriculture (USDA)	Strong (biological)	Yes	Strong	Strong	Limited
National Science Foundation (NSF)	Strong (basic science)	Yes	Strong	None	None
Deparment of Interior (DOI)	Limited (biological)	Yes	Limited	Limited	Strong
National Oceanic and Atmospheric Administration (NOAA)	Strong (biological)	Yes	Medium	Strong	None

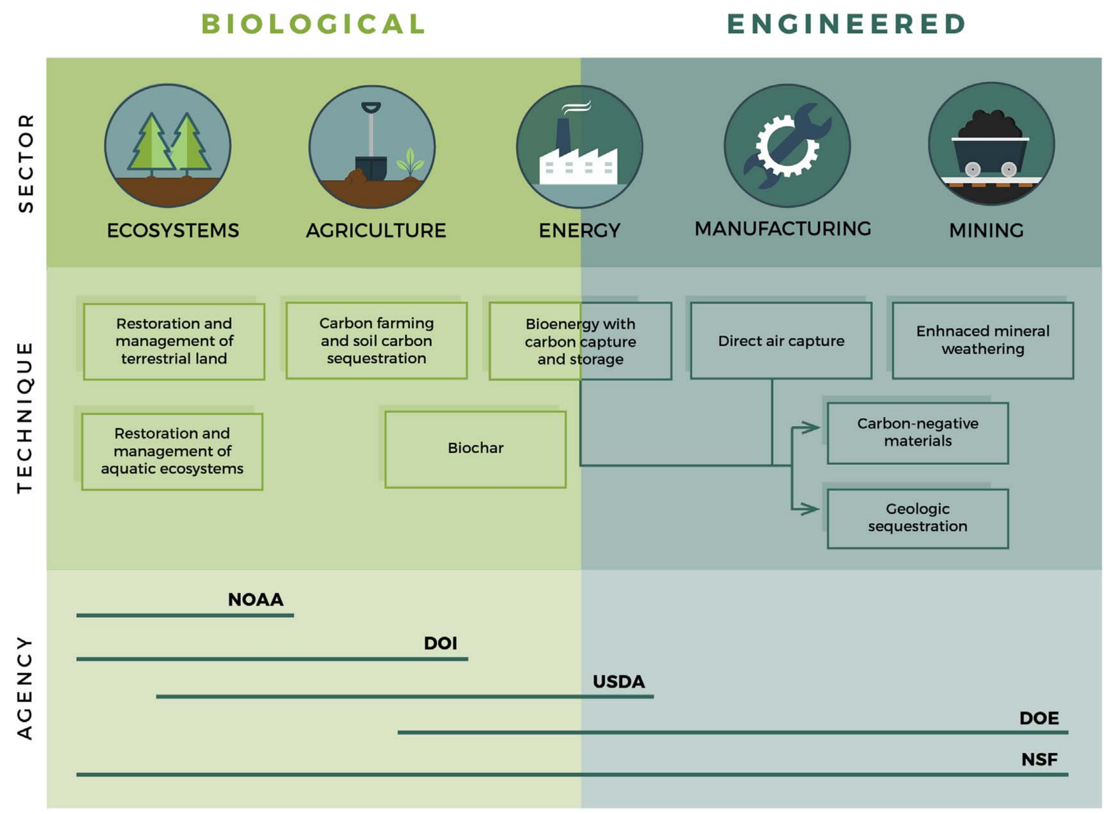

Figure 2. CDR sectors, techniques, and relevant agencies.

CDR RD&D, including barriers and opportunities. These include DOE, USDA, DOI, NOAA, NSF, EPA, and USGCRP (SI text). Table 2 and figure 2 summarize this discussion.

2.3. Barriers to agency coordination and execution

There are several barriers to enhanced CDR RD&D that emerge from an examination of RD&D needs, agency authority, expertise, and existing efforts. Here, we apply lessons from science, engineering, public management, and public policy to identify such barriers. We distinguish between two main types of barriers: intra-agency (within an agency) and inter-agency (among agencies). Intra-agency barriers will likely emerge at most agencies implementing CDR RD&D. Inter-agency barriers are particularly important for RD&D on biological CDR approaches, in part because different agencies manage or influence lands within a geographically connected landscape, and changes triggered by one agency have the potential to either reinforce or undermine changes undertaken by a different agency.

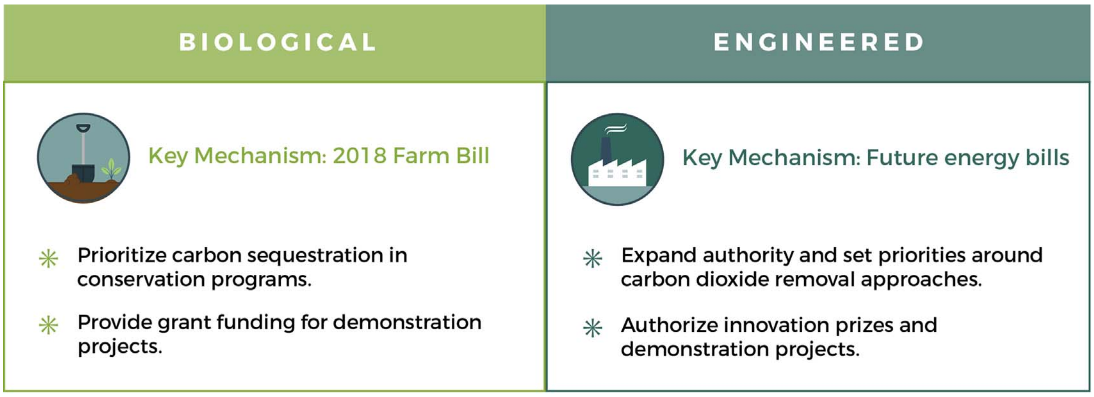

Figure 3. Legislative opportunities to enhance CDR RD&D.

Intra-agency coordination barriers arise from both long-lived fragmentation within agencies and the complexity of CDR approaches. DOE, for instance, has two program offices with considerable expertise in engineered CDR technologies: FE, and Office of Energy Efficiency and Renewable Energy (EERE), which includes the Biomass Energy Technologies Office (BETO). FE has led nearly all work on CDR to date (section 2.1), but does not focus on stand-alone biomass conversion technologies necessary for BECCS. Similarly, BETO focuses on feedstock logistics and biomass conversion, but does not support fossil energy co-conversion or CCS (Sanchez and Kammen 2016). The two offices began to work together in 2015, but have yet to build a joint effort (US Department of Energy 2015a). Future DOE deployment programs could connect both types of necessary expertise through a crosscutting initiative, a tool often used by DOE to collaborate across the agency (Office of Chief Financial Officer 2016).

Similar intra-agency coordination barriers exist at other agencies. For instance, USDA has several offices with management and science authority informing RD&D (table 3). These include the Agricultural Research Service, Economic Research Service, Natural Resource Conservation Service, Farm Service Agency, and US Forest Service. Across different CDR technologies, these offices again represent distinct expertise and mandates that need to work in concert in order for RD&D to be most effective. Commitment by leaders, including political appointees, at each agency could help to overcome these barriers (Borins 2002).

The second barrier is inter-agency collaboration on biological CDR. Notably, agencies have different levels of scientific expertise, ability to promulgate regulations and offer grants, and land ownership, though they work on similar ecosystems. Land-based RD&D programs are more likely to be effective if they are designed to take advantage of the differences between agencies, promote science exchange across the federal government, avoid unnecessarily burdensome inter-agency processes, and advance research on the comprehensive range of ecosystems encompassed by the participating agencies.

3. Evaluation of potential RD&D program design

Several policy and management interventions can enhance RD&D outcomes across the US federal government. Potential interventions include compelling or pursuing intra-agency and inter-agency collaboration, setting incentives through legislation, and engaging in international efforts.

Key enablers for successful programs include embracing technological diversity and administrative efficiency, fostering agency buy-in, and achieving commercial deployment. We base these criteria off several considerations, drawn from an understanding of CDR technologies and public management. First, technological diversity will advance research on a range of CDR technologies and approaches, not prematurely picking winners and losers. Second, administrative efficiency will ensure that RD&D programs are adaptive to interim results, harness existing coordination mechanisms, and avoid lengthy or unproductive processes. Third, agency buy-in will help build on the existing agency strengths and constituencies, overcome differences between agencies, and promote information exchange across government. Finally, a focus on achieving and then evaluating commercial deployment will facilitate cost reductions, explore and capitalize on co-benefits, and clarify the sustainable scale of CDR. Below, we evaluate proposals for executive branch and legislative implementation on the basis of these criteria.

3.1. Executive branch implementation

The White House possesses several authorities and attributes that could ensure robust implementation within the executive branch, given sufficient political commitment. First, it can compel intra-agency operations improvements and inter-agency processes via executive order. Second, it can host convenings

Table 3. Agencies involved in land use science or management. The list is not comprehensive but highlights the range of focus necessary for CDR RD&D.

Parent Agency	Office/Division	Science or Management	Primary Land Type	Primary Focus
USDA	Agricultural Research Service	Science	Agricultural lands and rangelands	Agricultural sciences
	Economic Research Service	Science	Agricultural lands	Agricultural economics
	Natural Resource Conservation Service	Management	All	Technical assistance on private lands
	Farm Service Agency	Management	Agricultural lands and rangelands	Conservation programs
	US Forest Service	Management	Forests and rangelands	Multiple mandates
DOI	US Geologic Survey	Science	All	Natural and geosciences
	National Park Service	Management	All	Preservation and education
	US Fish and Wildlife Service	Management	Wildlife habitat	Species conservation
	Bureau of Land Management	Management	All	Multiple mandates
NOAA	National Environmental Satellite, Data, and Information Service	Science	All	Data provision
	National Marine Fisheries	Management	Aquatic ecosystems	Protection and restoration

necessary to build support for, and awareness of, CDR across a range of sectors. Third, it has a strong communications operation for raising public awareness, which is often lacking at other agencies. These communications operations can, for instance, increase public acceptance. Finally, it has science expertise, historically headquartered in the OSTP. OSTP advises the President and Executive Office of the President on science and technology, leads inter-agency efforts to develop sound policies and budgets, and engages with the private sector, state and local government, and other nations (Teague 1976). Based on these attributes, White House-led implementation can satisfy all four criteria for successful RD&D. Co-benefits will likely be an important motivator and enabler for political commitment (figure 1).

There are, however, several other options for executive branch implementation, aside from White House leadership. For instance, other agencies or existing inter-agency working groups implementing RD&D can engage in similar convening, priority setting, communication, and engagement tasks under existing their mandates and authority. As we discuss further below, agency-led implementation may miss opportunities to prioritize technological diversity and, in some cases, commercial deployment. Agency-led processes could, however, generate a greater level of agency buy-in or administrative efficiency.

We note the potential for state- or private sector-led RD&D efforts, should executive leadership be unavailable. The semiconductor industry, for example, has experience in leading public-private partnerships for RD&D (Diaz Anadon *et al* 2016). Several states also fund energy RD&D using electricity surcharges. These initiatives are generally limited in size, but could advance CDR RD&D if properly designed. They also may lack technological diversity or administrative efficiency, given the number of actors and technologies involved.

3.2. Intra-agency coordination

Intra-agency coordination can be directed from the White House, or could arise from within the agencies themselves. Two main interventions exist: (1) agency priority setting, including executive orders, and (2) the budget process. Here, we evaluate the strengths and weaknesses of both White House or agency-led coordination. Given low political barriers, intra-agency coordination can be implemented in the early stages of a CDR RD&D program.

The White House can lead both priority setting and budget interventions. First, it could encourage or compel renewed intra-agency commitment to CDR in five primary agencies: DOE, USDA, DOI, NOAA, and NSF, including both research and demonstration, by executive order. Here, the effectiveness of White House action would benefit from developing the executive order in consultation with leadership at each Agency implementing RD&D, paying close attention to statutory limitations.

Second, the White House could coordinate budgets for CDR RD&D. Early budgets should focus on the

Box 1. The National Nanotechnology Initiative.

The National Nanotechnology Initiative (NNI) is coalition of federal agencies, 13 of which conduct R&D, and 12 of which regulate and enable education on nanotechnology. The NNI was first launched by President Bill Clinton under executive order in 2000. In 2003, Congress enacted the 21st Century Nanotechnology Research and Development Act to provide a statutory foundation and organize the Initiative (Wyden 2003). The NNI is part of the National Science and Technology Council (NSTC), a cabinet-level council chaired by the President and Director of OSTP. In addition to conducting research and exploring regulatory issues related to the environment and public health, and safety, the NNI conducts public outreach activities and engages with international consortia. The NNI has been the major driver for nanoscience and nanotechnology developments and applications in the US and in the world for over a decade (Roco 2011). It has also been held up as model for CDR research, in part because of its active role in public engagement (Gordon 2010).

historical strengths of Agencies and their respective offices. If technology roadmaps for CDR are unavailable (e.g. (SEAB CO_2 Utilization Task Force 2016, National Academy of Sciences 2016)), these budgets could effectively build on existing projects and programs, rather than authorizing new programs. Crosscutting initiatives can catalyze intra-agency efforts, especially at DOE and USDA.

Agency-led implementation can likely implement similar priority setting and budget interventions, but in a more ad-hoc fashion. For instance, agencies could propose their own priorities or crosscutting initiatives, and encourage cross-agency interaction. Agencies can also ask their existing advisory boards for input on technology priorities and intra-agency coordination needs. As mentioned previously, these efforts would lack coordination, and might lack full technological diversity or a focus on commercial deployment. They could, however, compel a greater level of agency buy-in or administrative efficiency. On the basis of these potential limitations, we conclude that renewed intra-agency commitment could proceed more expediently via executive order.

3.3. Inter-agency coordination

Inter-agency coordination can proceed through the White House OSTP or the USGCRP, or through agency reorganization. Potential inter-agency efforts include technology roadmapping, information sharing, stakeholder engagement, and international engagement.

Examples of successful inter-agency processes abound, but one promising model is the National Nanotechnology Initiative (NNI), which coordinates research, examines regulatory issues, engages in public outreach, and coordinates with international bodies (box 1). The NNI has been praised for stimulating global interest in nanotechnology, and previously cited as a model for CDR research at the federal level (Gordon 2010, Roco 2011). In particular, NNI's broad latitude to examine regulatory issues and engage in public outreach would be assets to future CDR deployment.

Building on lessons from the NNI, the White House could promote inter-agency coordination on research prioritization and outcomes through OSTP. Potential actions include convening an inter-agency working group, promoting technology roadmapping efforts at agencies, and stimulating collaboration through scientific advisory boards. Such an approach might be adapted to CDR and could proceed along similar lines. Below, we briefly outline how OSTP would implement tasks based on the NNI.

First, the White House would convene an inter-agency working group through OSTP to set priorities, coordinate budgets, and share outcomes among relevant agencies. The inter-agency working group could be compelled by executive order, and would sensibly include DOE, USDA, DOI, NSF, NOAA, EPA, USGCRP, and NASA. Particular attention should be given to the multiple offices funding land-use science. Second, the working group would request that agencies deliver RD&D roadmaps for engineered and biological CDR pathways. These would be shared with the inter-agency working group for concurrence.

Finally, OSTP would engage in prioritization and agenda setting, working closely with the National Academy and DOE SEAB to prioritize future efforts. Another potential science advisory board to engage is the President's Council of Advisors on Science and Technology (PCAST), a council of independent experts that provide advice to the President. PCAST has experience guiding policy on early-stage technology development, and can supplement other advisory efforts (Gordon 2010).

Within a few years, the working group would develop new budgets and evaluate how best to continue an RD&D program. Budgets should include new programs and projects, informed by early results and prioritization efforts. The working group would also engage internationally (section 3.5), and explore potential regulatory issues. Within several years, the working group could evaluate if more formal inter-agency collaboration or agency reorganization is necessary, based on evidence gained from RD&D projects.

Should there be sufficient political commitment at the White House, an OSTP inter-agency working group would likely satisfy all criteria for successful RD&D. For instance, it could likely target commercialization and embrace technological diversity. The ability of OSTP to compel agency buy-in and administrative efficiency is less clear, but prior experience with the NNI suggests that this is possible.

As an alternative to a new inter-agency working group, USGCRP could lead inter-agency coordination of CDR research (US Global Change Research Program 2017). Prior evaluations of USGCRP have found that the program has strengths in science and discovery, but has been less effective at supporting decision-making and engaging stakeholders (National Academies 2016, National Research Council (NRC)

2007). A larger barrier, however, might be constraints in program mandate: for instance, USGCRP lacks a focus on commercial technology development, and has no authority for technology oversight or regulation. Because of these limitations, USGCRP-led implementation of RD&D might lack a commercial focus, and may be unable to compel agency buy-in.

One final option for inter-agency collaboration is agency reorganization. Here, inter-agency coordination barriers would be addressed through merging or restructuring of agencies with authority and expertise in CDR. For example, terrestrial land-use science expertise that exists both at USDA and DOI could be consolidated, potentially promoting administrative efficiency or agency-buy in. Yet reorganization efforts could substantially delay program implementation or backfire due to political resistance, clashing institutional cultures, or overreach. We caution against premature agency reorganization or other efforts that substantially alter the structure of land-use or engineered R&D programs at this time. Reorganization risks locking in counterproductive arrangements before key science and management uncertainties are resolved. Instead, we suggest that more formal engagement between agencies emerge organically and over time.

3.4. Legislative opportunities

There are a number of legislative opportunities to support CDR RD&D. These include budget authorization and allocation, periodic omnibus legislation, and smaller legislation. Below, we comment briefly on legislative interventions to enhance RD&D through each of these processes. As before, our analysis prioritizes enabling factors, in particular technological diversity and commercial deployment.

Budget authorization and allocation processes can authorize new CDR RD&D programs or enhance existing efforts. Typically, budgets are proposed by the executive branch, while Congress modifies and approves budgets. However, Congress has broad authority to modify or propose CDR RD&D programs, should the executive branch not develop budgets that prioritize CDR (section 3.2).

Typically, agriculture and energy policies in the US are set by periodic, omnibus legislation, colloquially known as 'farm bills' or 'energy bills.' Energy bills provide a platform to enhance DOE efforts. For example, two amendments to the 2016 Energy Policy Modernization Act would have supported carbon removal solutions if the bill had become law during the 114th Congress. One amendment sought to expand DOE's authority to award technology prizes to projects that separate CO_2 from dilute sources (Barrasso 2016). A second amendment could be designed to support demonstration of net-negative emissions projects (Manchin 2016). This amendment would have named net-negative carbon dioxide emissions projects as a programmatic priority, and authorized five years of funding for BECCS demonstration projects. Both of the amendments sought to expand the existing authority of DOE program offices, and suggest the role that legislative authorization will play in supporting CDR.

Similar legislative opportunities arise for biological carbon removal solutions, through both omnibus or smaller legislation (Huffman 2016). For instance, Congress can promote carbon sequestration by offering amendments to existing ecosystem restoration and conservation programs to encourage agencies to prioritize existing programs, activities, and funding (like wetland restoration and forest management) by their carbon sequestration capacity. In this regard, the Conservation Reserve Program (CRP) is one example of a promising avenue to incentivize deployment of CDR on private land. Under the CRP, a land manager can elect to carry out a selection of activities that can increase carbon stocks in biomass and soils, in exchange for annual payments under a 10 year contract (Farm Service Agency 2017). The carbon benefits of these practices are not currently quantified, but with minor changes, this program could be designed to add the expected quantity of carbon sequestration as a factor in the prioritization of contracts, and payments could be indexed to these quantities (Parks and Hardie 1995). Such changes would create a more direct incentive for sequestration and allow the program to quantify and report the overall CDR benefits it achieves. Other programs authorized under the conservation title of the Farm Bill also have potential for these kinds of changes, each tailored to the specific goals and criteria of the particular program.

Finally, Congress can compel executive branch action through smaller pieces of legislation. For instance, Congress can authorize and direct OSTP to lead inter-agency efforts, as it has for USGCRP (Hollings 1990). Such legislative actions are fairly common: for example, the 115th Congress has introduced bills directing OSTP to coordinate interagency efforts around space weather events, cybersecurity, and education in science and engineering. Such an effort may be necessary in the short term: for instance, OSTP activity has diminished under the Trump Administration, and has reduced staff levels from those of the Obama Administration. Congress can also mandate intra-agency or inter-agency efforts directly, bypassing the White House. These efforts may be less efficient than executive branch implementation, as agencies hold much expertise internally.

3.5. International engagement

The White House and OSTP can play an important role in promoting awareness of, catalyzing RD&D efforts for, and collaboratively developing CDR technologies internationally. For instance, the US can raise the profile of CDR technologies in multilateral energy technology development forums, including promoting development of CDR technologies as a 'grand challenge' in

need of worldwide attention (Bernstein *et al* 2016). Forums with overlapping priorities include Mission Innovation, the Clean Energy Ministerial, and the International Energy Agency. There has been some recent momentum around collaborative CDR RD&D: the International Energy Agency, of which the US is a member, has recently agreed to take up BECCS as a focus, while the US has been an active participant in the Global Research Alliance on Agricultural Greenhouse Gases, where enhancing soil carbon has been a key area of collaborative research (International Energy Agency 2017). In response to US efforts, CDR may become a focus for international RD&D, much like the growth of nanotechnology R&D programs following the US creation of the NNI (Roco 2011).

International engagement efforts will likely evolve quickly, given the numerous fragmented and loosely coupled regimes involved in global climate policy (Victor and Keohane 2010). We note, however, that the US has retreated from international technology development efforts under the Trump Administration (Sanchez and Sivaram 2017).

4. Conclusion

This article presents a synthesis of R&D needs, relevant agency authority, barriers to coordination, and interventions to enhance RD&D across the federal government of the US. Several important findings emerge. On the basis of agency authority and expertise, DOE, USDA, DOI, NOAA, and NSF are the most important agencies to conduct research, fund projects, monitor effects, and promulgate regulations. To date, agencies have focused on voluntary or piecemeal CDR programs. We identify both intra- and inter-agency barriers to enhanced RD&D.

We evaluate potential RD&D program design on four criteria: technological diversity, administrative efficiency, agency buy-in, and a targeting of commercial deployment. Analyzing implementation options, we conclude that the executive branch could effectively coordinate RD&D strategy through two complementary pathways: (1) renewing intra-agency commitment to CDR in five primary agencies, including both research and demonstration, and (2) coordinating research prioritization and outcomes across agencies, led by the Office of Science and Technology Policy (OSTP) and loosely based on the National Nanotechnology Initiative. Both pathways can be stimulated by executive order or Congressional mandate. The executive branch can also engage in international technology development efforts, while future Farm and Energy Bills provide legislative vehicles for enhanced programs. This analysis targets program implementation that is adaptable and strategic, yet lays the basis for sustained innovation.

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