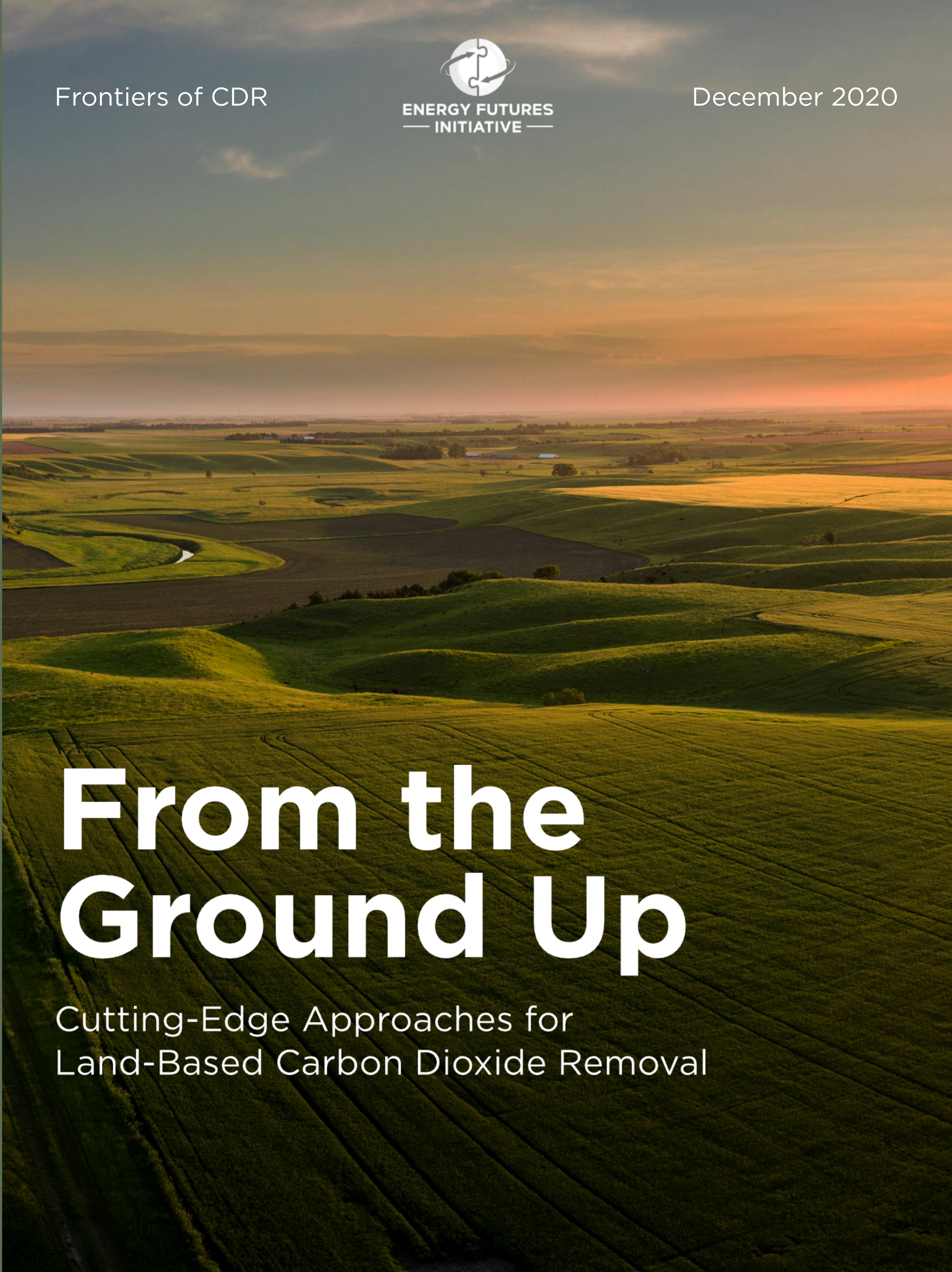

Frontiers of CDR

ENERGY FUTURES INITIATIVE

December 2020

From the Ground Up

Cutting-Edge Approaches for Land-Based Carbon Dioxide Removal

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About Energy Futures Initiative

The Energy Futures Initiative advances technically-grounded solutions to climate change through evidence-based analysis, thought leadership, and coalition-building. Under the leadership of Ernest J. Moniz, the 13th U.S. Secretary of Energy, EFI conducts rigorous research to accelerate the transition to a low-carbon economy through innovation in technology, policy, and business models. EFI maintains editorial independence from its public and private sponsors.

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Cover Photo: Early May aerial South Dakota sunrise over farmland. Photo by PatrickZiegler from Getty Images Pro.

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About this Series

In September 2019, EFI published *Clearing the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies*, a major report that outlined a 10-year, $11-billion research, development, and demonstration (RD&D) program to bring more carbon dioxide removal (CDR) approaches to deployment readiness.[1] Several of these approaches, such as bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) are garnering increased funding support in Congress, but other pathways have received much less attention. Building on the work of the Clearing the Air report, EFI identified three CDR "frontiers" deserving of deeper evaluation: **(1) technologically enhanced terrestrial and biological CDR; (2) marine CDR; and (3) carbon mineralization.** The need for a broad portfolio of CDR options at Gt scale, compatible with the geography and geology of different regions of the U.S. and the world, underscores the need for increased investment in these relatively underexplored CDR "frontiers."

EFI organized six virtual workshops, involving over 100 scientific and technical experts, to address these pathways. The workshops identified the range of CDR approaches, their respective stages of development, and high-priority RD&D needs and opportunities ("big ideas").

This series of reports combines the findings of those workshops with analysis from EFI to provide policymakers with new insight into the potential benefits of these frontier CDR pathways and detail key priority research areas to promote their development. The report in this series are:

- → *From the Ground Up: Cutting-Edge Approaches for Land-Based Carbon Dioxide Removal*
- → *Uncharted Waters: Expanding the Options for Carbon Dioxide Removal in Coastal and Ocean Environments*
- → *Rock Solid: Enhancing Mineralization for Large-Scale Carbon Management*

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The content of this report is not attributable to any of the workshop participants, and the views expressed here are EFI's and do not reflect the views of the participants or their employers.

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Key Findings and Recommendations for Policymakers

Key Findings

- **Innovations across several areas of science and technology open the door to new pathways for biological and terrestrial carbon dioxide removal (CDR).** While natural solutions for carbon capture and storage in trees, plants, and soils merit increased action by policymakers, this report focuses on cutting-edge technologically enhanced pathways. Innovations in biotechnology (including genetic engineering, synthetic biology, and genome editing), large-scale data analytics, high performance computing, and artificial intelligence have opened up pathways with the potential to supercharge the amount of CDR from terrestrial ecosystems.

- **Increasing the carbon dioxide (CO_2) uptake in soils and terrestrial ecosystems can have significant co-benefits.** A major benefit is the replenishment of soil organic carbon (SOC), which contributes to soil health and fertility but has been depleted over centuries of human agriculture. Terrestrial CDR methods for croplands can also bring higher yields, reduced demand for water and fertilizer, and improved nutritional quality. Carbon credits also can result in new revenue streams for farmers. The potential co-benefits should serve as a further incentive to expand CDR RD&D and accelerate the deployment and diffusion of technologically enhanced biological and terrestrial CDR approaches.

- **Cross-cutting RD&D opportunities can help close data gaps for terrestrial and biological CDR and accelerate deployment.** These cross-cutting opportunities include more robust models; new measurement, monitoring, and data tools; lifecycle analysis to better document net carbon removal; and strategies for incentivizing adoption and diffusion of new crops.

Recommendations

- **Increased federal investment in biological and terrestrial CDR RD&D should support a broad portfolio of approaches extending across the entire biological and terrestrial ecosystem, including soils, plants, and trees.** The priority areas for increased biological and terrestrial CDR RD&D include:

  - Enhancement of SOC through various approaches, including application of biochar, to replenish depleted soils and enhance agricultural productivity;
  - Fundamental research to identify plant organism traits that govern the absorption and conversion of CO_2 and develop methods to enhance those traits;
  - Purpose-engineered plant cultivars employing both conventional breeding and biotechnology techniques to create plant species with deeper and more robust root systems; and
  - Transformation of annual crops to perennial crop systems.

  The September 2019 EFI *Clearing the Air* report recommended a focused investment portfolio for biological and terrestrial CDR RD&D totaling more than $1.5 billion over 10 years. The report also recommended establishment of a $2 billion CDR demonstration program that could include large scale demonstrations of biological and terrestrial CDR alternatives selected through a competitive process.

- **The application of biotechnology to advancing biological and terrestrial CDR approaches should proactively address the ethical, legal, and social concerns raised by biotechnology innovation.** While experts have deemed biotechnologically modified crops to be safe, any RD&D in this area poses uncertainties because changes to organisms can be self-sustaining and do not respect jurisdictional boundaries. The design of CDR RD&D should directly address these concerns and provide for full compliance with U.S. and international scientific guidelines.

- **Biological and terrestrial CDR RD&D efforts should emphasize co-benefits wherever possible to enable rapid deployment and diffusion, which in turn offers the potential to achieve significant impacts on net CO_2 emissions within a relatively short timeframe.** Advances in agricultural science and technology, including new seed strains and improved soil management practices, have a history of rapid market diffusion. The concentration of large quantities of the major crops, combined with a robust system of outreach and education encourage rapid rates of deployment. Development of CDR approaches that have demonstrable co-benefits will be more attractive for rapid market introduction.

- **The biological and terrestrial CDR RD&D portfolio should also focus on development of improved methodologies for measurement of carbon reduction impacts to support new revenue streams as well as advance carbon policy objectives.** Better monitoring, reporting, and verification (MRV) of carbon reduction benefits from all forms of land-based CDR, including both natural as well as biotechnologically enhanced methods, can provide the foundation for valuation of biological and terrestrial CDR carbon credits that ultimately could comprise a carbon market.

- **The Department of Agriculture (USDA) should be the lead agency on biological and terrestrial CDR efforts.** USDA houses several research agencies with expertise in the biological and terrestrial sciences, as well as conservation and extension efforts that can help with demonstration and deployment. USDA could accelerate RD&D by adding CDR to the mission objectives of its RD&D agencies, adding CDR practices to its deployment-focused conservation and forestry programs, and establishing a strong internal coordination process under the auspices of the Under Secretary for Research, Education, and Economics. The September 2019 EFI *Clearing the Air* report recommended that the Under Secretary lead the CDR RD&D programs within the Department as well as serve as a co-chair for the proposed Large Scale Carbon Management Subcommittee of the National Science and Technology Committee.

- **USDA should implement the Agriculture Research and Development Agency (AGARDA), dedicated to high-risk, high-reward research support, with an initial priority emphasis on CDR.** The 2018 Farm Bill authorized and funded a new USDA agency—AGARDA—to focus on cutting-edge agricultural research, but it has not been set up yet by the department. Standing up AGARDA and expanding funding for existing cutting edge research organizations, such as the DOE Advanced Research Projects Agency—Energy (ARPA-E) and the DOE Office of Science, can support novel or more innovative concepts for biological and terrestrial CDR but may otherwise be outside the framework of existing research entities.

Cutting-Edge Approaches for Land-Based Carbon Dioxide Removal

The Need for Technologically Enhanced Biological and Terrestrial CDR

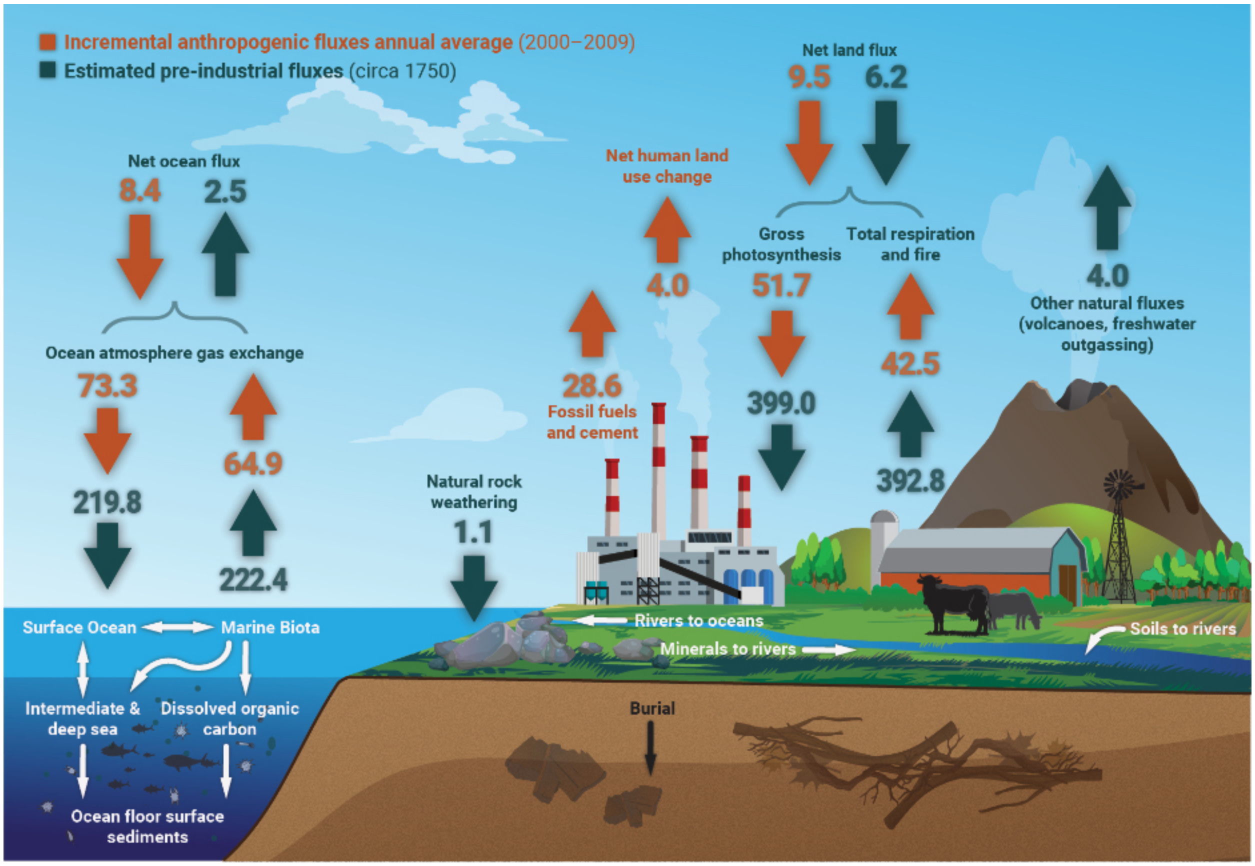
The Role of Biological and Terrestrial CDR in the Global Carbon Cycle

Terrestrial systems—soils, plants, and trees—provide food, fiber, and materials essential to human well-being. These systems play a key role in the global carbon cycle, currently absorbing approximately 25 percent of anthropogenic CO_2 emissions.

In pre-industrial era, the exchange of CO_2 between land-based ecosystems, oceans, and the atmosphere was largely in balance. As anthropogenic emissions of CO_2 have

FIGURE 1

Global Carbon Cycle



The global carbon cycle involves the exchange of CO_2 among the atmosphere, land, water, and subsurface. Green arrows denote estimated natural fluxes prior to the Industrial Era (circa 1750). Orange arrows denote anthropogenic fluxes averaged over the time period 2000-2009. Frontier CDR options can increase the existing negative fluxes—including terrestrial photosynthesis, rock weathering, and ocean fluxes—to combat climate change Source: EFI, 2020. Compiled using data from Intergovernmental Panel on Climate Change, 2013.

BOX 1

About Carbon Dioxide Removal

Carbon dioxide removal (CDR) refers to methods to remove carbon dioxide (CO_2) from the atmosphere and upper levels of the oceans and sequester or convert the CO_2 into an inert form. CDR is an essential complement to CO_2 emissions reductions to achieve net-zero emissions goals and subsequently net-negative emissions, thereby providing the opportunity to reverse some of the effects of historical greenhouse gas (GHG) emissions and “restore” the climate.

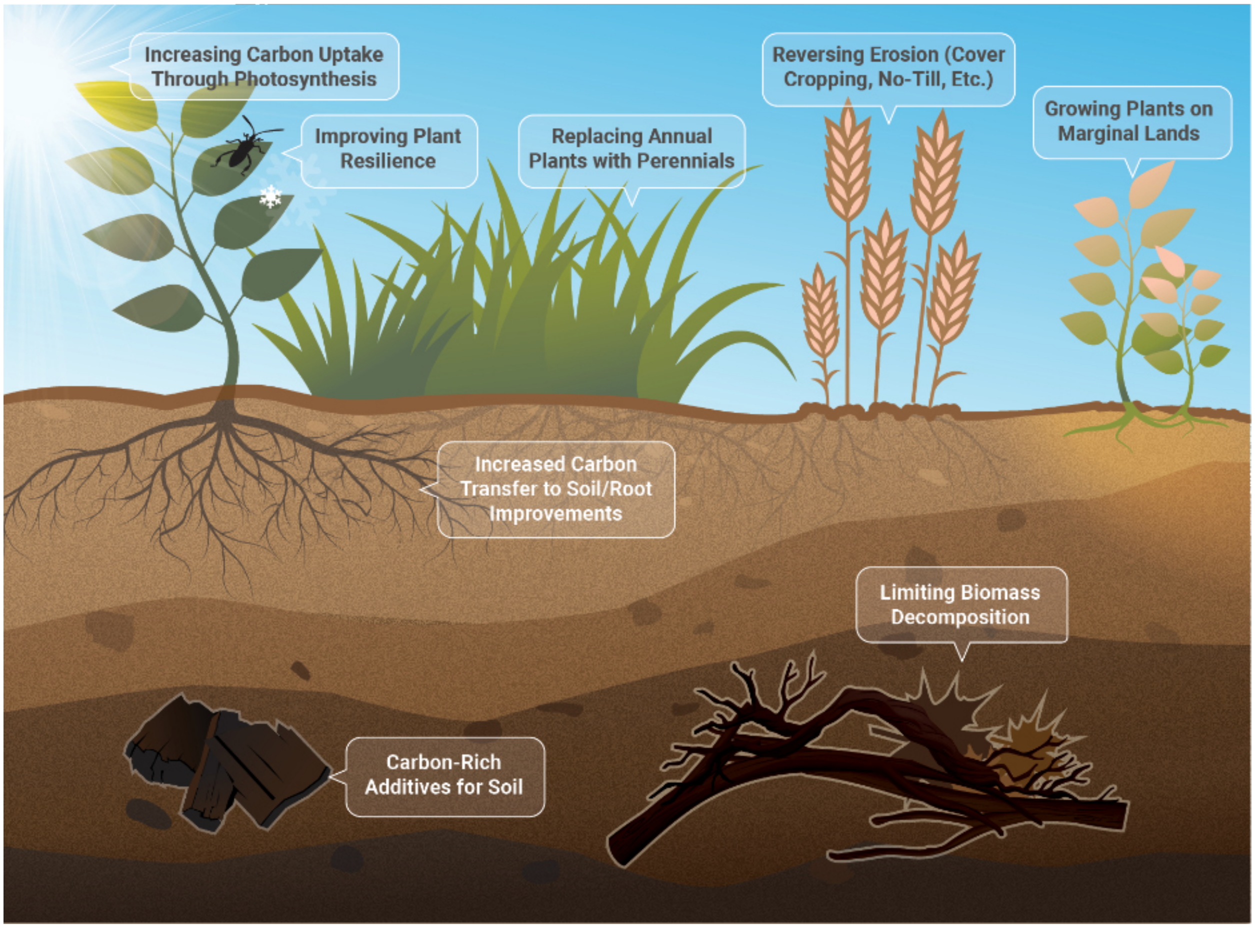
The 2018 Intergovernmental Panel on Climate Change (IPCC) *Special Report on Global Warming of 1.5°C* (*SR1.5*) outlined the importance of reaching net-zero emissions by 2050 in order to limit warming to 1.5 degrees.[2] SR1.5 estimated that 3 to 7 billion metric tons (gigatons, or Gt) of CDR per year would be required globally by 2050 and up to 15 Gt per year by the end of the century.[3]

There are a variety of well-established **natural CDR pathways** to increase the size of natural carbon sinks, such as planting more trees; adopting sustainable agricultural soil management; expanding coastal ecosystems; and increasing natural geochemical CO_2 removal. Expanding natural CDR pathways, while necessary, will not be sufficient to meet the SR1.5 goals, and certainly not to move towards climate restoration. The carbon removal capacity of natural systems can be **technologically enhanced**through the application of modern technology—including use of biotechnology to enhance CDR in soils, plants and trees; enhancing the reactivity of CO_2-absorbing rocks; increasing ocean biomass through cultivation or artificial fertilization; and reversing the trend toward increased acidity in the oceans. **Direct technological capture** pathways involve engineering extraction such as direct air capture (i.e., atmospheric scrubbing) and direct ocean capture through electrochemical conversion, both of which produce a concentrated stream of gaseous CO_2. The captured CO_2 can then be injected into subsurface saline aquifers or mineralizing rock formations. Alternatively, it can be converted into long-lived carbon-based materials.

increased since the beginning of the industrial era, terrestrial ecosystems have absorbed increasing amounts of CO_2 but have not kept up with the rate of growth of anthropogenic emissions (Figure 1). At the same time, human activity has degraded these ecosystems’ carbon-absorbing capacity through deforestation and unsustainable agricultural practices.

The terrestrial biosphere role in the global carbon cycle involves absorbing atmospheric CO_2 through photosynthesis, converting it to organic matter (such as carbohydrates), and releasing oxygen back into the atmosphere. This is partially offset by CO_2 released into the atmosphere through decomposition and microbial respiration, or through fire. Carbon is stored on multidecadal timescales as woody biomass and soil organic matter (SOM), and on shorter timescales in leafy biomass and detritus.

FIGURE 2
Biological and Terrestrial CDR Pathways



Purpose-engineered crop cultivars can develop and deploy a variety of terrestrial CDR techniques that improve subsurface and aboveground systems. Source: EFI, 2020.

Opportunity for Technologically Enhanced Biological and Terrestrial CDR

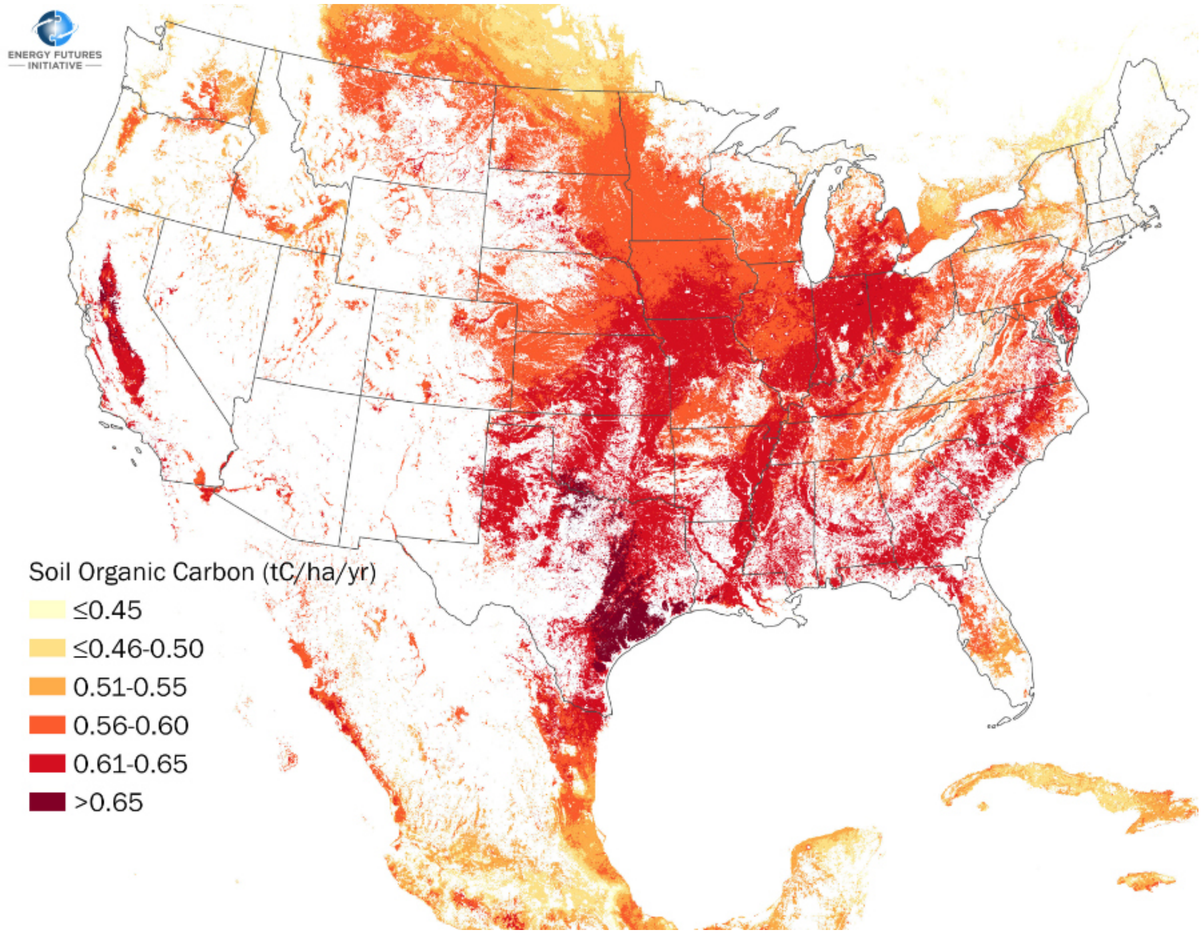
Increasing the level of natural methods of CDR from biological and terrestrial ecosystems is feasible and desirable but subject to limitations. For example, forestry pathways—including afforestation, reforestation, and improved forest management—are among the most well-established and can be expanded with appropriate policy support. There are, however, practical limitations, such as land area needs and competing demands for food and fiber, which ultimately constrain their scale of deployment. For example, the United Nations Trillion Tree Initiative, if fully implemented, could require foresting a global landmass nearly equivalent in size to the entire United States.

Exciting new scientific research opportunities in terrestrial CDR pathways have the potential to supercharge land-based ecosystems. Technologically enhanced biological and terrestrial CDR can greatly expand the range of options for capturing and storing carbon in terrestrial ecosystems, as shown in Figure 2.

The wider range of pathways include adding

FIGURE 3

Potential for Soil Organic Carbon Replenishment on Croplands in the United States



This figure depicts the annual potential increase in SOC. The U.S. has as a particularly large opportunity to increase SOC stocks on cropland in the top 30 centimeters of soil under a medium scenario defined as an increase of 27 percent of SOC over 20 years. Source: EFI, 2020. Compiled using data from Zomer et al., 2017.

carbon as a soil amendment, increasing the rate of CO_2 uptake in plants through photosynthesis, increasing the transfer of carbon from plants to soils through enhanced root systems, enabling improved plant and tree species that can grow on marginal lands, and improving plant and tree resilience to insects, disease, and climate change.

Technology-driven pathways for terrestrial CDR have a high deployment potential (at relatively low cost) for multiple reasons. There is globally a massive land area devoted to agriculture (approximately 30 percent of the Earth's surface is land cover, of which roughly 50 percent of the habitable land is for agriculture), and much of the agricultural land is dedicated to only a few dominant species (which could allow for the rapid deployment of new cultivars optimized for carbon sequestration). The prospects for deployment and ultimate carbon retention will need to be calibrated according to region-specific factors such as climatic conditions and soil type.

Technologically Enhanced CDR to Replenish Soil Organic Carbon

Expansion of biological and terrestrial CDR approaches can be a vital tool in mitigating climate change, but its full potential value derives from the other benefits it can provide (see Co-benefits section on Page 24). A crucial benefit is the replenishment of SOC. A key facet of terrestrial CDR techniques is that most of the carbon absorbed will eventually make its way to the soils, where it is stored as SOC. SOC is a longer-term storage mechanism than biomass (especially non-woody biomass), which can decompose, combust, or otherwise result in carbon being released back to the atmosphere. SOC plays a central role in ecological and agricultural health by contributing to soil fertility, soil water retention, soil structure, plant health and nutrient supplies, erosion resilience, and crop yields.[4]

A huge amount of SOC, however, has been lost (and often oxidized into CO_2, contributing to climate change) due to human activity. Since the dawn of modern industrial agriculture, estimates suggest that 50 to 70 percent of SOC has been lost in cultivated soils.[5] Nearly three-fourths of U.S. cropland has lost SOC over a 30-year period, with the greatest losses experienced in parts of the Midwest and Southeastern United States.[6] Terrestrial CDR can increase the carbon content of soils, reversing some of these losses. As Figure 3 shows, the greatest potential for replenishment is in the same regions with the greatest SOC loss.

Prevention of further losses of SOC can be prevented through natural CDR measures such as such as no-till agriculture and cover cropping. Soils depleted in SOC can be replenished through pathways that increase carbon uptake and storage in plants, as a portion of that carbon will eventually reach the soil. SOC levels also can be directly enhanced by application of carbon-rich materials to soils, whether organic or synthetic (such as biochar).

Soil biology and chemistry represent key research frontiers in understanding the processes governing SOC and improving retention of SOC as a long-term method of carbon sequestration. One key area of research is the nexus between plants, soils, and the rhizosphere, the microbiome that surrounds plant roots. Soil microbes play numerous roles in the subsurface and can be a double-edge sword, leading to both an increase of carbon storage in soils as well as the loss of soil carbon to the atmosphere.[7] These interactions are illustrated in Figure 4.

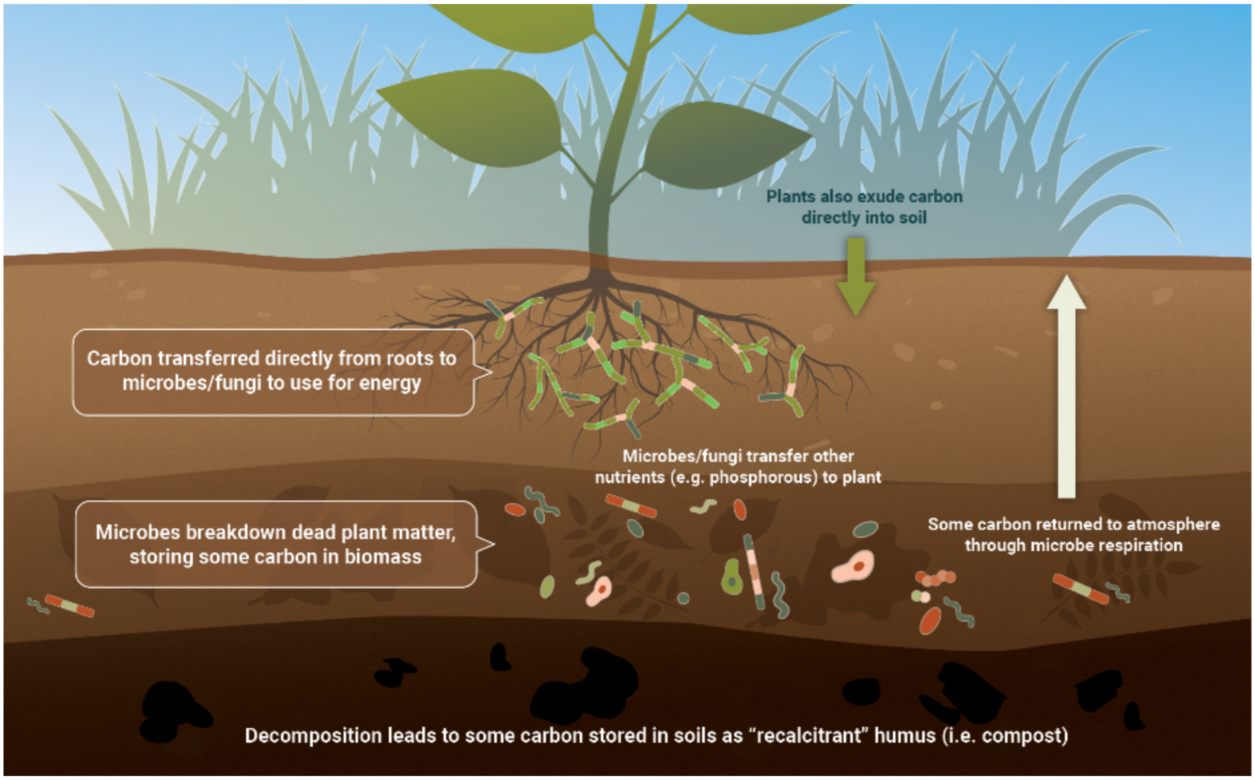
Research opportunities to better understand the potential for CDR related to microbial activities include:

- better understanding of root-microbe-soil interactions;
- mechanistic understanding of the microbial basis for soil carbon persistence;
- management of the underground microbiome in concert with deploying cropping systems; and
- feeding microbes in a bioreactor to accelerate their production of nitrogen-rich compounds that will persist over long timescales in the soil.

EFI Biological and Terrestrial CDR Workshops

In 2020, EFI organized workshop meetings of leading scientific researchers in the fields of biology, agronomy, forestry, and ecology to address these questions and further define

FIGURE 4
Root-Microbe-Soil Interactions



Technologically enhanced CDR can replenish soil organic carbon, which plays a central role in ecological and agricultural health by contributing to soil fertility, soil water retention, soil structure, plant health and nutrient supplies, erosion resilience, and crop yields. Source: EFI, 2020.

the research opportunities in cutting-edge, technologically enhanced CDR.[a]

The motivation for the workshops was to explore the research opportunities to address fundamental questions about biological and terrestrial CO_2 removal and sequestration such as, for example:

- What if plant systems can capture and store more carbon in root systems in a way that ultimately stores more carbon in soils?
- What if plant and microbial ecosystems can increase the replacement of soil carbon being depleted in agricultural systems?
- What if these measures can improve crop productivity while also reducing the need for water and fertilizer?
- How can cutting-edge technologies be applied to forestry CDR?

Interest in the workshops was further underscored by the opportunity to discuss

a. The workshops did not cover Bioenergy with Carbon Capture and Storage (BECCS), as it has already received significant attention relative to understudied CDR pathways discussed in this report.

how scientific and technological advances in biotechnology, data analytics, high performance computing and artificial intelligence might open the door to new levels of understanding of biological and terrestrial ecosystems.

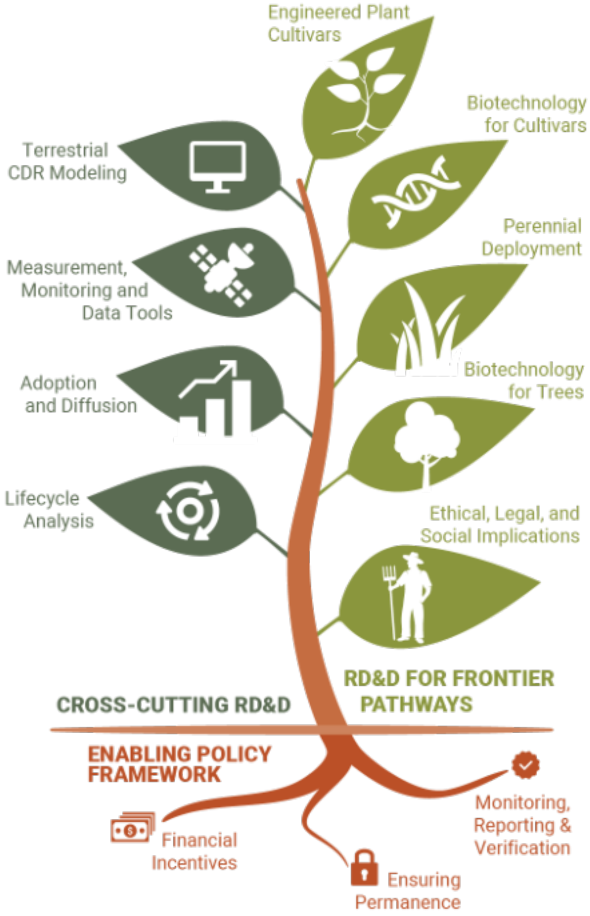
The workshop meetings were organized into eight specific areas (illustrated in Figure 5), including both CDR frontier pathways and cross-cutting issues:

1. Identifying and isolating key useful traits in biological materials;
2. Applying the tools of biotechnology to engineer better plants with those useful traits;
3. Expanding applications for more carbon-storing perennial plant systems and greater use of marginal lands;
4. Applying biotechnology to trees;
5. Assessing the ethical, legal, and social implications of biotechnology CDR applications;
6. Developing new tools for measuring and monitoring terrestrial carbon sequestration;
7. Improving computer models of biological and terrestrial CDR processes;
8. Researching rates of adoption and diffusion of new crop varieties and management practices; and
9. Analyzing lifecycle impacts of biological and terrestrial CDR pathways.

Workshop participants also discussed how policy mechanisms could help support RD&D and deployment of biological and terrestrial CDR.

FIGURE 5

Biological and Terrestrial CDR RD&D Opportunities and Enabling Policy Framework



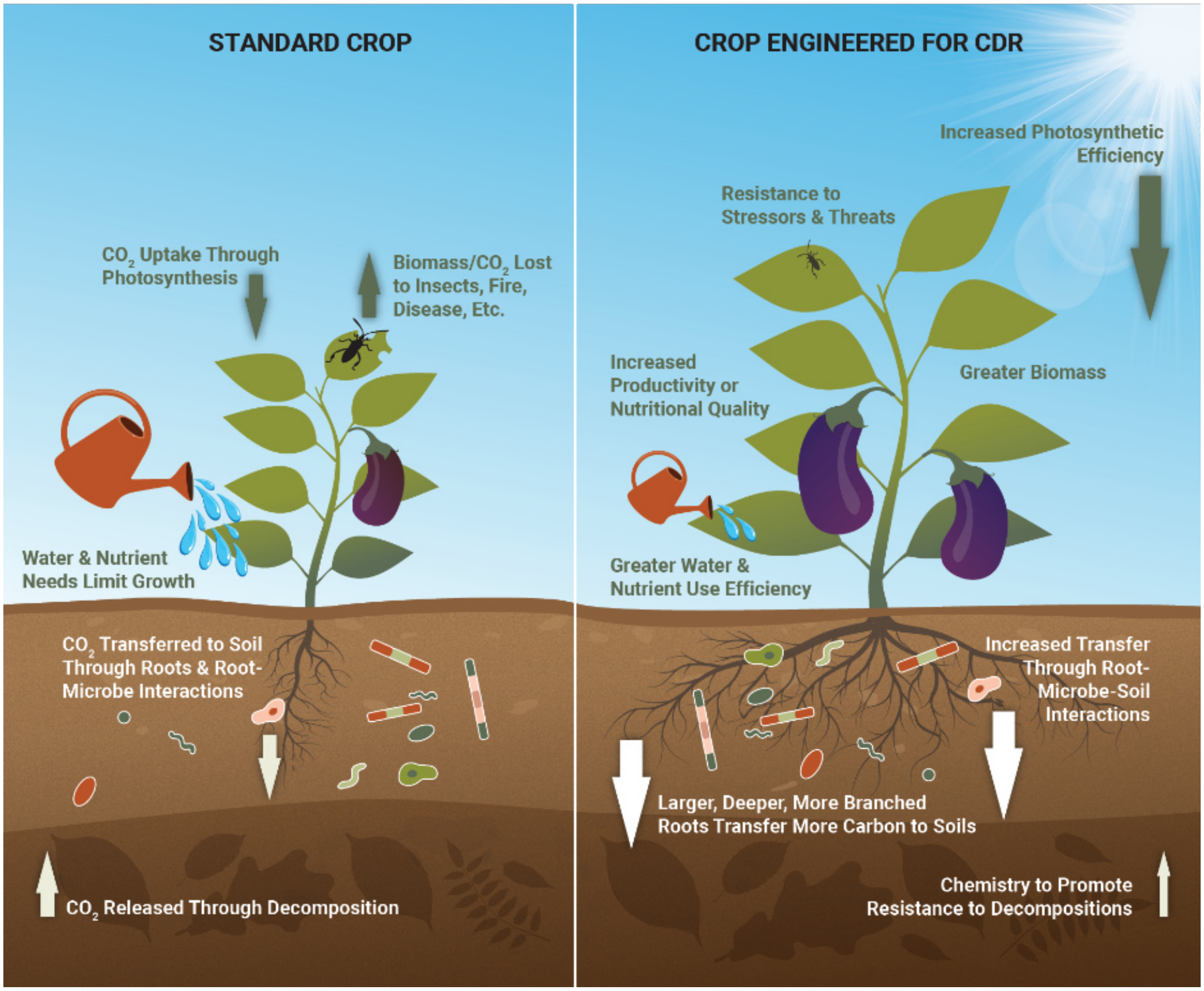
A combination of enabling policies and increased RD&D in priority areas is necessary to achieve terrestrial and biological CDR at scale. Source: EFI, 2020. Select icons from The Noun Project.

Summary of Biological and Terrestrial CDR RD&D Opportunities

There are several high-priority biological and terrestrial CDR research topics that could lead to rapid, large-scale deployment opportunities if successful. The major research opportunities, challenges and priorities identified by workshop participants are summarized in Table 1.

FIGURE 6

Traits of Interest for Engineered Crop Cultivars



There are many traits of interest impacting the whole plant, root systems, and/or sustainability factors that, in addition to reducing CO_2, can provide co-benefits, like cost savings from efficient water and nutrient use and climate resilience. Source: EFI, 2020. Adapted from the Salk Institute.

RD&D Priorities for Biological and Terrestrial CDR Frontier Pathways

The principal RD&D objective for terrestrial CDR is to develop and deploy new pathways for enhanced carbon uptake in crop plants, soils, and trees in a manner that does not decrease production of essential goods like food and fiber. This section outlines underexplored, cross-cutting pathways that could have substantial potential.

Identifying Useful Traits in Engineered Crop Cultivars

Purpose-engineered plant varieties (cultivars) are a primary means for developing and deploying terrestrial CDR techniques.[8] New and improved cultivars can also help modern

TABLE 1

Identified Research Opportunities for Biological and Terrestrial CDR RD&D

Research Need	Research Opportunities
Identifying Useful Traits – Traits directly indicative of carbon sequestration are unclear. – Belowground traits are hard to measure.	→ Improving the ability of genotype-phenotype genome-wide association studies to quickly identify genes controlling traits. → Scientific convergence on which traits should be measured. → Technologies to measure/quantify traits at scale. → Identify easy-to-measure aboveground surrogate traits. → Tools for high-throughput, belowground phenotyping. → Robust ecosystem models for belowground traits to converge with good-enough local models.
Synthetic Biology for Crops – The current biosystems design principles and toolkits cannot meet the needs for precise engineering of CDR traits. – High-quality genome sequences of all relevant crop species are not available. – High efficacy transformation systems are not available for all species.	→ Research consortium efforts to establish robust biosystems design principles and develop new capabilities for gene circuit design, build, test, and computational learning from experimental test results. → Large-scale genome sequencing effort to generate high-quality genome and transcriptome (gene activity) sequence data for many representative genotypes in the common lab conditions, and high-throughput capabilities to validate gene function. → Technologies for rapidly translating CDR traits from model species to crop species.
Perennial Plant Systems and Marginal Lands – Converting grain crops from annuals to perennials is not feasible in the next 5-10 years. – Predictive models of soil carbon sequestration are not well developed for perennial systems. – Farmer acceptability to perennials is low due to lack of annual technology update and persistent pathogen issues.	→ New biosystems design strategies for converting annual to perennial crops without compromise on yield and disease resistance. → Modification of existing annual crop CDR models for better modeling CDR in perennial systems. → Improved disease resistance/productivity through genetic engineering and incentive to increase favorability.
Synthetic Biology for Forestry – Need to translate cultivars practices to forestry – Adoption and diffusion for forestry could require different mechanisms	→ Woody crop management on marginal lands → Large-scale deployment on agricultural lands → Increase high-throughput phenotyping → Applying biotechnology approaches to trees → Synergies with other forestry CDR pathways

Research Need	Research Opportunities
Ethical, Legal, and Social Implications (ELSI) – ELSI have caused problems for biotechnology in the past because they were treated as an afterthought – CDR could involve GMOs and their release into the environment – International regulations on GMOs pose an additional obstacle – Possible ethical imperatives to address food scarcity and environmental degradation	→ ELSI implications of various terrestrial CDR pathways → Public outreach strategies and governance frameworks → Balancing productivity/farmer compensation with CDR
Measurement, Monitoring, and Data Tools – Methods are underdeveloped for lab use and widespread use in field to capture heterogeneity (spatiotemporal variation). – Rate of incorporation of ^{13}C is variable as a challenge in quantifying effects on small concentration molecules (metabolites, proteins).	→ Integration of ^{13}C tracer methods into high-resolution, lab-based molecular profiling studies. → Capture heterogeneity along root, plant, soil, and climate types using selected extreme genotypes/cultivars. → New monitoring technologies (easily adoptable and efficient) beyond traditional ^{13}C.
Terrestrial CDR Modeling – Belowground traits are difficult to measure.	→ Improve lab-to-field performance prediction studies. → Extensive trait-trait correlation studies to identify high-confidence linkages to easy-to-measure surrogates. → New belowground measurement technologies that are widely deployable, non-invasive, reliable and/or quantitative.
Analyzing Lifecycle Impacts – Risk of unanticipated adverse lifecycle effects	→ Understanding adverse impacts such as potential for invasive species; carbon leakage; fertilizer needs; and threats to crop-soil-microbial interface
Adoption and Diffusion – Aboveground yields can be compromised. – Intensive management is needed. – Land use changes might be tricky. – Current purpose of land use is not geared in favor of carbon sequestration.	→ Economic incentives are a powerful driver of farmer/landowner buy-in. → New technology developments bring economic benefits. → Incentivize services and not carbon budgeting (as that is tough to monitor transparently). → Intentional incentives (private or government) for farmer buy-in to carbon sequestration as "services" performed. → Early engagement with private companies.

Source: EFI, 2020.

food production systems confront the contemporary challenges of a growing human population, climate change stressors, rapid topsoil erosion, reduced soil fertility, and a decline in natural pollinators.[9] Once traits are identified, they can be introduced through traditional breeding methods and by biotechnology techniques.

Specific areas of interest for trait exploration are shown in Figure 6 and include:

- **Whole plant:** increased photosynthetic efficiency and atmospheric CO_2 capture and allocation; preservation or improvement in productivity (e.g., food yield or nutritional value).

- **Root systems:** greater biomass; root architecture; deeper roots; root branching; greater fine root production and turnover; increased residence time of plant-derived carbon forms; chemistry that can promote recalcitrance (resistance to decomposition) in soil; and symbiosis between the plant, the rhizosphere, and soil minerology and chemistry.

- **Sustainability:** water and nutrient use efficiency; abiotic/biotic stress tolerance; nutritional value preservation; root-microbe-soil interactions; biodiversity conservation; insect, disease, and fire resistance; resilience to future climate stressors.

Further RD&D is needed to determine the relative importance of traits for carbon storage, identify inexpensive ways to pinpoint those traits, develop means to improve precision and efficacy of targeted trait improvement, and improve ways of measuring carbon accumulation aboveground and belowground. Fundamental research is needed to develop the tools needed to maximize the ability to rapidly generate and test multiple variants in a range of settings (from lab to multiple field testing sites), and to develop phenotyping approaches (e.g. high-throughput, automated measurement of plant traits) to capture and quantify heterogeneity in traits of interest within and across root and plant types and soil profiles. A key research need is the ability to translate from model species, which have relatively well understood genetics, to food, fuel, and other widespread crops.

The costs and timescale for this type of RD&D may vary by factors such as the type of plant species and geographic area related to current (and anticipated future) climate conditions.

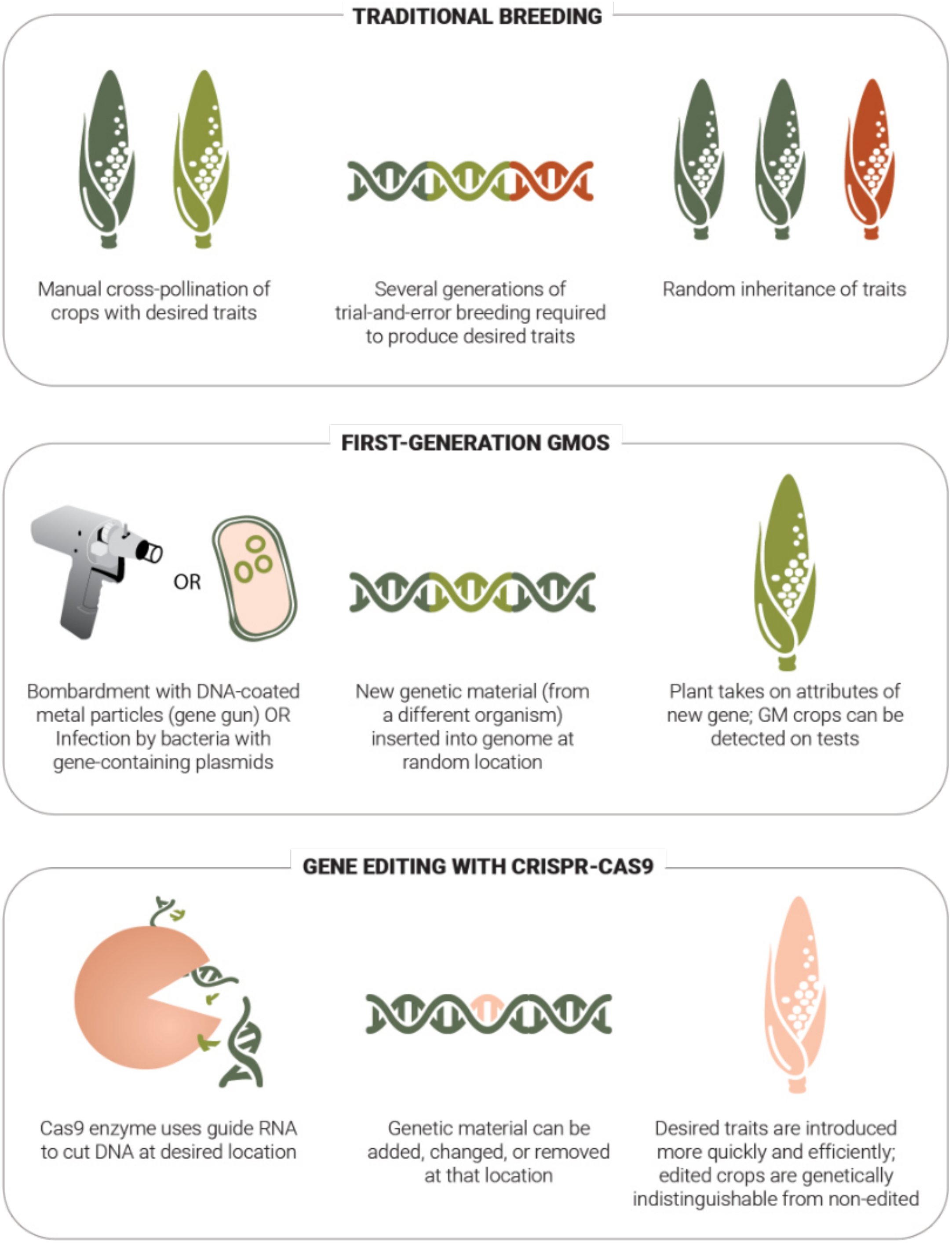
Applying the Tools of Biotechnology for Engineered Crop Cultivars

Genetics and underlying principles of plant selection are used worldwide to develop improved cultivars, but new biotechnology techniques, generally referred to as synthetic biology, offer greater opportunities for accelerated genetic and trait improvement efforts.

Synthetic biology is an approach that applies engineering principles to biology. Its distinguishing feature is a focus on designing parts of organisms that can be modeled, understood, calibrated, and assembled to create redesigned organisms with new useful purposes and abilities, analogous to the assembly of circuits to make a computer.[10,11] Synthetic biology builds on advances in genomics and gene synthesizing; molecular, cell, and systems biology; and computing.[12]

The last decade has seen several advances in biotechnology. Of particular note is the shift from the genetic modification techniques of the 1980's and 1990's to genome editing methods like the CRISPR-Cas9 system[b], a

FIGURE 7
Terrestrial CDR Techniques



Identified traits can be introduced to crop cultivars through a number of methods, including traditional breeding, first-generation genetic modification, or new methods like gene editing with CRISPR-Cas9. Source: EFI, 2020.

technique developed from the immune systems of certain bacteria that allows for the targeting of specific sequences of genetic material (Figure 7). A September 2020 study by the Information Technology and Innovation Foundation concluded that genome editing is an under-emphasized platform technology with broad potential for emissions reduction.[13]

Genome editing and biotechnology methods could be used for improvements to both food production and biological capture of CO_2 from the atmosphere (and subsequent storage in soils). Further research on new genetic improvement and trait measurement methods is needed to achieve greater precision, and faster turnaround times in the development and validation of new CDR technologies. Such advances would offer opportunities for more efficient CDR through storage in soils beyond what traditional genetics and breeding techniques can achieve.

This type of research could assist with the better understanding of gene functions related to CDR, which are largely unknown in non-model species. Translating identified traits from model to non-model species is a key research objective for ongoing cultivars research efforts, such as the Salk Institute's Harnessing Plants Initiative (HPI), which recently received a major grant from the Bezos Earth Fund.[14] HPI plans to develop traits of interest—roots with greater mass, depth, and decomposition-resistant suberin content—in model plants and then transfer them to food crops such as corn, soybeans, rice, wheat, cotton, and canola.[15]

Genomic resources developed for both model and non-model plants would complement biological and terrestrial CDR options and help transfer the functional genomics knowledge from model plants to crop species. For example, model plants such as *Arabidopsis* have excellent resources for molecular and functional genomics studies and toolboxes for rapid gene function discovery. The adoption of genome-wide association studies and genomic predictions as direct gene discovery approaches in crop species could help advance our understanding of critical gene functions for terrestrial CDR.

Expanded Applications for Perennial Plant Systems and Use of Marginal Lands

Perennial systems are those that live for multiple years and have a great potential for CDR by contributing a large amount of carbon to underground storage as soil organic matter.[16] Perennial systems have great potential for biological carbon storage as perennials have much greater diversity than annuals due to their longevity over many years. They also have more extensive and deeper root systems that enable greater carbon capture and storage than annuals.[17] Opportunities for the deployment of perennials include:

- → conversion of annual croplands to perennial grasslands or forests;
- → deep-rooted perennials (e.g., bioenergy crops, native grasses) on marginal lands that have been abandoned from cropland regardless of whether they are harvested for refineries or biomass digesters; and
- → planting perennials on brownfields, fallowed land, roadside margin strips, and municipal lands.

Perennials face many of the same challenges

b. CRISPR stands for "clustered regularly interspaced short palindromic repeats" and Cas9 is an abbreviation of "CRISPR-associated protein 9" as annuals and require similarly robust RD&D that includes multiple technologies and species to understand the genetic architecture. Enhanced and improved understanding of perennial systems would therefore help further CDR efforts in annual systems as well due to their synergies.

Many of these opportunities for herbaceous perennials would also apply to trees. There are several tree species that could be suitable candidates for deployment on marginal lands in the U.S. because of their asexual reproduction and rapid maturation. These include native species such as poplar, willow, silver maple, and black locust, as well as non-native trees such as eucalyptus. Afforestation of marginal lands, especially in urban areas, can bring non-climate benefits as well, such as decreases in local air pollution and diminishment of the urban heat island effect.

Applying Biotechnology to Trees

Well-established natural CDR pathways already exist for forestry, including afforestation, reforestation, and forest management that accelerates regeneration, thins unsustainable forests, extends harvest rotations, protects against fire/pests/disease, etc. Afforestation and reforestation could also involve planting trees on marginal lands, as with perennials, or intermingling with crops (alley cropping). There are also more frontier approaches that involve preserving woody biomass for longer periods of time, including innovative landfilling or burial options, or creation of new, long-lived wood products. Various ways have been proposed to scale up natural forestry management practices to enhance CDR. such as the Trillion Trees initiative (see Box 2).

Forest management is another terrestrial CDR pathway that could be enhanced with biotechnology.[18] Trees are already engineered with conventional breeding techniques to

BOX 2

The Trillion Trees Initiative

The One Trillion Tree initiative is a World Economic Forum (WEF) program, launched at the 2020 WEF Annual Meeting in Davos.[20] It is meant to support the United Nations (U.N.) Decade on Ecosystem Restoration, and bears similarities to the U.N. Environmental Programme's One Billion Tree Initiative,[21] which was in turn inspired by the work of Wangari Maathai, a Nobel Peace Prize winner and founder of the Green Belt Movement environmental organization in East Africa.[22] There had been other previous efforts with similar targets, such as former President George H. W. Bush's America the Beautiful initiative that set a goal of planting one billion trees annually from 1992 to 2000.[23] Preceding the WEF One Trillion Tree initiative, there was a separate Trillion Trees effort led by environmental organizations including the World Wildlife Fund.[24] One commonly cited study from Bastin et al. speculated that a trillion trees could sequester 100 to 300 Gt of carbon (or about 400 to 1,000 Gt of CO_2-equivalent) cumulatively at full maturity, though these figures have been disputed,[25] and the study's authors caution that they cannot be interpreted as a one-to-one equivalent of carbon removal potential.[26] The study bases this estimate on 0.9 billion hectares of new forest land that could be planted globally without impinging on croplands or urban areas. Such an area would be slightly larger than the contiguous United States.

make them more commercially useful; these same techniques, and new ones, could be applied to increasing carbon storage by changing tree morphology, resource needs, and resilience. Additionally, biotechnology using genetic editing of trees has many of the same challenges as crop cultivars, including unanswered questions of which traits will work best to sequester carbon and how these traits interact with the environment. This approach is starting to garner some attention; for example, in 2020 the Society of American Foresters (SAF) reaffirmed its support for R&D and regulation of genetically modified trees, specifically approving of the use of new technologies like CRISPR-Cas9.[19] SAF mentioned increased carbon sequestration among potential benefits of such research.

Ethical, Legal, and Social Implications of Synthetic Biology CDR Applications

The application of biotechnology techniques to plant cultivars and tree species represents a very promising avenue to increase the carbon management productivity of biological and terrestrial ecosystems. The concept of biotechnology however can raise public concerns about potentially unknown and possible adverse side effects on other values such as nutritional value and biodiversity of biological and terrestrial ecosystems. Bio-innovation of any form poses uncertainties because it can be self-sustaining, that it can increase the potential for unintended consequences, and does not respect jurisdictional boundaries. It is therefore prudent that any federal RD&D program focused on biological and terrestrial CDR address ethical, legal, and social implications (ELSI) as an integral part of its programmatic design to help address and mitigate such risks. CDR research outcomes will need to be carefully reviewed within the domestic and regulatory frameworks that have been put in place for oversight of genetically modified organisms (See Box 3).

FIGURE 8

Coordinated Framework for the Federal Regulation of Biotechnology

In the U.S., genetically modified plants are regulated by the Environmental Protection Agency, the Food and Drug Administration, and the U.S. Department of Agriculture. Coordination among these agencies will be critical for the successful deployment of CDR technology. Source: EFI, 2020.

For biological and terrestrial CDR there is a particular concern if it involves the use of biotechnology with GMOs on landscapes that are unaffected by human activity. A recent National Academy of Sciences, Engineering,

BOX 3

Regulatory Oversight for Ethical, Legal, and Social Implications of Synthetic Biology and Biological and Terrestrial CDR

Since their initial introduction in 1995, crops improved using tools of modern biotechnology (genetically modified crops) have been planted and accepted by U.S. farmers at an unprecedented rate. These crops express traits that provide growers with increased yields; improved harvest quality; fewer applications of insecticides; improved weed control resulting in fewer herbicide applications; and no-tillage options. Yet despite these positive attributes, some remain skeptical of the safety of GM crops.

Domestic regulatory oversight of genetically modified organisms (GMOs) falls under the purview of the U.S. Department of Agriculture (USDA), the Food and Drug Administration (FDA), and the Environmental Protection Agency (EPA) based on the use of the underlying recombinant technology (as illustrated in Figure 8). Success in achieving deployment of biotechnology CDR methods in major agricultural production regions will necessitate partnering with experienced regulatory and communications experts for guidance and strategic planning as the CDR technology proceeds towards deployment. Federally funded biotechnology CDR RD&D programs should be augmented with experienced regulatory and biosafety personnel to ensure that all relevant U.S. and foreign country-specific biosafety data requirements are satisfied as well as achieving compliance with international treaties and guidance with respect to environmental, food safety, and transboundary movement.

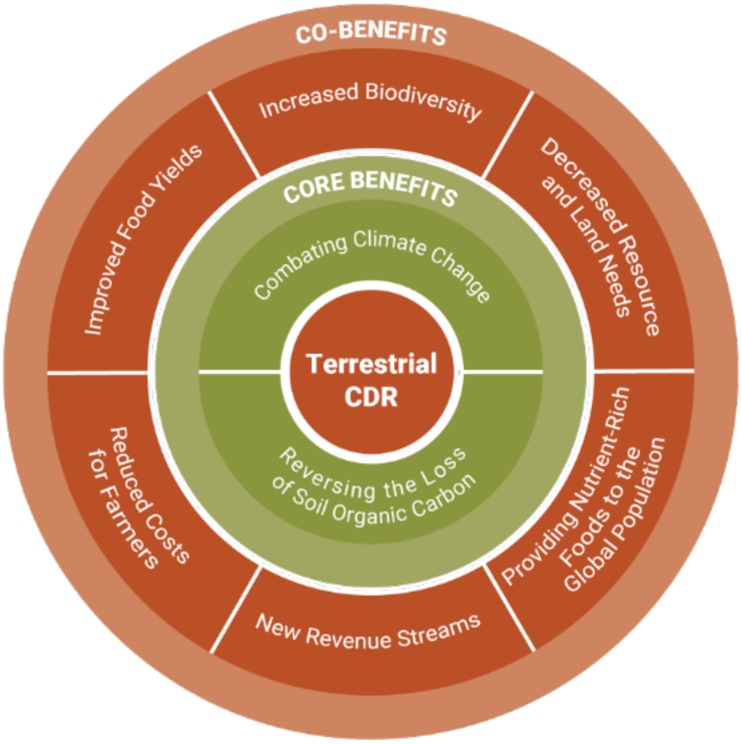
Achieving the full potential of these technologies may also require improved alignment of regulatory requirements with risk. Some researchers believe that the regulatory burden (especially outside the U.S.) on genetically modified and gene-edited organisms is disproportionate to the risk such organisms pose, and not based in science.[28] Efforts to align regulatory risk and burden must strike a balance among integrating the latest scientific knowledge, avoiding unnecessary cost to the economy, and consideration of the views of stakeholders raising ELSI issues.

Biological and terrestrial CDR will not be able to deliver on its promise to address climate change and help rebalance the global carbon cycle unless it is internationally adopted. At that level, its application will be governed by the Cartagena Protocol on Biosafety that covers the transfer, handling, and use of GMOs. Although the U.S. is not currently a member of the protocol, the U.S. scientific community generally adheres to it. This protocol is a supplemental agreement to the Convention of Biological Diversity (CBD) that espouses the conservation of biodiversity, the sustainable use of biodiversity, and the fair and equitable sharing of the benefits of biodiversity. Another supplemental agreement is the Nagoya Protocol, which addresses access to genetic resources and the fair and equitable sharing of the benefits of biodiversity.

While the U.S. is not a party to the CBD or (consequently) its protocols, it does participate in some international biodiversity efforts: the U.S. is an observer at the CBD Conferences of the Parties, and in 2017 joined the International Treaty on Plant Genetic Resources for Food and Agriculture, which supersedes the Nagoya Protocol for access and benefit-sharing around a set of common food crops.

FIGURE 9

Co-benefits of Biological and Terrestrial CDR



In addition to its carbon emissions benefits, biological and terrestrial CDR provides a number of co-benefits, such as supporting biodiversity, improving food yields while decreasing resource needs, and providing adequate nutrients to feed the global population. Source: EFI, 2020.

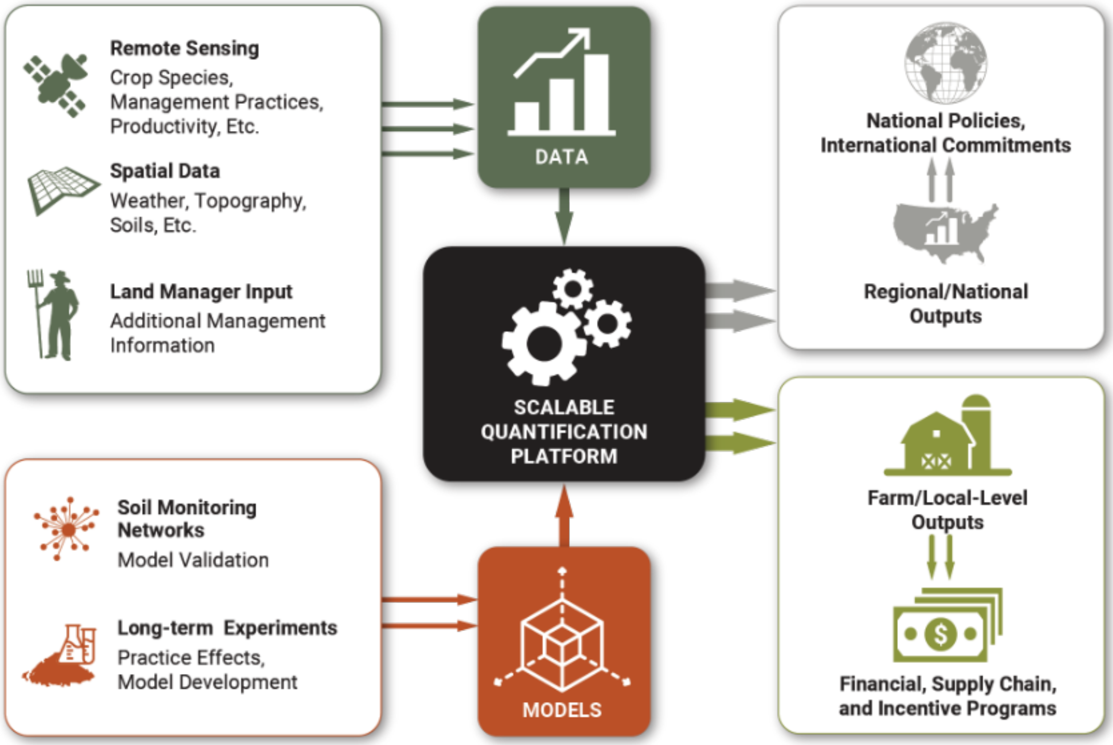
and Medicine (NASEM) study concluded that genetic engineering poses low risk.[27] Even so, specific biotechnology CDR RD&D needs to be carefully consider possible unintended ecologic consequences, and in so doing to build the confidence of key stakeholders and the general public. These concerns also should consider the affirmative ethical obligation to apply biotechnology to alleviate food scarcity and environmental degradation. The issue of use of biotechnology to enhance biological and terrestrial CDR should consider how multiple outcomes can be achieved in a mutually beneficial manner.

Co-benefits of Terrestrial and Biological CDR

While RD&D in biological and terrestrial CDR is crucial because of its GHG mitigation potential and its benefits for SOC, it is also worth pursuing because of the wealth of additional benefits it can provide (Figure 9). These include supporting biodiversity, improving food yields while decreasing resource needs, and providing adequate nutrients to feed the global population. Some of these benefits will be realized indirectly, through the reduction of GHGs. For example, under higher CO_2 levels, some of the major crops are seeing decreases in nutrient concentrations; CDR could be a tool to reverse that process. Replenishing SOC will also

FIGURE 10

Integrated Model-Data Platforms for Measurement, Monitoring, and Decision Support



Modeling and monitoring tools will both be crucial to the scale-up of terrestrial CDR methods. Several facets of deployment, including policy support and market formation, depend on these tools. NASEM recommends that platform systems integrating existing and new data from field sites, spatial data layers of model drivers, remotely sensed activity data, and potentially, crowd-sourced data from farmers, are needed to achieve CDR at a gigaton per year scale. Source: EFI, 2020. Adapted from NASEM, 2018.

benefit crop productivity, decrease resource needs, and fortify soils against erosion.

Co-benefits can also be realized by using the tools of biotechnology to achieve greater carbon storage in tandem with other goals, such as robust food yields and optimal nutritional quality. In addition to being able to feed more people and generate more economic value, higher-yielding crops can also reduce the amount of land, water, and fertilizer needed to meet demand, conferring additional environmental and economic benefits. Pursuing CDR and higher yields concurrently will also make adoption and diffusion of CDR approaches easier, as growers will be incentivized to adopt technologies and practices that improve productivity.

Crosscutting RD&D Priorities for Biological and Terrestrial CDR

Measurement, Monitoring, and Data Tools for Terrestrial Pathways

The ability to accurately and inexpensively measure and monitor soil carbon sequestration is paramount to the success of terrestrial CDR. A standardized and transparent measurement protocol and/or certification process for best practices related to soil carbon storage could help connect natural farming systems to payment plans for practices that store carbon. One option could be a centralized, fully integrated, and open source data platform that houses pertinent information on all aspects of monitoring, reporting, and verification (Figure 10). There are a host of data tools and platforms that could prove useful toward this effort (see Appendix D: Selection of Data Tools and Platforms to Support Biological and Terrestrial CDR).

Over shorter time periods (e.g., annual timescales), the scientific community does have the ability to detect changes in soil carbon, especially through the use of isotope labeling that allows for the determination of where carbon is entering the soil from the cultivars. Additional research is needed to improve these isotopic techniques in the laboratory for testing and validation in controlled settings rather than relying on field testing alone. The ability to measure carbon sequestration over longer time periods is limited and labor-intensive (but not impossible) due in part to the complex nature of ecosystems and lack of suitable measurement approaches that capture heterogeneity in the plant/soil system.

As new techniques are perfected for measuring the rate of CO_2 capture due to biological and terrestrial CDR, it creates opportunities to assign value to the levels of removal as part of any future climate policy regime. This in turn may facilitate legislation to codify the methodologies and procedures for measuring the negative carbon emissions and establishing criteria and procedures for validation of the estimates. One such legislative proposal is The Growing Climate Solutions Act of 2020 (S. 3894/H.R. 7393), which was introduced in both houses of Congress with bipartisan co-sponsors.

Terrestrial CDR Modeling

Modeling the potential direct land impacts and global carbon impacts of biological and terrestrial CDR techniques will be instrumental in assessing and prioritizing promising CDR approaches and accelerating cost-effective RD&D and deployment. These top-down modeling methods can be enhanced with the bottom-up measurement methods and estimates described in the previous section.

Integrated assessment models (IAMs) are global-scale models used to evaluate the impacts of climate change and identify cost-effective mitigation options. Biological and terrestrial CDR beyond afforestation and reforestation currently is poorly represented in IAMs (especially at the regional level). These models also assume globally harmonized policy implementation; however, biological and terrestrial CDR outcomes can vary significantly by location and thus require more research on such land use policy frameworks.

The current stock of other modeling tools (including ecosystem and land-based models) are imperfect but have been improving over time. These models will require continual improvement in lockstep with knowledge gained from the lab and field, otherwise models will quickly fall out of date with the current input data on which they rely. Additional work is needed to expand the representation of the plant types that can be modeled such as perennials, grasses, and woody species along with improvements at integrating landscapes and local scale data using data-model fusion techniques that incorporate empirical observations into the logic of the models. Ongoing model improvement and validation will be critical to this overall effort.

Research Opportunities to Accelerate CDR Adoption and Diffusion

Ultimately, new approaches to biological and terrestrial CDR, including new plant varieties and land management techniques, must achieve widespread adoption and diffusion to make a meaningful contribution to CDR.

Research is needed to create a rubric that determines which species to plant (and where) depending on soil type, climate, and native species so that land managers can customize deployment options based on location. Deployment and carbon retention potential are region-specific and influenced by factors such as climatic conditions and soil type, which affect productivity, sustainability, and the carbon storage capability of plant types. Given the huge variety of local land and climate conditions, any deployment strategy is likely going to need more than one species to provide enhanced CDR benefits. Species that flourish with little to no ecological competition are known as dominant species and tend to constitute a large amount of an ecosystem's biomass.[c] The distribution and adoption of cultivars co-optimized for carbon storage could be aided by precisely targeting dominant species for new cultivars replacement. Given the abundance of these species, engineering them for deeper roots or greater carbon uptake presents an opportunity for significant carbon storage.

Fortunately, innovation in agricultural technologies and practices have a track record of rapid diffusion. The Green Revolution from the 1960s to the 1980s demonstrated rapid changes of deployment of new crop varieties to boost productivity and support growing populations. High-yielding rice varieties came to account for the majority of cultivated rice land area in Indonesia, Pakistan, and the Philippines, as well as a significant percentage in India, Burma, Malaysia, and South Korea.[29] More recently, genetically modified soybeans introduced in 1996 have come to account for 89 percent of all U.S. soybeans.[30] Genetically modified corn and cotton have also come to occupy a significant amount of their respective markets (Figure 11).[31]

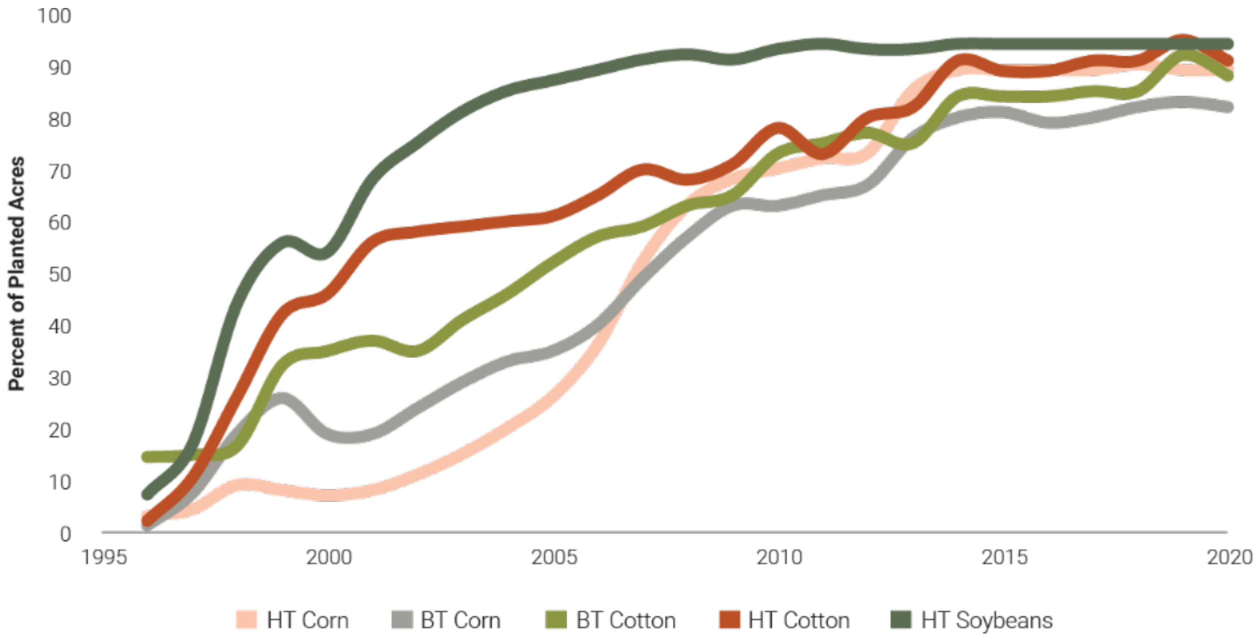
The avenues for disseminating new cultivars warrant additional research and coordination. Currently, many seed markets are dominated primarily by Bayer, Monsanto, Corteva (formerly of DowDuPont), and Syngenta, which collectively control the majority of corn, cotton, and soybean seed sales in the United States.[32] Given the sheer size of their market share, these companies are in a strong position to promote and distribute new cultivars to achieve CDR at scale. These companies already provide information through their field advisors directly to farmers who purchase their seeds.

Another dissemination approach could be collaborations between charitable organizations and farmers to incorporate new technologies and practices. For instance, The Nature Conservancy promotes a sustainable farming program, which explicitly aims to achieve better carbon storage in plants and soils.[33] While such programs may have less reach than seed corporations in dissemination of new cultivars, this model could still offer the resources and training to further adoption efforts among farmers for new cultivars.

A third option for dissemination is the Cooperative Extension System (CES), managed by the USDA National Institute of Food and Agriculture (NIFA) as well as Land-

c. For example, corn and soybean production dominate the Midwest, while crops such as wheat and sorghum are more prevalent in Kansas and North Dakota. Cotton is popular along the Mississippi River and in parts of Texas, while rice is a major crop in Arkansas and California.

FIGURE 11
Adoption of Genetically Engineered Crops in the United States



Herbicide-tolerant (HT) and insect-resistant, or bacillus thuringiensis (Bt) varieties of major crops reached widespread deployment rapidly after their introduction in 1996, and now account for the majority of planted acres. Source: EFI, 2020. Compiled using data from USDA Economic Research Service, 2020.

Grant Universities throughout the United States. This well-established system supports field trials tailored to specific states and growing conditions and provides farmers with information about different cultivars and best management practices. CES provides a complement to dissemination through major seed companies, since smaller farmers who do not work as closely with the companies often rely on it for information and education.

Analyzing Lifecycle Impacts of Biological and Terrestrial CDR

The potential risk of unanticipated adverse lifecycle effects needs to be rigorously studied to minimize ecosystem disruption from deployment of new plant cultivars or other CDR pathways. Possible lifecycle impacts to consider include:

- the introduction of non-native species that become invasive;
- carbon leakage, wherein productivity losses due to CDR are compensated for by an increase in carbon-intensive practices elsewhere in the world;
- impacts on fertilizer needs and associated nitrogen runoff or emissions of nitrous oxide (N_2O), another greenhouse gas contributor to climate change; and
- threats to the crop-soil-microbial interface, which could lead to the loss of ecosystem services, biodiversity, and release of new pests and disease vectors.

BOX 4

Synergies with Other Terrestrial CDR Solutions

There are many additional land-based CDR solutions outside the scope of this paper, including carbon mineralization, BECCS, and crop-based solutions for other GHGs. These solutions have synergies with the cutting-edge CDR pathways described in this report and could therefore also benefit indirectly from RD&D in this area.

Inorganic Carbon Storage through Mineralization

In addition to the major opportunity to increase (or fortify existing) stocks of SOC, inorganic carbon storage can also occur in soils through mineralization. Of the estimated 2,500 billion metric tons of carbon (equivalent to 9,160 $GtCO_2$) in global soils, more than one-third (approximately 38 percent) occurs as inorganic carbon.[34] Inorganic carbon can accumulate in soils through the natural weathering process of silicate minerals into carbonates, particularly in arid and semi-arid regions.[35] Mineral additions of powdered silicate rock to global croplands could promote CDR and also lead to co-benefits such as helping to ameliorate soil acidification.[36]

Rock Solid: Harnessing Mineralization for Large-Scale Carbon Management in this series provides additional details on CDR through mineralization, including in agricultural soils.

Bioenergy with Carbon Capture and Storage (BECCS)

The biotechnology methods discussed in this report could be combined with other biological CDR pathways. For example, while much of the focus in crop cultivars has been on food crops, the same RD&D could likely be applied to energy crops. Increased carbon sequestration during these crops' lifetime may offset some of the lifecycle emissions concerns that have been raised with BECCS. Cross-cutting RD&D in modeling, measuring, and lifecycle analysis will also benefit BECCS.

Biotechnological Mitigation of Other Greenhouse Gases

The usefulness of biotechnology also goes beyond CDR. Scientists have also proposed using genetic modification or gene editing to reduce emissions of other GHGs, such as by improving plants' nitrogen use efficiency (thereby decreasing fertilizer nitrogen emissions), or by altering rice to produce less methane.[17]

Policy Framework for Deployment of Biological and Terrestrial CDR

A key component of any effort to scale up terrestrial CDR is an enabling policy framework. Policy is necessary to address several of the cross-cutting challenges facing biological and terrestrial CDR RD&D (and CDR in general). It is important that enabling policies are developed now to permit a smoother transition from RD&D to deployment.

Financial Incentives

Markets that value soil carbon are currently underdeveloped and will be critical to maximizing the deployment potential of new or improved plant cultivars for CDR at scale. As a complementary measure, markets for aboveground biomass (e.g., biofuels, second-generation bioproducts, biomass digestion) would also need to increase in parallel to maximize terrestrial CDR. Society will need to begin connecting potential supply of new plant cultivars optimized for carbon storage to demand at payment rates that comport with our capacity to measure the current opportunity for carbon storage using plant cultivars. In short, there must be a market for terrestrial CDR pathways for these methods to be deployed. Furthermore, the return on investment for agricultural production should not be exclusively defined by yield but also include the opportunity to reduce capital inputs through parallel adoption of new technology.

Currently there are insufficient financial incentives and enabling policies for farming practices that store carbon and provide soil health improvements (including for local individuals such as seed producers and farmers/landowners). However, the challenges to market creation can be addressed through a comprehensive federal policy and regulatory framework.

A principal feature of such a policy framework could incent activity-based agricultural systems where farmers are paid for performing an activity (soil carbon storage) rather than focusing on a particular outcome (e.g., crop yield). This framework could build on the experience of existing, non-CDR programs such as the Environmental Quality Incentives Program (EQIP), administered by the USDA Natural Resources Conservation Service (NRCS). EQIP is a voluntary program that provides financial and technical assistance to farmers who implement "conservation practices" that address resource concerns and provide environmental benefits. Additionally, improvements in the cost and timing for regulatory approval of transgenic traits could be streamlined to help promote viable markets for soil carbon storage.

One of the ultimate questions for policymakers involves how to set up and regulate a carbon market in an expeditious manner that encompasses the agricultural sector. Addressing this question could help inform which technologies and strategies should be pursued to reduce emissions from agriculture prioritize ongoing research needs, and address future challenges.

If a carbon market was established that included carbon credits for carbon storage, it would help create a strong incentive to deploy biological and terrestrial CDR methods. This includes actively developing the requisite modeling and decision support tools to quantify the carbon storage and help farmers establish best practices. This process could lead to behavior change and the adoption of new practices that change perspectives within the farming community about opportunities beyond food yield.

Ensuring CO_2 Permanence

Another role of policy and markets is mitigating the risk inherent in terrestrial CDR approaches. One of those risks is reversal, the unintended loss of carbon that was previously stored. Risks to terrestrial CDR include improper soil management practices and land-use change.[37] Climate change itself may also create new risks to the permanence of biological and terrestrial CDR, such as increased risk of drought and range expansion or proliferation of pests and pathogens.[38] However, soil carbon can also be protected and made less vulnerable to reversal by planting perennials and cover crops with deep root systems, enhanced nutrient management, and reduced erosion (e.g., no-till agriculture).[39]

Markets and policies that promote CDR deployment can also compensate for the possibility of reversal by requiring permanence standards (such as the 100-year standard that is common with forestry projects)[40] or by some form of insurance system, such as the buffer pool approach taken by some existing carbon credit markets.[41]

Monitoring, Reporting, and Verification

Monitoring, reporting, and verification (MRV) is critical to scaling up any CDR approach; it is essential for both market formation (governing authorities and market participants in both voluntary and compliance markets must be assured that carbon is actually being removed) and risk mitigation (MRV is necessary for preventing, identifying, and mitigating reversal). Successful MRV for terrestrial CDR approaches will depend on the measurement and monitoring RD&D described above, but it also depends on governance systems.

MRV practices for SOC storage are not as well-established as those for other CDR methods, such as afforestation and reforestation. Some voluntary carbon offset standards lack methodologies for soil carbon projects, and those that do have them often cover only select categories of projects (e.g., wetland ecosystem restoration, grassland projects).[42] Neither of the current U.S. compliance markets (the California Cap-and-Trade program and the Northeast Regional Greenhouse Gas Initiative) provide credits for any soil carbon CDR approaches as of 2020. Even those voluntary and compliance markets globally that do have methodologies for soil carbon storage are not necessarily equipped to handle the technologically enhanced approaches discussed in this report. In developing MRV standards for these approaches, however, the U.S. can look to the experience (both the successes and the challenges) from both other areas of CDR—such as forestry—and from other countries—such as Alberta's Quantification Protocol for Conservation Cropping.

Implementation: Funding, Organization, and Management

The September 2019 EFI *Clearing the Air* report included a comprehensive set of recommendations for implementation and management of a federal CDR RD&D initiative, including biological and terrestrial approaches.[43] This section summarizes the key points on funding, organization, and management that were discussed in depth in the earlier CDR report.

Federal Funding

Federal funding has played an essential role in facilitating development and distribution of new agricultural technologies.[44] Federal funding, both new funding as well as re-targeting existing research funding, is essential for leading the national effort on cutting-edge, terrestrial CDR development.

The proposed federal funding for an expanded biological and terrestrial CDR RD&D program totals $1.575 billion over 10 years, as summarized in Table 2 above. (A more detailed budget table can be seen in Appendix B.) The report also proposed a $2 billion demonstration project fund that also could be used to support large-scale demonstrations of carbon mineralization selected on a competitive basis.

Developing new and improved plant cultivars optimized for carbon storage will require extensive on-the-ground field trials that

TABLE 2
Biological and Terrestrial RD&D Portfolio Summary ($millions)

	Year 1	5-Year Total	10-Year Total
Short Rotation Forestry	$18	$76	$116
Soil Carbon Storage	$51	$316	$631
Bioenergy with Carbon Capture and Sequestration	$21	$318	$728
Disruptive Research/Novel Concepts	$0	$40	$100
TOTAL	**$90**	**$750**	**$1,575**

Source: EFI, 2020.

include long-term monitoring over multiple timescales to determine the heterogeneity, variability, and durability of soil carbon and any associated environmental impacts from introducing new plant cultivars. In short, the scientific community needs to go from the greenhouse to the field. The costs for doing such analyses (i.e. directly measuring carbon accrual in soils following shifts to deep-rooted plants) can be high.[d]

Funding arrangements and levels for a biological and terrestrial CDR RD&D effort should include support for non-federal RD&D performers through mechanisms such as competitive grant programs. The federal RD&D portfolio also should include a dedicated focus on high-risk, high-reward research support through entities such as the new USDA Agriculture Research and Development Agency (AGARDA) and the DOE Advanced Research Projects Agency—Energy (ARPA-E) and Office of Science. To the extent possible, establishing funding continuity in appropriations would help minimize workflow disruptions and give greater confidence to researchers that experiments could be executed without interruption across multiple years.

Organization and Management

The EFI *Clearing the Air* report identified USDA as the current primary facilitator and conductor of terrestrial CDR RD&D and proposed that the Department could assume the role as the lead for interagency coordination. *Clearing the Air* also included specific management recommendations for USDA, including:

- adding biological and terrestrial CDR to the research objectives and missions of key research entities, including the Foundation for Food and Agriculture Research (FFAR), and the National Institute of Food and Agriculture (NIFA);
- designating the Under Secretary for Research, Education, and Economics (REE) as the lead coordinator for biological and terrestrial CDR activities scattered across USDA

d. A federal initiative can also draw on existing innovation resources within the federal government with experience in long-term research, such as ARS's Long-Term Agoecosystem Research Network.

under the current organizational structure (Figure 12); and

→ entering an expanded Memorandum of Understanding with DOE to incorporate CDR into current joint research on biotechnology.

Other agencies involved in terrestrial CDR efforts should include DOE, National Science Foundation (NSF), EPA, and the National Aeronautics and Space Administration (NASA). The two principal agencies, USDA and DOE, have a proven track record of RD&D collaboration from co-leading the Biomass Research and Development Board since 2000. State extension agencies could also craft region-specific deployment approaches.

Implementation of a RD&D enterprise could be initiated by Presidential Executive Order. Congressional authorizing legislation would ultimately be desirable; historically, such as in the case of the U.S. Global Change Research Program, Congress acted on authorizing legislation for new interagency science and technology initiatives promptly in response to executive branch-proposed initiatives. Legislation could also provide multi-year authorizations to guide future appropriations. Congress may wish to consider additional options for implementation, such as establishing a quasi-governmental entity to manage a broad CDR initiative and a dedicated funding source. In 2020, bipartisan groups in both houses of Congress introduced the Carbon Removal, Efficient Agencies, Technology Expertise (CREATE) Act, which followed the recommendation from *Clearing the Air* that the National Science and Technology Council (NSTC) establish a new Committee on Large-Scale Carbon Management. The CREATE Act proposes that USDA representatives sit on the executive committee and chair the terrestrial working group (along with DOE).

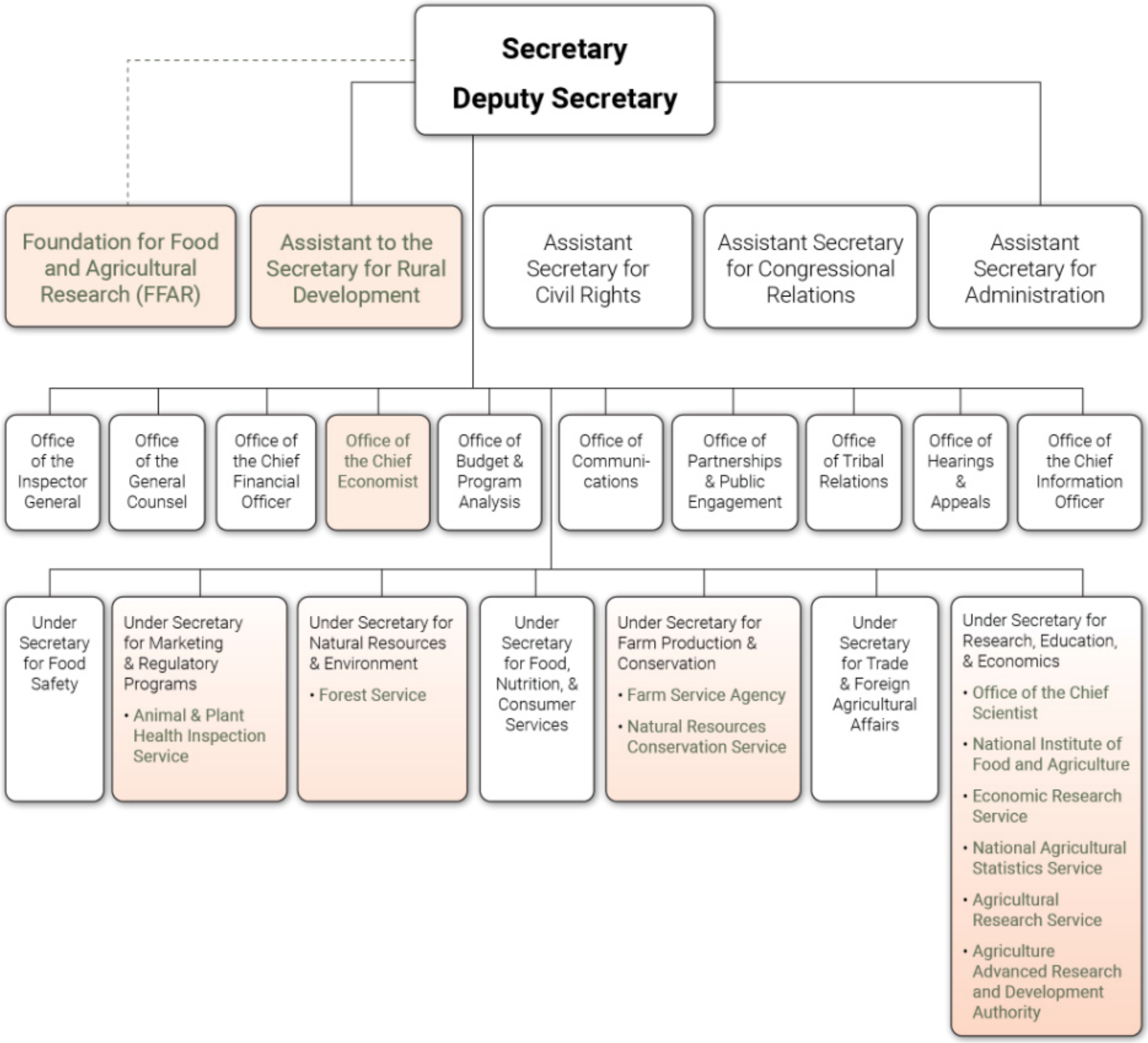
Current Federal Government RD&D Activities in Cutting-Edge Biological and Terrestrial CDR

There are no fewer than five federal agencies and numerous other entities that could fund or perform RD&D efforts for terrestrial CDR related to general conservation practices, traditional plant breeding techniques, and genetic engineering in addition to other technological approaches. A partial selection of those programs is shown in Appendix C: Entities Funding or Performing RD&D for Biological and Terrestrial CDR. One of the most promising programs is the Department of Energy, Advanced Research Projects Agency (ARPA-E) Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS) program. This effort is focused on the development of new plant cultivars that increase the amount of sequestered soil carbon and depth of storage by 50 percent, reduce N_2O emissions by 50 percent, and increase water productivity by 25 percent.[46,47] While such programs have helped to advance the science related to biological and terrestrial CDR, they currently are not on a scale to effectuate the rapid and wide-scale improvements required to make consequential contributions to CDR on a meaningful timescale.

The 2018 Farm Bill authorized the establishment of AGARDA through USDA to identify and develop potential breakthrough technologies in agriculture, modeled after the Department of Defense (DOD) Defense Advanced Research Projects Agency (DARPA) and the DOE ARPA-E.[48] Although the program has yet to be implemented, its proposed structure would accelerate agricultural advances faster than USDA research that is subject to greater regulation.[49]

More recently, in February 2020, USDA announced its commitment to a new department-wide Agriculture Innovation Agenda that ultimately seeks to increase

FIGURE 12
USDA Offices with Relevance to CDR



There are at least seven USDA offices and organizations (highlighted in orange) that could support CDR RD&D, but they are spread throughout the organization. Designating a coordinator for CDR activities could be beneficial to the Department's CDR efforts. Source: EFI, 2020. Compiled using data from USDA, 2020.

agricultural productivity by 40 percent and decrease GHG emissions 50 percent by 2050. To facilitate a reduction in agricultural emissions, USDA seeks to enhance stocks of soil carbon through better soil and forestry management practices.[50]

Appendix A

Clearing the Air Funding Levels for Land-Based CDR R&D Portfolio

TABLE 3

Land-Based CDR R&D Portfolio ($millions)

Portfolio	Funding Agency	Funding Organization or Office	Year 1	5-Year Total	10-Year Total
Forestry					
Enhanced Forest Stock Monitoring	USDA	USFS	$5	$25	$35
IAMs and forest impacts modeling	NSF	SBE	$3	$15	$30
	USDA	USFS	$3	$15	$30
Preservation of harvested wood	USDA	USFS	$1	$3	$3
	EPA	ORD	$1	$3	$3
Extension and Outreach	USDA	USFS	$0	$0	$0
Subtotal, Forestry			**$18**	**$76**	**$116**
Soil-Based Carbon Storage					
Fundamental Research	USDA	ARS	$10	$50	$100
	DOE	SC (BER)	$5	$25	$50
	NSF	GEO	$5	$25	$50
Enhanced Soil Monitoring	USDA	NRCS	$3	$15	$30
	NASA	ESD	$2	$10	$20
High-carbon input crop phenotypes	USDA	ARS	$5	$145	$395
	USDA	*ARS (redirected)*	*$0*	*-$65*	*-$195*
Cultivation system optimization	USDA	ARS	$5	$27	$62
Biochar impact studies	USDA	ARS	$3	$15	$30

Portfolio	Funding Agency	Funding Organization or Office	Year 1	5-Year Total	10-Year Total
Reactive minerals in agricultural soils	USDA	ARS	$3	$15	$30
Modeling and predictive tool development	USDA	ARS	$5	$25	$25
	NSF	GEO	$5	$25	$25
Scaling up agricultural sequestration	USDA	NRCS	$0	$4	$4
Subtotal, Soil-Based Carbon Storage			**$51**	**$316**	**$631**
Bioenergy with Carbon Capture and Sequestration					
Algal biomass capture	DOE	SC (BR)	$2	$28	$63
	DOE	EERE (BETO)	$2	$28	$63
Biomass supply, logistics, and pretreatment	USDA	NIFA	$2	$37	$80
	NIFA	EERE (BETO)	$2	$37	$80
Biomass conversion to fuels with biochar	DOE	EERE (BETO)	$4	$69	$144
	USDA	NIFA	$4	$69	$144
Advanced biomass-to-power conversion	DOE	FE	$5	$50	$154
Biomass to fuel with CCUS	DOE	EERE (BETO)	$0	$0	$0
Subtotal, Bioenergy with Carbon Capture and Sequestration			**$21**	**$318**	**$728**
Disruptive Research/Novel Concepts					
AGARDA	USDA	AGARDA	$0	$40	$100
Subtotal, Disruptive Research/Novel Concepts			**$0**	**$40**	**$100**
TOTAL, Land-Based and Biological			**$90**	**$750**	**$1,575**

DOE = Department of Energy. ARPA-E = Advanced Research Projects Agency-Energy. EERE = Office of Energy Efficiency and Renewable Energy. BETO = Bioenergy Technologies Office. FE = Office of Fossil Energy. SC = Office of Science. BER = Biological and Environmental Research. EPA = Environmental Protection Agency. ORD = Office of Research and Development. NASA = National Aeronautics and Space Administration. ESD = Earth Sciences Division. NSF = National Science Foundation. GEO = Directorate for Geosciences. SBE = Directorate for Social, Behavioral, and Economic Sciences. USDA = United States Department of Agriculture. USFS = U.S. Forest Service. ARS = Agricultural Research Service. NRCS = Natural Resources Conservation Service. NIFA = National Institute of Food and Agriculture. AGARDA = Agriculture Advanced Research and Development Authority. Source: EFI, 2020.

Appendix B

Entities Funding or Performing R&D for Land-Based CDR

TABLE 4

Selection of Federal Entities Funding Performing R&D for Land-Based CDR

Agency	Program	Relevant Activities
DOE	ARPA-E ROOTS	→ Development of new plant cultivars to reduce atmospheric CO_2 concentrations and achieve various environmental co-benefits.[51]
	Biological and Environmental Research	→ Fundamental research on plant biology, microbes, biogeochemistry, systems biology, synthetic biology, and modeling.[52]
DOI (USGS)	Land Carbon	→ Investigates biological carbon sequestration, terrestrial carbon fluxes, carbon monitoring methods, and land management policies and best practices.[53]
FFAR	Next Generation Crops	→ Development of non-traditional crops focused on diversification, trait identification and resiliency, accelerated breeding methodologies.[54]
	Soil Health	→ Promotion of healthy soils through best management practices.[55]
NASA (SMD)	Carbon Monitoring System	→ Monitoring, reporting, and verification of carbon stocks and fluxes.[56]
NSF	Innovations at the Nexus of Food, Energy, and Water Systems	→ Study of the biological and biogeochemical processes that govern the food, energy, and water nexus.[57]
NSF (MCB)	Investigator-initiated research projects	→ The following cross-cutting areas of research, most notably where they elucidate the rules governing life's processes, should be given high priority for funding in all clusters in MCB core programs: Integrating Across Scales; Transformative Methods and Resources; Molecular and Cellular Evolution; Synthesizing Life-Like Systems; and Genomes to Phenomes.[58]
USDA (ARS)	No single program or crosscut	→ Broadly supports agricultural systems and natural resources through research and analysis,[59] including through its extensive network of National Programs such as the Plant Genetic Resources, Genomics, and Genetic Improvement program.[60]
USDA (USFS)	Climate Change Mitigation Research	→ Conservation and carbon sequestration in forest ecosystems.[61]

Agency	Program	Relevant Activities
USDA (NIFA)	Agriculture and Food Research Initiative: Resilient Agroecosystems in a Changing Climate Challenge Area	→ Climate risk management and reduction of GHG emissions related to agricultural systems.[61]
	Global Change and Climate Programs	→ Focuses on issues related to the impacts of climate variability and change on plants including species type, cultivars, planting and breeding times, and organic and inorganic carbon cycling in soils.[62]
	Land-Grant Colleges and Universities	→ Numerous research topics at the intersection of agriculture and the environment.[63]
	McIntire-Stennis Cooperative Forestry Research	→ Forestry research centered around production, utilization, and protection of forest resources, including issues associated with fires, insects, and disease infestation.[64]
	Sun Grant	→ Enhance energy security, support agricultural production, promote rural economic diversification, and bolster biomass and bioenergy R&D through the pursuit of bio-based energy technologies.[65]
USDA (NRCS)	Soils	→ Delivery of periodic surveys focused on science-based soil information.[66]
USDA (REE)	Agriculture Advanced Research and Development Authority	→ Authorized in the 2018 Farm Bill that focuses on high-risk, high-reward R&D related to food and agriculture.[67]

DOE = Department of Energy. DOI (USGS) = Department of the Interior (U.S. Geological Survey). FFAR = Foundation for Food and Agriculture Research. NASA (SMD) = National Aeronautics and Space Administration (Science Mission Directorate). NSF (MCB) = National Science Foundation (Division of Molecular and Cellular Biosciences). DOT = Department of Transportation. USDA (ARS) = U.S. Department of Agriculture (Agricultural Research Service); (USFS) = Forest Service; (NIFA) = National Institute of Food and Agriculture; (NRCS) = Natural Resources Conservation Service; (REE) = Research, Education, and Economics. Source: EFI, 2020. Compiled using data from DOE, DOI, FFAR, NASA, NSF, USDA, and DOT.

Appendix C

Selection of Data Tools and Platforms to Support Land-Based CDR R&D

TABLE 5

Selection of Data Tools and Platforms to Support Land-Based CDR R&D

Name	Description
Adoption and Diffusion Outcome Prediction Tool (ADOPT)	→ Advancements in data analytics could help inform the potential for new technology adoption through ADOPT, which assesses how a new agricultural innovation could diffuse within the agricultural community.[69]
Multi-Resolution Land Characteristics Consortium (MRLC)	→ Hosts the National Land Cover Database (NLCD) to provide scientists and policymakers with a detailed overview of land cover in the contiguous United States.[70] The MRLC consortium consists of multiple federal agencies and departments who coordinate information and data involving the land use, land-use change, and forestry sector.[71]
National Agricultural Statistics Service (NASS)	→ Hosts data and information on crops and cropland in the U.S. which is known as CropScape.[72,73]
National Cooperative Soil Survey	→ Consolidates data and information about soils from a consortium of federal, regional, state, and local entities.[74]
Rapid Carbon Assessment (RaCA)	→ Aims to develop robust estimates and inventories of soil carbon stocks in the United States.[75]
SoilGrids Project	→ Online data tool that allows users to visualize soil organic carbon content around the world.[76]
Soil Survey Geographic (SSURGO) Database	→ Serves as a repository for data collected through field measurements from the National Cooperative Soil Survey, which has been conducted for over a century.[77] Note that the Gridded SSURGO or gSSURGO database is similar to SSURGO but provides spatial data in format suitable for geographic information systems, including data for soil organic carbon.[78,79]
VegScape	→ Provides assessments of crop vegetation[80] using remote sensing data from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) satellite.[81]

. Source: EFI, 2020.

Abbreviations

ADOPT	Adoption and Diffusion Outcome Prediction Tool
AGARDA	Agriculture Advanced Research and Development Authority
ARPA-E	Advanced Research Projects Agency - E
ARS	Agricultural Research Service
BECCS	bioenergy with carbon capture and sequestration
BER	Biological and Environmental Research
BETO	Bioenergy Technologies Office
Bt	bacillus thuringiensis
Cas9	CRISPR-associated protein 9
CBD	Convention on Biological Diversity
CDR	carbon dioxide removal
CES	Cooperative Extension System
CO_2	carbon dioxide
CRISPR	clustered regularly interspaced palindromic repeats
DAC	Direct Air Capture
DARPA	Defense Advanced Research Projects Agency
DOE	Department of Energy
DOD	Department of Defense
DOI	Department of Interior
DOT	Department of Transportation
EERE	Office of Energy Efficiency and Renewable Energy
EFI	Energy Futures Initiative
ELSI	ethical, legal, and social implications
EPA	Environmental Protection Agency
EQIP	Environmental Quality Incentives Program
ESD	Earth Sciences Division
FDA	Food and Drug Administration
FE	Office of Fossil Energy
FFAR	Foundation for Food and Agriculture
FS	Forest Service
GEO	Directorate for Geosciences
GHG	greenhouse gas
GM	genetically modified
Gt	gigaton
HPI	Harnessing Plants Initiative
HT	herbicide tolerant
IAMs	integrated assessment models
IPCC	Intergovernmental Panel on Climate Change
MCB	Division of Molecular and Cellular Biosciences
MRLC	Multi-Resolution Land Characteristics Consortium
MRV	monitoring, reporting, and verification
N_20	Nitrous Oxide
NASA	National Aeronautics and Space Administration
NASEM	National Academy of Sciences, Engineering, and Medicine
NASS	National Agricultural Statistics Service
NIFA	National Institute of Food and Agriculture
NRCS	Natural Resources Conservation Service
NSF	National Science Foundation
ORD	Office of Research and Development
RaCA	Rapid Carbon Assessment
RD&D	research, development, and demonstration
REE	Research Education and Economics
ROOTS	Rhizosphere Observations Optimizing Terrestrial Sequestration
SAF	Society of American Foresters
SBE	Directorate for Social, Behavioral, and Economic Sciences
SC	Office of Science
SMD	Science Mission Directorate
SOC	soil organic carbon
SSURGO	Soil Survey Geographic
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey

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