# U.S. Department of Energy
# Advanced Research Projects Agency – Energy (ARPA-E)

# Request for Information (RFI)
# DE-FOA-0002577
# On
# Engineered Strategies for Net-Negative Emissions Pathways via Enhanced Terrestrial Ecosystems

**Introduction**

In order to avoid the most severe impacts of climate change, there is near unanimous consensus within the scientific community that global temperature rise must be held below 2 degrees Celsius. While limiting harmful greenhouse gas emissions and decarbonizing the global economy are vital steps toward achieving this goal, current projections indicate a need for an additional 20 GT/year of *negative* emissions capacity by 2100[1]. Realizing this magnitude of negative emissions capacity will be an enormous challenge, but it will also be a notable opportunity to lay the groundwork for an entirely new sector of economic activity and resource allocation. ARPA-E recognizes that the immense scale of this new carbon dioxide removal (CDR) industry will require a diverse suite of solutions, each of which comes with unique advantages and disadvantages in terms of sequestration potential, commercial readiness, cost, and energy efficiency. Among these solutions, terrestrial ecosystems offer a relatively near-term, large-scale, and energy-efficient sink for atmospheric carbon.

There are two broad categories of carbon removal via terrestrial systems: aboveground and belowground. Belowground, soil carbon sequestration via available technologies is estimated to be around 3 Gt/year globally[1], and advances in land management and related disciplines have the potential to significantly increase soil carbon uptake. Aboveground, sustainably produced biomass can offer long-term removal in place (e.g., forests), or be coupled with Bioenergy with Carbon Capture and Storage (BECCS) pathways to provide negative-emissions energy resources. **ARPA-E is interested in both aboveground and belowground solutions and is seeking information related to low-energy, low-cost, and large-scale technologies and strategies for terrestrial carbon dioxide removal, management, and sequestration, or "carbon farming."** ARPA-E is primarily interested in approaches targeting agricultural or fallow lands; however, any approaches that target terrestrial carbon sequestration or feedstock crop engineering for improved BECCS pathways are of interest at this time regardless of land type.

When considering the pros and cons of different CDR approaches, a significant metric for ARPA-E is the energy input requirement per ton of $CO_2$ removed. The energy input requirements for CDR range from practically zero, in the case of ecological carbon cycling, to up to 10 GJ per ton of atmospheric $CO_2$

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[1] National Academies of Sciences, Engineering, and Medicine 2019. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259.

removed for Direct Air Capture (DAC) Error! Bookmark not defined.. In the case of BECCS systems, the net energy requirement could

eventually go negative when enhanced terrestrial removal is combined with efficient energy production and geologic storage. Given the magnitude of negative emissions capacity required, DAC remains attractive as a guaranteed option for addressing hard-to-abate emissions, but a tremendous amount of emissions-free energy would be required for DAC to address even a fraction of the removal capacity needed to meet global climate targets. Meanwhile, billions of hectares of land are already contributing to the global carbon cycle and have the capacity to increase their carbon uptake by a substantial amount due to carbon depletion over the last 12,000 years[2]. While there is no doubt that DAC and other energy-intensive CDR approaches will be required to stay below 2 degrees Celsius, leveraging low-cost (both economically and energetically) solutions such as carbon farming and/or energy positive carbon removal via BECCS keeps the overall cost of removal low and frees up emissions-free energy resources to address other sectors in need of decarbonization. In addition to the broad climate and energy benefits of terrestrial carbon sequestration, increasing the concentration of carbon in terrestrial biomes can also ameliorate the general health and productivity of U.S agriculture, reducing the need for energy-intensive fertilizers and irrigation systems.

Increasing soil organic carbon levels is a promising and widely supported method of carbon farming; however, other technologies that seek to sequester carbon through increased plant and root biomass via enhanced photosynthesis are also of interest provided they are accompanied by management strategies that ensure net-negative emissions. For example, cover crop adoption has the potential to confer enhanced carbon removal rates, and these crops could be engineered to minimize input (e.g., fertilizer) requirements while maximizing carbon removal for net-negative emissions outcomes. Additionally, geochemical approaches that can store carbon in inorganic and/or mineral forms (e.g., charcoal, organic carbon occluded in silica phytoliths, calcium oxalate, calcium carbonate) are of interest if they have the potential to reach GT-scale negative emissions on an annual basis and align with a sustainable management strategy. For these and other carbon farming approaches, the ability to estimate the duration of carbon removal (e.g., 100 years) and identify influencing factors (e.g., management practices) is essential to determining the relative impact and value of these approaches when compared to the broader suite of CDR options.

Establishing new agriculture and bioeconomy industries around the commodification of negative emissions is a unique opportunity to address climate change while stimulating economic growth and advancing critical technologies; however, it is essential to consider how the implementation and expansion of carbon farming approaches can be designed to enable negative emissions without introducing perverse incentives that would impose a negative impact on communities, crop yields, food production, energy demand, or ecosystem services. Part of the solution to establishing a negative emissions industry that avoids perverse incentives is to pursue both parallel and exclusive approaches to carbon farming. Parallel approaches increase soil carbon *indirectly* via improved agricultural techniques and management practices. In this approach, farmers benefit primarily from increased productivity and improved soil quality with carbon sequestration as a positive secondary benefit. Exclusive approaches, on

[2] Sanderman, Jonathan, Tomislav Hengl, and Gregory J. Fiske. "Soil carbon debt of 12,000 years of human land use." Proceedings of the National Academy of Sciences 114.36 (2017): 9575-9580.

the other hand, target carbon sequestration *directly*, enabling farmers to profit primarily and explicitly from capturing carbon with the potential for secondary profits via aboveground biomass production.

**ARPA-E is seeking insight into both parallel and exclusive approaches to terrestrial carbon removal and sequestration, including, but not limited to, approaches that employ recent advancements in biological, geochemical, or hybrid technologies. Additionally, ARPA-E is requesting information on how agriculture systems and feedstock crops may be engineered and bred to better feed into economically viable BECCS pathways for large-scale, near-term carbon removal opportunities.**

Table 1, included in the questions below, outlines some of the broad approaches that have been identified as promising methods of carbon farming. ARPA-E requests responses to this RFI include the information specified in this table, to include innovative approaches to carbon farming that are capable of delivering significant (e.g., 2X) increases in the carbon removal potential of terrestrial ecosystems. ARPA-E is not interested in approaches that are presently available and do not present a specific technical challenge (e.g., low/no-till, rotational grazing). More detailed questions with respect to the specific mechanisms that would enhance carbon removal via terrestrial biomes can be found below Table 1. The most valuable submissions to this RFI will include non-proprietary information related to specific technical processes such as those illustrated in Table 1 as well as responses to the detailed questions about scalability and related environmental and economic impacts.

**Please carefully review the REQUEST FOR INFORMATION GUIDELINES** below. Please note that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.**

**Purpose and Need for Information**

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future research programs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an opportunity to contribute views and opinions.

**REQUEST FOR INFORMATION GUIDELINES**

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that could be considered proprietary or confidential**.

Responses to this RFI should be submitted in PDF format to the email address **ARPA-E-RFI@hq.doe.gov** by **5:00 PM Eastern Time on October 22, 2021**. Emails should conform to the following guidelines:

- Please insert “Responses for Carbon Farming RFI” in the subject line of your email, and include your name, title, organization, type of organization (e.g., university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise in the body of your email.

- Responses to this RFI are limited to no more than 10 pages in length (12-point font size).
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential methodologies.

**Table 1:**

Please provide responses and information about any of the following. It is not expected that any one respondent would answer all, or even many, of these prompts. Citations are encouraged as appropriate. Respondents are also welcome to address other relevant avenues/technologies that are not outlined below.

*Table 1. Descriptions and impacts of potential carbon farming technologies.*

| Technology Category | *Example* | Potential Approach | Speciation/ Mineralogy of Carbon Stored | Net $CO_2e$ Removed Per Acre Per Year | Durability (< 5, 5-50, >50 yrs) | Eligible Land Types (e.g., Fallow, Crop) |
|---|---|---|---|---|---|---|
| **Biological** | | | | | | |
| Plant (Increased Source) | *Improved photosynthesis (photorespiratory bypass)* | | | | | |
| Plant (Increased Sink) | *Increased root exudates of organic carbon* | | | | | |
| Microbe | *Microbial consortium that mineralizes plant exudates* | | | | | |
| Fungal | *Fungal hyphae and improved carbon capture through mutualistic relationships with plants* | | | | | |
| Other | | | | | | |
| **Geochemical** | | | | | | |
| Mineralization | *Application of crushed silicate rock to crop fields* | | | | | |
| Thermochemical Conversion | *Producing biochar to incorporate into the soil* | | | | | |
| Other | | | | | | |

| Technology Category | *Example* | Potential Approach | Speciation/ Mineralogy of Carbon Stored | Net $CO_2e$ Removed Per Acre Per Year | Durability (< 5, 5-50, >50 yrs) | Eligible Land Types (e.g., Fallow, Crop) |
|---|---|---|---|---|---|---|
| **Hybrid** | | | | | | |
| Biogeochemical Systems | *Advanced plants for phytolith formation* | | | | | |
| Other | | | | | | |
| **Bioenergy with Carbon Capture and Storage (BECCS)** | | | | | | |
| Plant Engineering for Regional and/or Process Optimization | *Advanced plants for economic production, transport, and conversion* | | | | | |

**Questions:**

Please provide evidence-based answers and/or commentary in response to the following (for each approach or technology provided in Table 1), Citations are encouraged as appropriate. ARPA-E does not expect that any one respondent would answer all, or even many, of these questions. Respondents are also welcome to address other relevant scalability and related environmental and economic impacts that are not outlined below.

1. ***Carbon farming mechanisms, energy requirements, and enabling tools***
    a. How does the approach increase terrestrial carbon sequestration? What is the specific mechanism that would be a target for improvement?
    b. The timescale of soil carbon sequestration ranges from days to millennia, and is subject to management practices and environmental conditions. How does the approach (1) mitigate external effects on carbon durability, (2) increase the durability timescale, and/or (3) guarantee duration of at least 50 years?
    c. What are the anticipated energy requirements of the proposed approach?
    d. Are there additional tools/methods/processes that would need to be developed and implemented in tandem with this technology?
2. ***Metrology and impact of carbon farming approaches***
    a. How does the approach improve the rate and/or density of carbon removal relative to currently-available approaches? What is the anticipated depth of exchange (e.g., top 45 cm)? What is the saturation point?
    b. What metrology would be useful for measuring and comparing different carbon farming approaches? How would these metrics be validated?
    c. Are there additional agricultural, environmental, or economic benefits associated with the deployment of this technology?
    d. Is there any potential for harmful off-target effects if this technology is deployed at scale?
3. ***Land use and scope of carbon farming approaches***
    a. How should land be classified for the purpose of carbon farming? How much land in the U.S. falls into each of these categories as you would classify them?
    b. What inherent or dynamic factors drive adaptation of the technology for each of these types of land?
    c. What is the potential for land to be remediated/reclaimed with carbon farming techniques? Over what time period can this potential be realized?
    d. Are there other ancillary benefits or value-added products that can result from exclusive carbon farming methods, for instance on non-arable or fallow land?
4. ***Technology to market considerations for carbon farming***
    a. What are the advantages specific to this approach? What are the risks that could threaten the deployment and scale-up of this approach?
    b. How does the approach fit within or disrupt existing technology and knowledge transfer pathways? What market development infrastructure (e.g., R&D networks, education, etc.) is needed to support technology adoption?

c. What are the most informative methods of comparison for carbon assets (e.g., comparing the value 1 t $CO_2$ stored today with an estimated durability of 50 years to 1 t $CO_2$ stored 20 years from now with an estimated durability of 500 years)?

d. How might lifecycle accounting methods need to change and/or be supplemented (e.g., hybrid LCA and biogeochemical modeling) in order to accommodate factors such as additionality and durability when it comes to estimating the carbon benefits of implementing certain practices? How might these accounting methods inform the use of buffer pools or other risk mitigation mechanisms to reduce the uncertainty of terrestrial carbon durability?

e. What are the best tools for evaluating the land-use and economic implications of widespread carbon farming adoption? Are these tools able to accommodate new assumptions regarding carbon storage potential, yield impacts, and economic drivers for practice change?