GYAMI SHRESTHA

What Is the Big Picture in Carbon Removal Research?

The August 2022 passage of the Inflation Reduction Act enables a massive investment in reducing carbon emissions and mitigating their effects. It also focuses attention on strategies for removing carbon dioxide from the atmosphere—and as it happens, carbon dioxide removal (CDR) is already being extensively studied in federal research projects. In 2020, the US Carbon Cycle Science Program Office, which I had been leading, put out a data call requesting input from all member agencies about current and upcoming federally funded CDR research, observations, and other pertinent activities. Seeing the results of this data call, my colleagues and I were surprised to learn that there were already 600 federal research projects on or related to CDR at that time, and more continue to come in.

For those of us within the program, the response to the data call was like discovering a gold mine under our feet. Activity on CDR has been ramping up fast, with both government and industry making investments and taking other actions to expand underlying knowledge, develop necessary technologies, and build capacity. To work efficiently in our capacity as federal employees and avoid duplicating efforts, we need to know what's already known and being studied. We also need information to identify gaps and establish fruitful new collaborations and partnerships. For me, the experience of working collaboratively with the group on CDR research highlights several lessons about coordinating multiagency activities around complex topics—and it particularly demonstrates the importance of continually looking for ways to broaden the conversation.

My personal relationship to CDR has followed a path with many twists and turns. The US Carbon Cycle Science Program, established by the Carbon Cycle Interagency Working Group (CCIWG) in 1999, is a longstanding interagency partnership established to lead and facilitate federally funded carbon cycle research in collaboration with the science community. I became director of the program in 2012 and, soon after, developed my first inklings of how CDR connected with the program's objectives. At the time, the term "negative emissions" was gaining popularity among mainstream carbon cycle scientists as representing a reduction in carbon emissions—including both carbon dioxide and methane—to well below zero, meaning that carbon emissions would be removed from the atmosphere. At first, I paid little heed; this talk of negative emissions seemed pie in the sky and far removed from the practical coordination work that I did with the program and the CCIWG.

My attitude began to shift when I was invited to participate in a 2013 workshop on the topic at the International Institute for Applied Systems Analysis in Vienna, Austria. During the workshop, I realized that the concept was closely related to my own research expertise in soil carbon sequestration and biochar (a kind of charcoal produced by burning biomass in a low-oxygen environment). More critically, I realized that negative emissions matched with one of my program's

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major priorities: to "strengthen the scientific foundation for management decisions in numerous areas of public interest related to carbon and climate change in the US and other regions." By not addressing negative emissions, the group might not be fulfilling its mission and—even more importantly—might be missing an important piece of the climate puzzle.

One immediate challenge was that although CDR had potential as a climate change mitigation strategy, the knowledge base needed to grow. The term, and the topic, needed to be better understood within the United States. Much remained unknown about the interactions between the climate, carbon cycle, and anthropogenic negative emissions technologies in determining how carbon would be distributed between atmosphere, land, and ocean reservoirs in the future. After the workshop, I continued brainstorming and collaborating with a team of renowned international carbon experts in an effort to build this expertise. We coauthored a 2015 review in *Nature Climate Change* of what was known on the topic and what remained to be explored.

The next breakthrough came in 2018 and 2019, with the publication of three highly influential scientific consensus reports all pointing to the need for more attention to CDR. In its 2018 report, the Intergovernmental Panel on Climate Change (IPCC) provided clarity by defining CDR as the process of removing carbon dioxide from the atmosphere and described the practices or technologies that remove carbon dioxide as achieving "negative emissions." The IPCC also outlined two primary, and very different, types of CDR. One type includes enhancing existing natural processes that remove carbon from the atmosphere by increasing its uptake by vegetation, soil, or other carbon sinks. The other type involves using chemical processes to capture and store carbon dioxide directly from the atmosphere. The 2018 *Second State of the Carbon Cycle Report*, a consensus study led by the US Carbon Program team, highlighted opportunities to use knowledge of the carbon cycle to make informed and potentially innovative carbon management and policy decisions. Shortly afterward, the National Academies of Sciences, Engineering, and Medicine (NASEM) released its report on negative emissions technologies, which delved into the technology side of CDR.

As is often the case in science, work builds on other work—and as is often the case in government, a confluence of events can spur action. These reports provided the impetus for me, along with my CCIWG colleagues, to mobilize around the need to explore CDR research more thoroughly. Our team began to brainstorm new ideas, opportunities, and knowledge gaps ripe for collaborations among agencies and the scientific community.

We realized it was time to further broaden the conversation, and in 2019 and 2020 I helped launch rounds of engagement with stakeholders focused specifically on CDR. We then formulated the Interagency CDR Research Coordination Group (I-CDR-C) with interested colleagues from around the federal government to better understand their perspectives on the state of CDR research. We conducted public engagement sessions with the scientific community more broadly, including at the National Academies, the American Geophysical Union's annual conferences, and other venues. One message that emerged loud and clear from these interactions was that a lot was already happening, much of it with federal funding or other involvement.

To be effective, interagency planning needed to account for these existing activities. The I-CDR-C group meets regularly to discuss interagency CDR research progress and opportunities, helping develop partnerships that focus specifically on CDR and a strong foundation for a multi-agency research agenda. Our meetings have become crucial for sharing information and developing relationships. Initial priorities have emerged from these discussions, including using natural climate solutions and engineered approaches based on carbon cycle science; building and expanding multisector partnerships; improving observational capabilities; and enhancing decisionmaker readiness.

While I was certainly aware of the US federal agency research enterprise's robust support of CDR research, many details were still missing from the picture. Investments were spread out over time and across many agencies and programs. And while public- and private-sector CDR investments and interests were rapidly gaining momentum, there was no current quantification of the level of research dollars dedicated to CDR technologies

and practices. Yet decades of federally funded research and observation activities—if elucidated—could inform CDR efforts and investment opportunities across sectors, where interest was accelerating.

The I-CDR-C group soon realized that we needed to map the landscape so that we, and others in the community, could make optimal use of it. In late 2020, following months of deliberations, the group developed an inclusive data call of federal carbon removal research activities. And although the data call requested information on federally funded research, observations, and activities related to CDR, it didn't stop there. A broader range of activities, though they may not be explicitly denoted as CDR research, could offer critical contributions to the state of the science. The data call was designed to gather information on federal carbon monitoring, removal, and management projects that might inform CDR activities now or in the future. Ultimately, our plan was to produce a comprehensive compendium of all federal carbon removal research, encompassing pertinent research activities across terrestrial, oceanic, atmospheric, and societal dimensions.

The 600 federal research projects and activities that currently populate the compendium have already provided a wealth of valuable information. First, they illustrate how these activities are spread across agencies, which can suggest possible opportunities for partnership. While the US Department of Agriculture has submitted the most CDR projects thus far, many other agencies are involved. Funding and interest for CDR-related projects are increasing across all the major agencies with a carbon research portfolio. For instance, the Department of Energy recently announced the Carbon Negative Shot initiative. The National Institute of Standards and Technology is focused on measurements, characterizing direct air capture with carbon storage (DACCS) materials and processes and permanent carbon storage. The National Oceanic and Atmospheric Administration has established an internal CDR task force. The US Geological Survey focuses on geologic and biological carbon sequestration. NASA leads the Carbon Monitoring System, Earth System Observatory, and other carbon-related observations to study the impacts of management practices, including agricultural carbon sequestration, to guide mitigation research. At the National Science Foundation, multiple directorates are involved in funding CDR-related research including DACCS, soil carbon, and ocean iron fertilization.

The compendium of responses not only shows what topics are being studied; it helps to identify the most critical remaining research questions. For instance, there has historically been more attention to terrestrial activities, although interest in marine activities has grown over time, especially in the wake of an influential 2021 NASEM report on a research strategy for ocean carbon removal and sequestration. There is still an urgent need to better understand uncertainties in measuring carbon stocks and emissions related to CDR, via enhanced and revitalized monitoring, measurement, reporting, and verification. And there is also a dearth of data and research addressing impacts of CDR on local and disadvantaged or marginalized communities. Underlying these topics are fundamental questions that have yet to be sufficiently answered: Where, how, and how much carbon dioxide is emitted and distributed in the atmosphere globally? How much carbon dioxide can be feasibly sequestered into terrestrial and oceanic ecosystems with minimal negative consequences for ecosystems and people? And how this can be accomplished?

The compendium of federal CDR-related projects will be an indispensable tool, but without continually expanding the conversation within and beyond the federal government, it will not be enough. Work on CDR, while very broad, is often distinct from other areas of carbon cycle research.

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Looking back, some distinct lessons emerge. When working with or within the federal government, it's important to balance boldness against constraints—and to take advantage of opportunities to move the needle forward. It's also important to be strategic: taking time early on to gather information beats attempting to reinvent the wheel later. Finally, this effort shows how emerging challenges are defined and redefined in real time. And research agendas are often shaped by individual people's engagement. Ensuring those agendas are both strong and inclusive requires not just the right people, but all the people with something to say. Science can be siloed, as can the institutions supporting it. But the threat posed by climate change recognizes no such boundaries. Only by working together can we fully understand and develop strategies to overcome these threats and discover sustainable climate change solutions.

Gyami Shrestha *served as the director of the US Carbon Cycle Science Program Office for over ten years.*