RESEARCH ARTICLE

Carbon dioxide removal–What's worth doing? A biophysical and public need perspective

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Abstract

Carbon dioxide removal (CDR) has become a focal point for legislators and policymakers who are pursuing strategies for climate change mitigation. This paper employs a policy framework of collective biophysical need to examine two broad categories of CDR methods being subsidized and advanced by the United States and other countries: mechanical capture and biological sequestration. Using published data on these methods, we perform a biophysical input-outcome analysis, focusing on the U.S., and compare methods on the basis of three criteria: effectiveness at net carbon removal, efficiency at a climate-relevant scale, and beneficial and adverse co-impacts. Our findings indicate that biological methods have a superior return on resource inputs in comparison to mechanical methods. Biological methods are both more effective and more resource efficient in achieving a climate-relevant scale of CO2 removal. Additionally, the co-impacts of biological methods are largely positive, while those of mechanical methods are negative. Biological methods are also far less expensive. Despite their disadvantages and a track record of failure to date, mechanical CDR methods continue to receive large subsidies from the US government while biological sequestration methods do not. To achieve more optimal CDR outcomes, policymakers should evaluate CDR methods' effectiveness, efficiency, and biophysical co-impacts. We present tools for this purpose.

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Introduction

There is general consensus in the scientific community that it is imperative to reduce the level of atmospheric carbon dioxide (CO2), which is a primary driver of the climate change impacts now being widely observed. Atmospheric CO2 has reached 421 parts per million (ppm), the highest reported level to date and a vast increase over the 280 ppm at the start of the industrial revolution. Anthropogenic CO2 emissions globally are approximately 39 gigatons per year (Gt/yr) (36.4 Gt from fossil emissions; 2.9 Gt from land use change) [1]. The U.S. share is approximately 5 Gt/yr.

Although there is consensus about the problem, there is lack of agreement about solutions. Approaches being advanced include a rapid transition to non-carbon energy sources, and

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the drawdown of existing surplus atmospheric CO2, often called "carbon dioxide removal" (CDR).

CDR has become a focal point for federal legislators and policymakers in the United States who are pursuing strategies for climate change mitigation. Mechanical methods of CDR have received the most legislative traction and public financial support. The U.S. Department of Energy has funded research and development of carbon capture and storage (CCS) since at least 1997, and between 2010 and 2021 Congress provided $10.7 billion in subsidies for CCS and direct air capture (DAC) [2]. Another $1 billion was given in federal tax credits from 2010 to 2019. The 2021 bipartisan infrastructure package [3] provided an additional $12 billion for mechanical CDR, for a total of $23.7 billion. There has been no notable legislation providing new programs for carbon sequestration through biological methods. The $12 billion for mechanical CDR in the infrastructure package [3] was 66 times more than the $180 million included in this legislation for new programs related to biological sequestration, though that connection is indirect as the aim of these new programs is not specifically carbon sequestration. The Inflation Reduction Act (IRA) of 2022 expanded the 45Q tax credit for direct air carbon capture by 360% (from $50 to $180/ton) and by 170% (from $50 to $85/ton) for point source carbon capture, and also provided a direct pay option [4]. The cost to the public of this significant expansion of subsidies for mechanical carbon capture is unknown because tax credits are taken at the option of the carbon capture operators, but the cost may be tens of billions of dollars per year based on an interpretation of Congressional Budget Office estimates [5].The IRA also provided approximately $27.6 billion for agricultural conservation programs, forestry and coastal restoration, but very little of this funding is directed specifically toward carbon sequestration [6, 7].

In light of the growing attention to CDR among scientists, and the strong policy and financial support for CDR by the U.S. government (albeit mostly for mechanical methods), this paper presents a comparative analysis of CDR methods and offers evaluation tools for policymakers.

The problem and the need

The problem that CDR is meant to address is biophysical–an excess build-up of CO2 in the atmosphere. The term "biophysical" as used here has the same meaning as the definition in biophysical economics: "the study of the ways and means by which human societies procure and use energy and other biological and physical resources to produce, distribute, consume and exchange goods and services, while generating various types of waste and environmental impacts." The problem is also collective in that its effects are society-wide, indeed global, and its solution is a societal need [8–15]. We term these two drivers in combination "collective biophysical need," which is the framework for our analysis. The causes of the problem are anthropogenic: fossil fuel combustion and ecosystem destruction. Although the causes are anthropogenic, as a biophysical problem, the outcomes of any given remedy will be controlled by biophysical imperatives, constraints and effects. Thus, there is a collective (public) need problem and the success or failure of remedies are biophysically controlled. To address the crucial public policy question: "Which CDR methods are worth public investment?", we evaluate and compare CDR methods using biophysical criteria.

Assessment criteria and analytic approach

To assess which CDR methods are worth public investment, we determine their Biophysical Return On Resource Investments (B-ROI), adapted from the concept of EROI, Energy Return On Energy Invested [16, 17]. Whereas financial ROI looks at capital invested (*financial* inputs) and capital return (*financial* outcome), B-ROI looks at *biophysical* inputs (energy and biological, physical and natural resources) and the resulting *biophysical* outcomes of any CDR method. The biophysical outcomes are twofold: first is the net impact on the level of atmospheric CO2, and second are the ancillary effects (i.e., positive or adverse co-impacts). Examining ancillary outcomes is essential from a public need perspective because those biophysical "side effects" can be highly consequential for people and places (particularly frontline communities) and ultimately for the success or failure of climate change mitigation efforts overall.

From the framework of collective biophysical need we derive three criteria to perform an input-outcome analysis to determine B-ROI:

1. Effectiveness: Does the process achieve a net removal of CO2 from the atmosphere?
2. Efficiency: At a climate-relevant scale (removal and sequestration of 1 Gt CO2/yr), how much energy and land are required?
3. Co-impacts: What are the significant co-benefits or adverse impacts?

We term this approach a Biophysical Inputs-Outcomes Metrics (BIOM) analysis.

Scope

We examine two general approaches to CDR, *mechanical* and *biological*. Mechanical methods entail industrial facilities and the use of machinery and chemicals to separate out CO2, which is then transported, generally by pipeline, for use in industrial processes or products, or for mechanical injection into underground locations. The two mechanical approaches most widely publicly subsidized are: Carbon Capture and Storage (CCS), which captures CO2 as it emerges from emission sources (but does not remove CO2 already in the atmosphere); and Direct Air Capture (DAC), which draws CO2 from the atmosphere. (While other GHGs are also contributing to climate change, principally methane, this paper concerns only CO2 because mechanical CDR methods address only CO2, hence that is the only gas relevant for comparison with biological methods.) Biological methods of carbon dioxide removal are practices that protect, restore or increase the CO2 sequestration capabilities of biomass and soil systems, as in forests, grasslands or croplands. (In this study, we are concerned with land-based approaches, as those are more tractable to national legislative action than ocean CDR. Also, we do not consider Bioenergy with Carbon Capture and Storage (BECCS), which is a form of energy production, and this analysis is not concerned with energy production methods.) Our analysis of biological methods is based on data specific to the U.S. Separately, we also present a comparison of CDR methods on financial costs.

Methods

A major challenge for policymakers is the lack of standardized information that could enable a comparison of CDR methods based on how much of an investment in energy, land, and other biophysical inputs would be required to achieve a particular amount of CO2 removal. The scientific conventions, terminology and metrics among studies of mechanical and biological CDR are inconsistent and obscure. Also, CDR studies typically make projections of potential quantities of carbon removal (the outcome) based on varying assumptions, sometime unstated, about resource inputs, making reliable comparisons impossible.

To overcome these problems and enable a comparison of resource requirements on a consistent basis, we standardize our analysis for an outcome of 1 Gt CO2 net removal/yr–a minimal level to have any climate-relevant impact given projections that 6 to 20 Gt CO2/y removal will be required by midcentury [18–22]. 1 Gt removal would represent 2.5% of annual global

CO_2 emissions (39 Gt/yr) and 20% of annual U.S. emissions (5 Gt/yr). Using this standardized outcome, we compare resource requirements for various CDR methods.

For the biological methods, we translate published data and metrics into a measure of "sequestration capability" (total Gt/yr) of each method to enable a building block approach. For land requirements, the building block is net CO_2 sequestration per acre per year. This value can then be multiplied by a designated number of acres devoted to any one method or any combination of methods to determine the amount of land required to achieve 1 Gt (or any other amount) of net CO_2 sequestration (removal) per year. Using this standardization and building block method, biological methods can be compared to mechanical methods on resource input requirements. Our analysis looks at land and energy. Water is another significant resource input that could be examined using this approach.

Our analysis compares methods on net, not simply gross, CO_2 removal. For mechanical methods, we consider the full life cycle, which includes both CO_2 emissions and removals from an entire process. For biological methods, we look at flux, which refers to the exchange of CO_2 to and from the atmosphere as the net change due to CO_2 uptake by plant growth minus emissions from respiration, harvesting, fire, etc.

The data on mechanical methods are available in Sekera and Lichtenberger [23]. The data on biological methods are specific to the United States and are drawn from existing data sources [18, 24–29], and are presented in the Carbon Sequestration Calculator spreadsheet (S1 Data), which shows biological sequestration capabilities under current practices as well as potential with improved practices (reforestation and improved forest management; increased urban and suburban tree cover; cropland using no till, no till with cover crops, crop rotation, and conservation plantings; pasture and rangelands conservation; wetland conservation, restoration, and active management; and seagrass restoration). The spreadsheet is designed as a decision support tool to assist policymakers to evaluate alternative CDR methods nationally for the U.S., but this tool could be adapted for use in other contexts by obtaining and inserting applicable data.

Results

The Carbon Accountability Dashboard (Fig 1) serves as a biophysical performance summary that graphically depicts our BIOM analysis findings on various methods of CDR within the two overarching categories of mechanical capture and biological sequestration. All data on biological methods are specific to the United States. This graphic, and the explanatory Legend [S1 Text], which includes the detailed, underlying data, are offered as a tool to assist policymakers in evaluating alternative CDR methods.

We assess three fundamental criteria for each CDR method. The most fundamental criterion is *effectiveness*–whether or not the method achieves a net removal of atmospheric CO_2 (Column a). The *efficiency* of each method is assessed in terms of two critical input requirements–energy (Column b) and land (Column c). The *co-impacts* reflect both adverse impacts (such as CO_2 leakage or water contamination) and positive impacts (such as fire risk reduction or improved soil fertility) (Column d), and separately toxicity (Column e). We consider these together to determine the summative Biophysical Return On Resource Investment (B-ROI) (Column f) of each method, which can help answer the fundamental question "Is this method worth doing from a public need perspective?"

Effectiveness

Mechanical methods currently subsidized by the U.S. government are not reducing atmospheric CO_2. Carbon capture at emissions sources (CCS) does not remove CO_2 from the

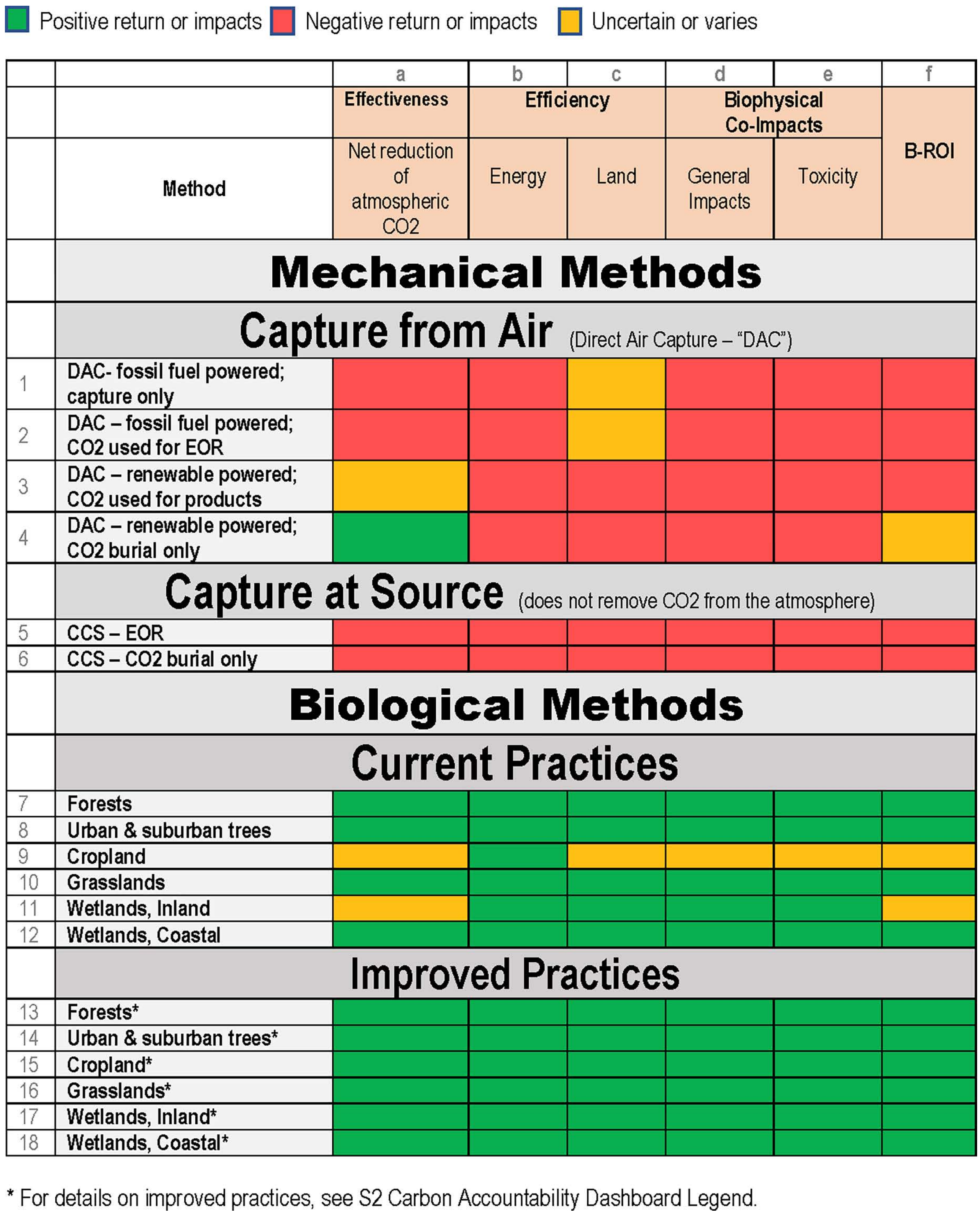

Fig 1. Carbon Accountability Dashboard. Explanations for each cell are in the Legend (S1 Text). Note that all designations exclude effects of "carbon offsets" or "carbon credits," which can counteract carbon removal accomplishments [30–35].

https://doi.org/10.1371/journal.pclm.0000124.g001 atmosphere. Direct air capture (DAC) can theoretically remove CO_2 from the atmosphere, but the net impact depends on the source of energy used to power it–DAC powered by fossil fuels results in CO_2 emissions exceeding removals [21, 36–39]. (DAC advocates argue that the CO_2 emitted by the fossil fuel powering the DAC can also be captured vis CCS, but this process itself emits more CO_2.) When the captured CO_2 is used for enhanced oil recovery (EOR), fossil fuel-powered DAC would ultimately result in an even greater net addition to atmospheric CO_2 because of the increased oil production and consumption. The largest DAC plant planned for the U.S. will use the captured CO_2 for EOR [40, 41]. Only when DAC is powered by a non-carbon energy source and the captured CO_2 is geologically stored can DAC result in a net reduction of atmospheric CO_2. Importantly, practically all studies of DAC emissions address the capture process only, omitting additional emissions from compression, pipeline transport, injection and storage. DAC is at a pilot stage and currently inconsequential in terms of climate change impact.

Available data on biological methods indicate that in almost all cases, these methods are effective, usually substantially so. Biological net sequestration refers to the uptake by plant growth minus emissions from respiration, harvesting, fire, etc. Biological methods included in our study are forest management, reforestation, regenerative agriculture, and wetlands management and restoration; our data are specific to the U.S. (see S1 Data for complete data on biological methods). Biological methods in most cases result in a net removal of atmospheric CO_2 and already have a collective net sequestration of nearly 1 Gt CO_2/yr in the U.S.

Importantly, all data on biological sequestration in this study are independent of "carbon offset" and "carbon credit" programs, which do not, on net, reduce emissions and can be counterproductive in terms of mitigation, and can result in adverse impacts [e.g., 30–35].

The largest carbon sink in the U.S. is forests (see S1 Data), which currently achieve net sequestration of 0.77 Gt CO_2/yr. Together with urban tree cover these areas currently sequester on net 0.9 Gt CO_2/yr. Improved forest management practices in existing forests (i.e., conservation and management practices that maximize biomass retention and carbon sequestration and storage and facilitate post-disturbance regeneration [42]), along with reforestation on just 2% of U.S. land, could result in an additional net sequestration of 0.584 GT CO_2/yr and 0.324 GT CO_2/yr, respectively, for a combined 117% increase. In the U.S. alone, a combination of improved forest management, reforestation, and additional urban trees could achieve a total potential 1.9 Gt CO_2/yr net sequestration.

Data on the effectiveness of croplands to capture and store carbon in the soil with current practices varies depending on whether the land has remained cropland for the past 20 years or was converted from some other land cover (usually forests, which account for 87% of the land converted to cropland) [25]). Cropland created at the expense of forest cover in the past 20 years results in current CO_2 emissions of 0.0542 Gt/yr, but cropland that has remained cropland sequesters a net 0.0145 Gt/yr. With improved practices (i.e., using cover crops, no till, crop rotation, and conservation plantings), U.S. croplands have an estimated capacity to sequester a net 0.16 Gt/yr.

Inland wetlands with current practices result in net emissions (0.0008 Gt CO_2/yr) due to peat production, which could be averted with peatland protection and restoration [43]. Coastal wetlands and seagrass currently sequester 0.0088 and 0.0004 GtCO_2/yr, respectively.

Given the current biological net sequestration rate of 0.9 Gt CO_2/yr in the U.S., and with the addition of reforesting 33 million acres (about the size of Louisiana), along with increased urban and suburban tree cover, improved agricultural practices, and restoration of wetlands and grasslands, the U.S. could sequester nearly 2 Gt CO_2/yr within 1–2 decades (times vary depending on geographic area and other factors, such as implementation and ramp-up period, maintenance and management practices, anthropogenic and natural disturbances, climate

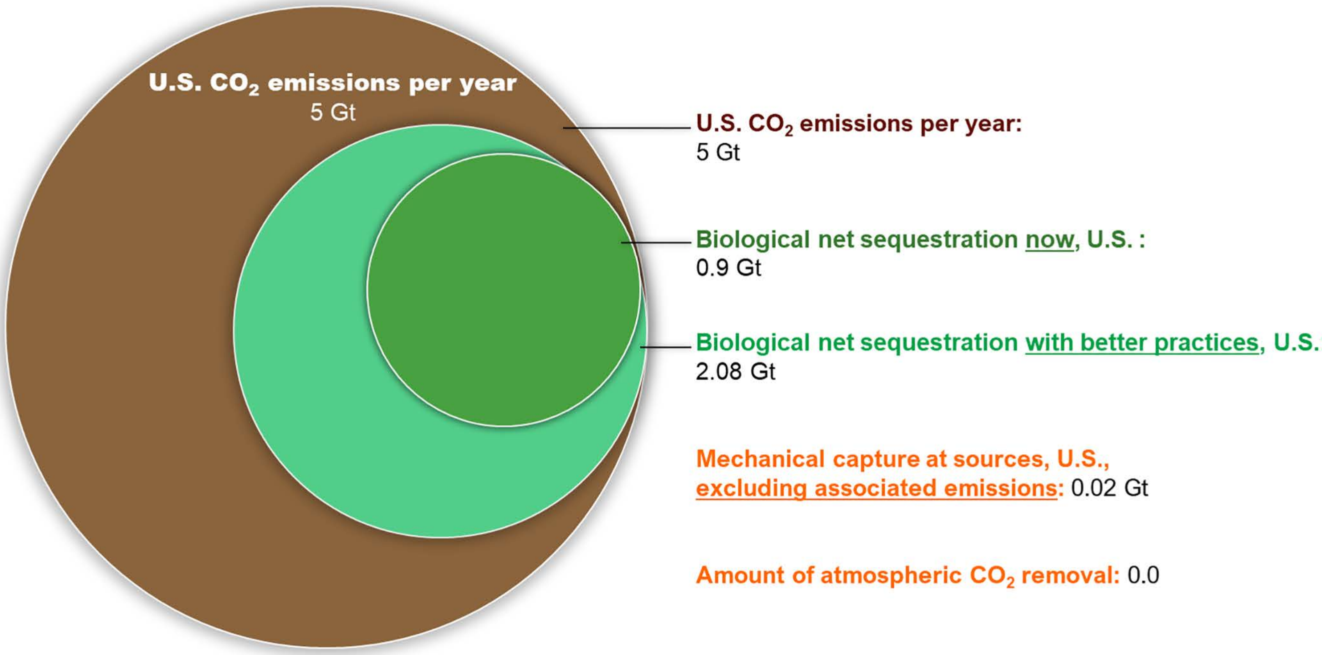

Fig 2. Annual amount of potential CO2 removal by biological methods with improved practices. With identified improved practices and ecosystem restoration on only 1.5% of US land, CO2 removal could be more than doubled, representing ~40% of US emissions. 1) Biological net sequestration refers to net uptake by plant growth minus emissions from respiration, harvesting, fire, etc. Biological methods included here are forest management, reforestation, regenerative agriculture, wetlands management and restoration. 2) 0.02 Gt represents gross capture per year at emissions sources according to the Global CCS Institute, but excludes emissions from CO2 capture process itself and from EOR oil production, transport, refining and combustion. Also note that all U.S. commercial capture is point-source capture, meaning no CO2 is being removed from the atmosphere (see S1 Data).

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events and extremes, species, pre-existing land degradation, etc.), equating to approximately 40% of U.S. current annual CO2 emissions of ~5 Gt/yr (see Figs 2 and 3).

Efficiency

We use the standardized outcome of 1 Gt/yr removal to compare resource requirements of mechanical and biological methods. Mechanical methods of CDR are extremely resource-intensive. For DAC to capture 1 Gt CO2/yr, (capture only, not the full removal process; and gross, not net), a liquid solvent DAC system would require an amount of energy nearly equivalent to the amount of electricity generated in the entire US in 2017. (A liquid solvent process is the system used by the only company with US plans to scale up to a million tons/yr of capture.) According to published data [18], to operate at the scale of 1 Gt CO2/yr capture, this system when powered by natural gas would require a land area more than five (5) times the size of the city of Los Angeles; if solar is used to replace the fossil fuel power source, then the required land area expands to ten (10) times the size of the state of Delaware. This does not count the land required for transport, injection and storage after the CO2 has been captured. In addition is the energy required for continuous compression of CO2 to a liquid or supercritical state and for transport, and the energy usage for the thousands of injection wells that would be needed at scale. Tens of thousands of miles of pipelines would be required to transport 1 GT/yr of captured CO2 [22, 28, 44, 45].

Conversely, biological methods have negligible energy requirements, and relatively small additional land area would be needed to achieve an additional 1 Gt CO2/yr net sequestration. This could be achieved, for example, through improved forest management and agricultural

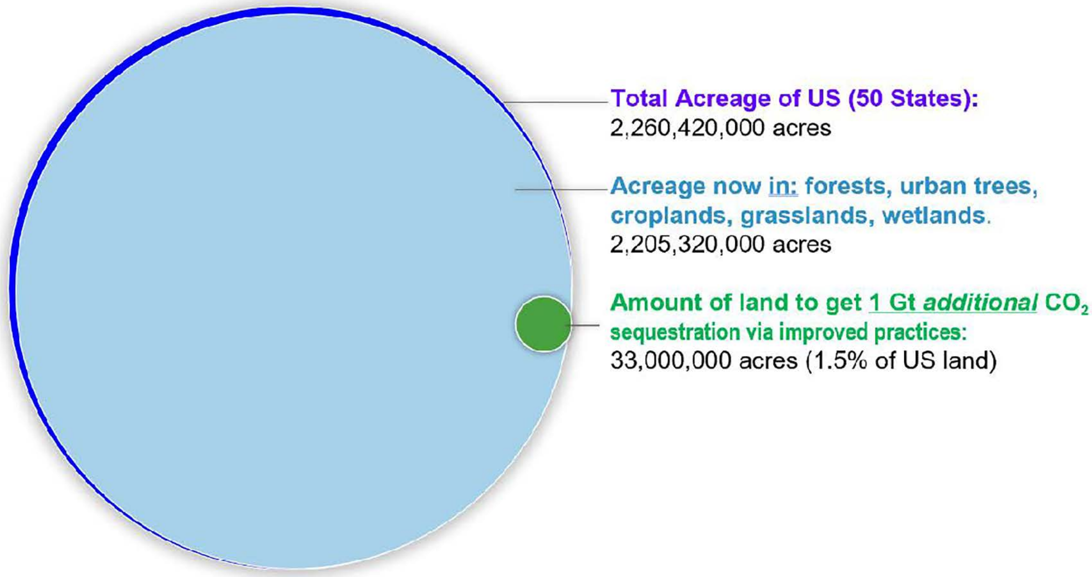

Fig 3. Amount of U.S. land required to achieve an *additional* net sequestration of 1 Gt CO2/yr with biological methods. Sequestering 1 Gt CO2/yr (in addition to the 0.9 Gt being sequestered currently by biological methods) could be done by reforestation on only 1.5% of U.S. land in combination with improved practices on existing land (see S1 Data).

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practices on existing productive lands and reforestation on 33 million acres or 1.5% of US land (see Fig 3, and columns M and N of S1 Data).

Claims that DAC requires far less land area than biological methods pertains to small pilot projects with climate-insignificant levels of capture, and ignores the issue of scale. Comparing land area requirements at scale reveals that net removal of 1Gt/yr CO2 by biological methods would require less land area than likely required by solar-powered DAC (liquid solvent system) (see Fig 4).

Co-impacts

Co-impacts of mechanical capture and storage have strong negative potential, and the adverse impacts would be particularly damaging when these processes are operated at climate-significant scale. The sudden release of CO2 from ruptures in transport pipelines or leakage from highly pressurized underground storage can cause asphyxiation of people and animals; fracturing of underground strata can cause earthquakes and water contamination; pipelines can result in reduced crop yields [46]; and the formation of carbonic acid (formed when water combines with CO2) can leach toxic metals out of rocks as well as lead to pipeline ruptures and release of toxic amounts of CO2. Illness or poisoning can result from handling toxic chemicals required for the CO2 capture process (particularly at scale), from chemical waste disposal post-capture, and from hazardous air pollution from fossil fuel-powered CCS at power plants and direct air capture [47–49]. In regions downwind of large DAC arrays, "CO2 depletion" can have "unwanted consequences or potential trophic cascades …" causing damaging effects on crops and local habitats [18]. Land used for solar-powered DAC capture, transport, and storage would be accompanied by ecosystem degradation and destruction, and the full life cycle process would create additional CO2 emissions.

Most methods of mechanical CDR use toxic chemicals. At the gigaton scale of operation, millions of tons of chemicals will be required. Chemicals used as sorbents and solvents for

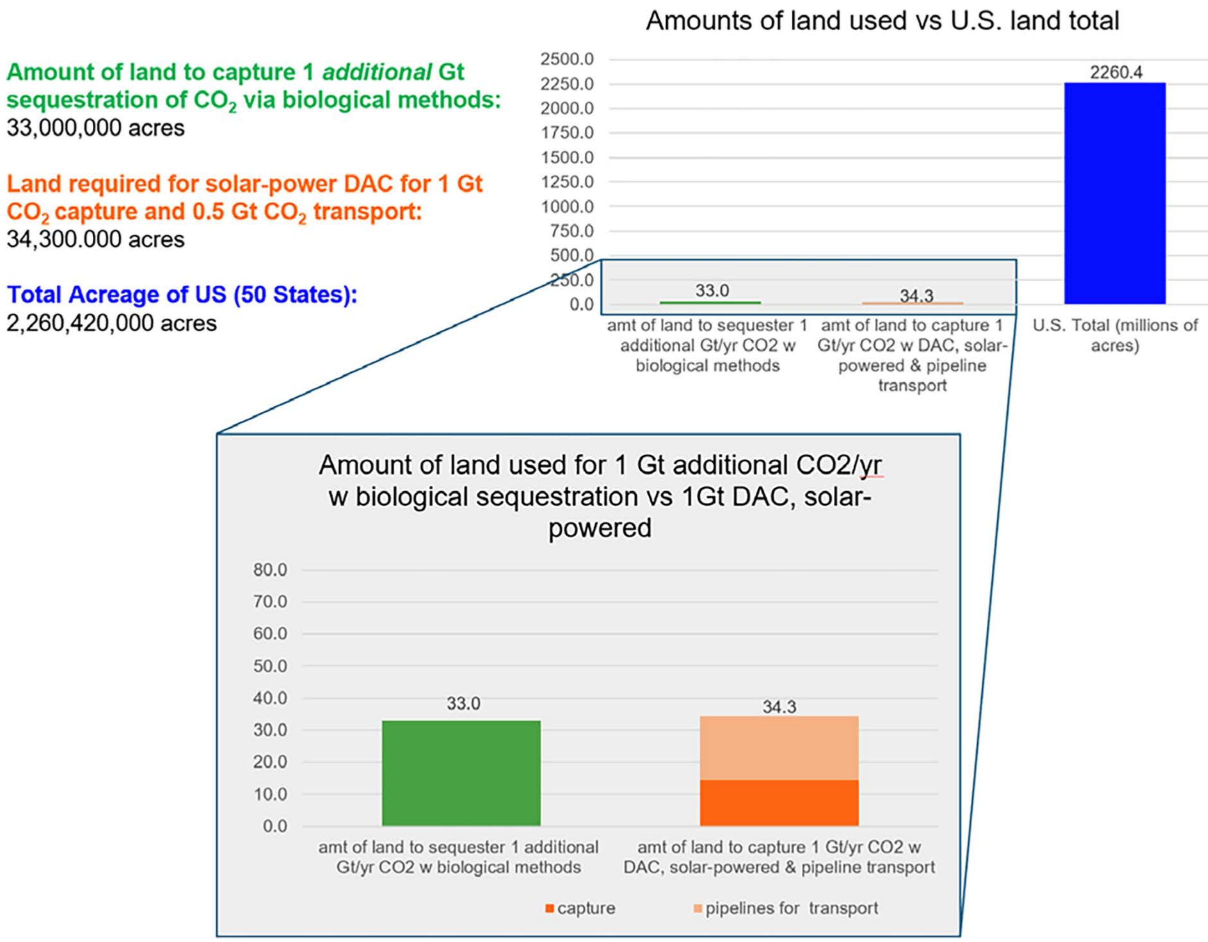

Fig 4. Amount of U.S. land required to achieve 1 Gt CO2/yr removal with biological methods vs solar-powered DAC. Solar-powered DAC could use as much land as biological methods to remove and store 1 GT CO2/yr. Biological methods would require 33 Macres to sequester 1 Gt additional CO2/yr (see S1 Data). 34.3 Macres could be required for solar-powered DAC (liquid solvent system) — 14.5 million acres for solar arrays and capture facilities [15], and 19.8 million acres for pipelines to transport ½ Gt CO2 to storage sites (based on a 50 ft. right of way for pipelines and a volume calculation based on current oil capacity of 21 Mbbl/day and the daily equivalent for a 1GtCO2/yr sequestration at 27.4Mbbl/day). This assumes that facilities for capture of ½ GtCO2/yr can be sited directly above geologic storage sites so no pipeline transport would be required.

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CO2 capture (many of which are made from fossil fuel feedstock), or produced in their manufacture, can include: lye, caustic potash, chlorine gas, and monoethanolamine made from ammonia and ethylene oxide. After their use in carbon capture processes, many of these chemicals must be disposed of, raising the danger of toxic waste dumping in the absence of adequate regulation or enforcement, with frontline communities most at risk. The larger the scale of operation, the proportionally greater likelihood of adverse impacts and mass casualty events, particularly in frontline communities.

Available data show that, overall, biological methods (including forests, croplands, urban and suburban trees, grasslands, and wetlands) can have a range of positive co-impacts, including: reduced air pollution; fire risk reduction; improved soil fertility; reduced soil erosion; higher nutrient density/higher nutritional value; flood control; watershed protection; water conservation; improved water availability for crop irrigation; energy conservation; reduced coastal land erosion; drought mitigation; urban heat reduction; and a variety of well-documented positive public and mental health effects from interactions with healthy ecosystems [e.g., 42, 50–66]. The positive effects of biological methods under improved practices are likely to increase in proportion to their scale of implementation.

Though there is concern about some biological methods supplanting land used for food production, this generally pertains to other parts of the globe rather than the U.S., and is much more a concern with BECCS than with reforestation or other forms of ecosystem restoration. Also, with well-informed planning, implementation, and management, biological methods can be effective while minimizing risk of potential negative tradeoffs (e.g., competing land-use pressures, biodiversity and other ecosystem services, etc.) [67].

B-ROI

B-ROI (Biophysical Return On Resource Investments) summarizes the results of the analyses of each of the three criteria: effectiveness, efficiency and co-impacts.

Effectiveness is a threshold criterion; for every method where effectiveness is negative, B-ROI is negative. For methods where effectiveness is positive or uncertain/variable, B-ROI may be positive, variable or negative depending on whether the associated factors of efficiency and co-impacts are negative or positive.

Nearly all mechanical methods have a negative B-ROI (see Fig 1). The B-ROI of CCS–source capture–is negative because it does not remove CO2 from the atmosphere. DAC powered by fossil fuels is not effective at reducing atmospheric CO2 because, on net, it emits more CO2 than it removes. As available data only considers capture, and given the additional emissions from compression, transport, injection and continuous storage at thousands of underground storage wells, fossil fuel-powered DAC is more counter-productive than available data suggest. DAC powered by a non-carbon energy source can, in theory, reduce atmospheric CO2 if the captured CO2 is geologically stored (and not used for EOR). However, it requires immense amounts of energy and land to operate at scale and is thus not resource efficient. Notably, all forms of DAC are likely to result in negative co-impacts.

Most biological methods have a positive B-ROI (see Fig 1). They are generally both more effective and more resource efficient than mechanical methods in achieving the outcome of 1 Gt/yr net CO2 sequestration, and the ancillary impacts of biological methods are largely positive. B-ROI is variable for cropland under *current* practices because effectiveness, efficiency, and co-impacts can vary based on practices: the B-ROI of inland wetlands is slightly negative under *current* practices because of peat production.

Financial cost

While our analysis focuses on non-monetary, biophysical costs and consequences of CDR, financial costs are both relevant and a generally prevailing concern of policymakers. From the public finance perspective, financial costs must be considered not in terms of private profitability but rather in terms of allocation of scarce public resources. Regarding biological methods, determining cost is complicated by regional variability [18, 21, 53, 68]. Further, most cost estimates for biological methods are stated in terms of cost per hectare, which is not comparable to the cost-per-ton-captured metric associated with mechanical capture. Only one study [18] was found to include cost estimates of biological methods in terms of cost per ton of CO2 sequestered.

Table 1 displays costs for mechanical capture and biological sequestration of 1 ton/CO2/yr. Costs for biological methods show net CO2 removed and sequestered, while the DAC figures are for gross CO2 captured only. The literature on DAC costs generally does not include the costs of compression, transport, injection, storage, monitoring, reporting and verification. Considering the cost of gross capture only, and ignoring the additional costs, DAC is 25 to 50 times more costly than biological net sequestration.

Table 1. Comparison of the financial cost of mechanical and biological methods of CDR.

Method	Cost/tCO2 captured or removed	Source
Direct Air Capture, *gross* capture, and *excluding* costs of compression, transport & storage	$500* - $1,100	[21, 36, 69, 70]
Reforestation/Afforestation	$20 or less	[18]
Improved forest management	$20 or less	[18]
Improved agricultural practices	$100 or less	[18]
Coastal blue carbon	$20 or less	[18]

* Lower cost estimates exist in the literature (including < $100/ton) but generally come from sources close to industry; upper range estimates are generally derived from thermodynamic considerations [e.g., 21, 36, 69].

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Discussion

Failures of market-mechanistic policymaking

In addition to the biophysical analysis, also of crucial importance for policymaking is the perspective of societal need as the policy driver. In terms of public policymaking, societal need differs fundamentally and crucially from market demand; societal (public) need is collective, and the nature of need is different from the nature of demand [11, 13, 71, 72].

In the U.S., CDR policymaking has rested on a notion of market demand and a view that markets will generate effective CDR solutions, with the role of government being to subsidize commercial actors in order to induce development of effective CDR technologies. Calls for research and development on mechanical methods has explicitly identified commercialization as the purpose of government financing, a public policy strategy of "technology push and market pull" [73]. In 2010, the Interagency Task Force on Carbon Capture and Storage called for "national policy frameworks" for commercialization of CCS [74]; the National Academies of Sciences prefaced its 2019 report on "negative emissions technologies" by indicating that it rested on NETs being an attractive commercial opportunity in the "international market" [18]; in 2020 the Congressional Research Service noted that the Dept. of Energy saw "the purpose of its CCS" funding being "to benefit the existing and future fleet of fossil fuel power generating facilities" [75]; and in 2022 the White House Council on Environmental Quality issued guidance to Federal agencies implementing "CCUS" projects across the country, stating repeatedly that "commercialization" is the purpose, even to the point of using public lands for commercial CO2 storage [76].

The technology-push, market-pull orientation of U.S. policymaking on CDR is represented in much of the literature on mechanical CDR [22, 77, 78], and has resulted in several decades and billions of dollars in public subsidies for mechanical carbon capture. Examples include tax credits for CCS and DAC such as the federal 45Q tax credit; carbon offset credit programs, such as the California Low Carbon Fuel Standard; subsidies for scoping and preparation for buildout of CO2 pipelines; and subsidies for alternative fuel production processes (e.g., ethanol, hydrogen) that rely on CCS to be considered "low-carbon". Additionally, there are federal subsidies that enable oil producers to extract new oil, seen as necessary to assure that CDR projects can be commercially viable [e.g., 79]. In this process, called "enhanced oil recovery" (EOR), drillers use captured CO2 to force out otherwise difficult-to-access, uneconomic, oil. In all but one of the existing 12 CCS projects in the U.S. the captured CO2 is used for EOR [80]. The argument that this process is superior to conventional oil production because some of the injected CO2 stays underground and that this "lower carbon" oil displaces the production of higher-carbon, conventionally-produced oil, is based on unsupported assumptions from economic theory and on an unsupported carbon accounting contrivance [23].

This policy approach has resulted in a track record of failures. The most extensive review [73] examined 263 CCS (this study uses the abbreviation "CCUS" to include projects in which the captured CO2 is solely injected underground, not in any way "utilized", so the correct abbreviation is "CCS") projects undertaken between 1995–2018 and found that the majority failed; larger plants with higher capture capacity are more likely to be ended or put on hold; much of the world had cancelled projects (European Union, Australia, Canada, China, United States); and a "growing sentiment" that the risks associated with scaling up the technology to "learn" more are not worth the large investments required. Though the study found private investment in mechanical CDR projects had been minimal, the trend has reversed in the U.S. with pipeline companies, venture capitalists and other companies now arising in growing numbers to take advantage of the public subsidies, such as the 45Q tax credit and California's Low Carbon Fuel Standard to undertake carbon capture, pipeline transport and underground storage of CO2.

A 2021 review of public records [81] on publicly-subsidized CCS projects at power plants in the U.S. similarly showed that all projects failed. A study by the U.S. Government Accountability Office [82] reviewed the 11 major publicly-subsidized CCS projects funded by the US Dept. of Energy from 2009 to 2018 and found that none of the 8 CCS projects at coal power plants were successful, and that only two of the three industrial site demonstration projects remained operational; the study expressed concerns about DOE management of all 11 projects, and highlighted the need for more active Congressional monitoring to improve accountability and reduce the risk of significant spending on projects likely to fail.

A 2020 federal investigation found that claimants for the 45Q tax credit failed to document successful geological storage for nearly $900 million of the $1 billion they had claimed [83, 84]. In a 2021 report on the 45Q tax credit program, the Congressional Research Service [80] noted the shortcomings of the present monitoring, reporting, and verification requirements, and suggested that "Congress may consider whether the IRS has adequately addressed concerns about improper claims".

The market-mechanistic policy perspective that has resulted in the series of failures encompasses two fundamental flaws in terms of CDR policy. First is the view of captured CO2 as a commodity with exchange value. Second is the idea that burying CO2 underground is a market activity.

The view of captured CO2 as a commodity with exchange value may be sound in theory but is in practice irrelevant: in terms of having climate-relevant impact on the stock of atmospheric CO2, the potential commercial demand for captured CO2 is either insufficient [22, 85–89], counter-productive [e.g., 86], or both. Using CO2 to produce fuel and many other products puts the CO2 back into atmosphere; the primary use is for EOR. There is not sufficient market demand of any kind at the multi-gigaton level of removal and storage required annually to have significant impact on the level of atmospheric CO2. Treating CO2 as a commodity, therefore, will not result in climate-relevant removal.

Secondly, the main justifications for government subsidies are to bring costs down and capture capabilities up. The analogy is frequently made to solar power, where government subsidies led to lower costs and market development. However, this is a false analogy, and a category error. In order to have a climate-significant impact, mechanically captured CO2 must be disposed of at the multi-gigaton level—injected and retained underground, perpetually. In the market exchange mechanism for solar power there is a product—energy—purchased by a customer. But, when the producer's product—captured CO2—is buried underground and the payor is the public this is not a market exchange [78]. Rather, the process is publicly-financed waste disposal [78, 90–92]. This is analogous to a sewage system [90].

A publicly-financed "sewer system" for disposal of fossil fuel emissions at the multi-gigaton level annually would require the construction of tens of thousands of miles of new CO2 pipelines [28], oftentimes the taking of land by eminent domain; the identification, scoping and preparation of acceptable underground "storage" sites; and negotiations between governments and private storage operators about who will bear long-term legal and financial responsibility for damages and harms from leakage, rupture, seismic events, and probable mass casualty events [47, 48, 93–95]. Co-impacts from every stage of the process are adverse, and would pose significant risks, particularly to frontline communities.

CDR impact and time frame

The prospect for mechanical methods removing CO2 on net at the multi-Gt level by mid-century is remote [19, 22, 79 citing 21, 67, 96, 97]. Whether the necessary surface infrastructure could even be built, and gigatons of CO2 injected underground, within a generation has been questioned [19, 87, 96, 98]. Moreover, DAC as now being subsidized in the U.S. will likely increase the amount of CO2 in the atmosphere while it scales up, given that the most scalable process (liquid solvent DAC) requires fossil fuel power. Though DAC advocates assert that a CCS point-source capture operation would be added to a DAC facility (such as the one currently planned in Texas) to capture the CO2 emissions from the fossil fuel power source, this claim has yet to be demonstrated in reality. Moreover, that point-source capture process itself generates additional CO2. In contrast, biological methods already remove atmospheric CO2, and their capabilities could be more than doubled with improved practices within one to two decades, with variability based on geographic area and other factors, to achieve more than 2 Gt/yr CO2 removal.

The findings of this study that biological methods exhibit superior effectiveness in comparison to DAC are consistent with data reported in the 2022 IPCC study [67], which presents scenarios to hold global temperature rise to below 1.5° - 2° C, including scenarios of rapid transition to non-carbon energy sources as well as CDR scenarios. According to the IPCC, not only are biological methods of CDR more effective than DAC (called "DACCS" in the IPCC report), but their effectiveness is projected to increase significantly over time (see Table 2).

Importantly, however, no carbon removal method would have immediate climate-significant impact on the level of atmospheric CO2 due to issues of scalability in the case of mechanical methods, and time for widespread adoption of improved practices and achievement of sequestration potential for biological methods. And, no method assures permanence. Indeed, forests can be destroyed or cropland can be mistreated, releasing CO2. Careful planning and management are critical for the long-term success of biological methods. For mechanical methods, assertions that mechanical underground storage is "permanent" are misleading given studies that highlight the impermanence of underground storage [75, 94, 95, 99–105].

Table 2. Global CO2 removal and sequestration/yr: Biological CDR and DACCS.

Method	Global GtCO2/yr by 2030	Global GtCO2/yr by 2050	Global GtCO2/yr by 2100
Annual net CO2 removal, managed land	0.86	2.98	4.19
DACCS	0	0.02	1.02

Source: [67, p 12–40].

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Accountability and technology

There has been essentially no verified carbon removal measurement associated with mechanical CCS and DAC subsidies that have been enacted. Investment in technologies for measuring, reporting and verification (MRV) are essential if CDR outcomes are to be verified and subsidy recipients held accountable. Funding is needed for measuring and monitoring the results of biological methods as well, including the further development of in situ tools for measuring above- and below-ground carbon stocks as well as advanced remote sensing technologies to supplement ground inventories.

Conclusions

Our BIOM analysis assesses CDR methods on three biophysical criteria: effectiveness, resource efficiency, and co-impacts. Effectiveness is the threshold criterion as it assesses whether each CDR method actually achieves a net removal of CO2 from the atmosphere. The resource efficiency criterion provides a standardized comparison of resource (i.e. energy and land) investments required for each method at climate-relevant scale. The co-impacts criterion weighs other biophysical outcomes of each method–whether positive or negative–for ecosystems, people and communities. Taken together, these three criteria inform a Biophysical Return On Resource Investments (B-ROI) assessment for each method. We also present a cost comparison.

Point-source capture is irrelevant to the goal of atmospheric carbon dioxide removal because it aims only to reduce new emissions and does nothing to remove CO2 from the atmosphere. Direct air capture has been inconsequential at the levels practiced to date, and scaling it up to be consequential would entail resource use inefficiencies and additional risks and harms. The charges most commonly made against biological methods are that they require too much land and are too ephemeral. Yet, evidence shows that in comparison to mechanical methods, biological methods are both more effective and more resource efficient (in energy consumption and land requirements) in achieving net CO2 removal at climate-significant scale. Assertions that mechanical underground storage is "permanent" are misleading given studies that highlight the impermanence of underground storage. The co-impacts of biological methods are generally positive, while those of mechanical methods are negative; and they are more financially cost-effective. Importantly, biological methods could be increased with improved practices and minimal additional land area within the next decade and increasingly throughout this century.

The policymaking apparatus in the U.S. has largely been attuned to considerations of market viability, which results in policies and legislation that fail to address our collective biophysical need and are harmful. The federal government has long been providing, and is now accelerating, financial subsidies to market actors for mechanical carbon capture that data shows to be ineffective, resource-inefficient, and harmful in terms of co-impacts. Sound fiscal policies are required to remove distortionary incentives and also to finance effective decarbonization actions and financing tools (such as direct payments or green bonds for biological sequestration) that will meet the collective need for effective and efficient decarbonization [106, 107]. Without a new policy framework, the results will be continued suboptimal outcomes for climate change mitigation at best and foreseeable hazards for people and places at worst.

This paper highlights the need for a biophysical lens for policymakers to evaluate and compare CDR methods on their biophysical capabilities, costs, and consequences. Our analysis and our results suggest a new policy framework based on B-ROI, in addition to financial cost.

Under such a framework, in order to receive public subsidy, a CDR method should (expanding on the criteria identified by Herzog [108]):

1. be effective at achieving net removal of CO2 from the atmosphere (the threshold criterion);
2. be resource-efficient at the gigaton scale in comparison to other methods;
3. operate with positive biophysical impacts or without serious negative impacts; and
4. be financially cost-effective in comparison to other methods.

Given the findings of our analysis, we make the following recommendations regarding the public funding of CDR:

- Public funding for mechanical methods should be ended or narrowly restricted. Of the mechanical methods, only renewable-powered DAC with CO2 storage (excluding EOR) meets the minimum threshold criterion of effectiveness. However, the resource demands (energy and land requirements at scale) must be recognized, and the long-term liability for the many predictable risks and damages to people and ecosystems throughout the life cycle process must be borne not by the government but by the DAC-implementing subsidy recipient.
- Substantial public funding should be enacted to directly support proven biological methods, including those assessed in this study. To be clear, government financial support for biological sequestration must be in the form of *direct* investments, not via "offset" programs or "carbon credits" arrangements, which can counteract much of the effectiveness of biological sequestration [30–35] and are often harmful to indigenous peoples [35].
- Public funding should simultaneously be enacted to invest in measurement and monitoring technologies, including remote sensing and in-situ technologies for measuring carbon both above and below ground. Such tools are essential if CDR outcomes are to be verified, subsidy recipients held accountable, and for methods to be proven worthwhile (or not–thus freeing up funding for more effective, efficient, and beneficial methods).

We offer our Carbon Sequestration Calculator (S1 Data) and Carbon Accountability Dashboard (Fig 1) with its explanatory Legend (S1 Text) as decision support tools for federal policymakers in the U.S. These tools could be adapted for different scales or locations where data is available or can be obtained.

Supporting information

S1 Data. Carbon sequestration calculator. A spreadsheet that: 1) Contains the data and displays the calculations that show biological sequestration capabilities in the U.S.: a) under current practices; and b) potential with improved practices (reforestation and improved forest management; increased urban and suburban tree cover; cropland using no till, no till with cover crops, crop rotation, and conservation plantings; pasture and rangelands conservation; wetland conservation, restoration, and active management; and seagrass restoration) in the U.S. b) Contains data sources for all data used in the spreadsheet calculations.
(XLSX)

S1 Text. Carbon accountability dashboard legend. A legend to accompany the Dashboard, Fig 1. The Legend contains explanations for each cell in the Dashboard. Data sources are also indicated.
(DOCX)

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