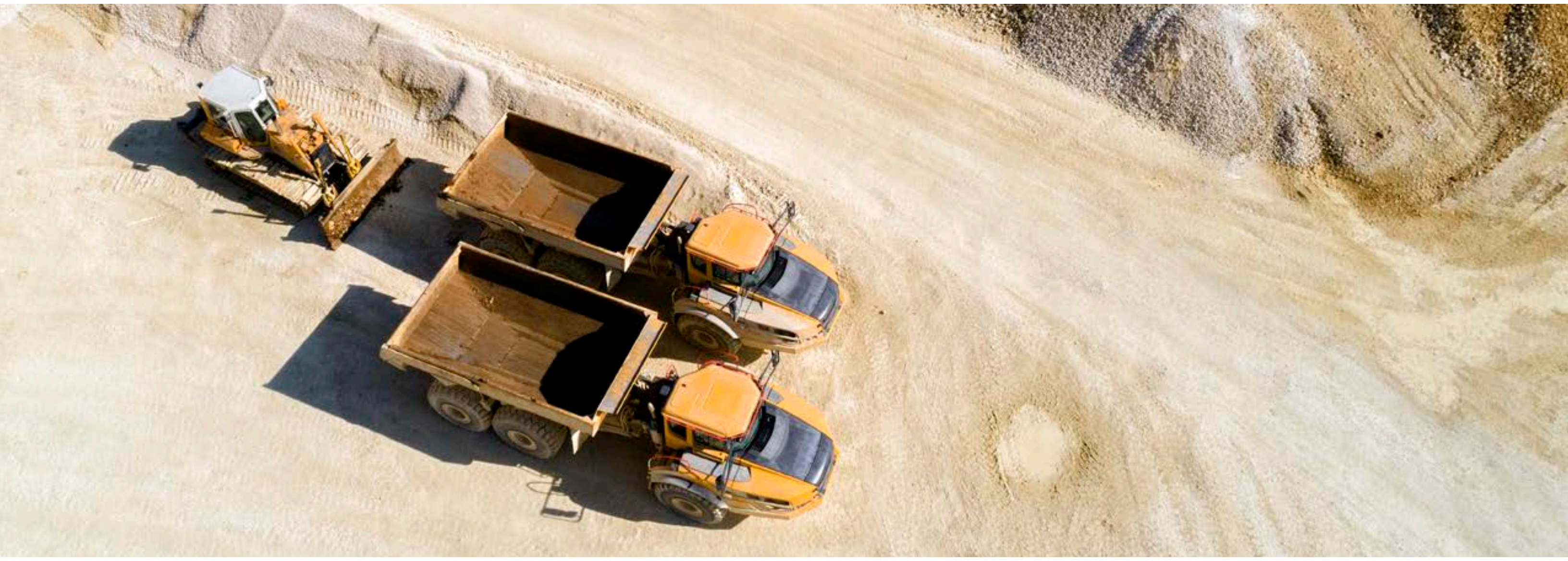

Sustainable carbon removal

INSTITUTE *for* CARBON REMOVAL
LAW AND POLICY

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This report was supported by a grant from the New York Community Trust.

Suggested citation: Morrow, David R. & Simon Nicholson. 2021. *Sustainable Carbon Removal*. Washington, DC: Institute for Carbon Removal Law and Policy, American University. https://doi.org/10.17606/88h7-nn35

Executive Summary

Carbon removal, which involves capturing carbon dioxide (CO_2) from the atmosphere and sequestering it, can help us meet the goals of the Paris Agreement. The key question is not just how to make large-scale carbon removal operational, but how to make it sustainable.

Sustainable practices balance environmental, social, and economic goals. Sustainable carbon removal balances those goals in order to meet the needs of the future without compromising the ability of current generations to meet their own needs.

To operationalize this idea, we need to ask two questions: How should we measure the environmental, social, and economic impacts of carbon? How should we decide when carbon removal strikes the right balance between future and present needs?

Analyzing carbon removal at different levels can illuminate environmental, social, and economic risks and opportunities. Levels of analysis range from broad technological categories, like reforestation, to specific projects, like Climeworks' Orca direct air capture project in Iceland. Most analyses have focused on broad technological categories, but more fine-grained analyses are crucial for delivering actionable advice.

Finding metrics for environmental, social, and economic impacts is vital for quantifying positive and negative impacts and comparing approaches. One possibility is to use the indicators for the UN's Sustainable Development Goals, which are politically negotiated, internationally accepted metrics of environmental, social, and economic sustainability.

Determining which approaches are most sustainable requires balancing different positive and negative impacts that may not be easily comparable. There are several ways to do this, ranging from intuitive judgments to multicriteria decision analysis, although any decisions about which approaches are most sustainable are ultimately political decisions.

In summary, to develop sustainable carbon removal, we need to identify sustainability metrics, such as the indicators behind the Sustainable Development Goals; apply those metrics at different levels of analysis; and develop strategies for determining which approaches strike the right balance between environmental, social, and economic goals.

1. The Role of Carbon Removal in Climate Policy

The world still pumps more than 40 billion metric tons of carbon dioxide (CO_2) into the atmosphere each year.[1] Much of that CO_2 accumulates in the air, warming our planet. Atmospheric levels of CO_2 have risen from about 280 parts per million before the Industrial Revolution to about 350 parts per million in 1990, reaching over 415 parts per million today. That CO_2 will continue to warm the planet until we stop adding more of it to the atmosphere than we take out.[2] Reaching this point of "net-zero" CO_2 emissions will therefore play a central role in stabilizing global temperatures, but doing so in time to hold warming below 1.5°C or 2°C, as required by the Paris Agreement, remains a daunting challenge.

Meeting either of those targets will require CO_2 emissions to fall at precipitous rates, as Figure 1 illustrates. Suppose that global CO_2 emissions could peak immediately and begin to fall in 2022, and that humanity never pursues or achieves net-negative emissions. In that case, the world would have to cut emissions by 10.5% every year to have a two-thirds chance of limiting warming to 1.5°C. That amounts to a formidable 64% reduction in global CO_2 emissions by 2030, compared to 2021. Furthermore, for every year that passes before emissions peak, the paths to the Paris targets become even steeper and more challenging. If the world muddles through this decade so that emissions follow the middle-of-the-road mitigation scenario used in the latest Intergovernmental Panel on Climate Change (IPCC) reports, global CO_2 emissions would then have to plunge by 38.4% every year after 2030 for even a 50% chance of limiting warming to 1.5°C. Getting emissions to peak early enough and fall quickly enough poses an enormous social, political, and technical challenge, especially given the Paris Agreement's aim of cutting emissions "in the context of sustainable development and efforts to eradicate poverty."[3]

Carbon removal—the process of removing CO_2 from the atmosphere and locking it away for decades, centuries, or longer—can play an important part in meeting that challenge. (See Appendix A for an introduction to carbon removal.) Crucially, however, most of the work in achieving the Paris targets will have to come from emissions reductions; carbon removal is a supplement to cutting emissions, not a replacement for doing so. This report examines the roles that carbon removal could play in climate policy, and especially on the relationship between carbon removal and sustainability.

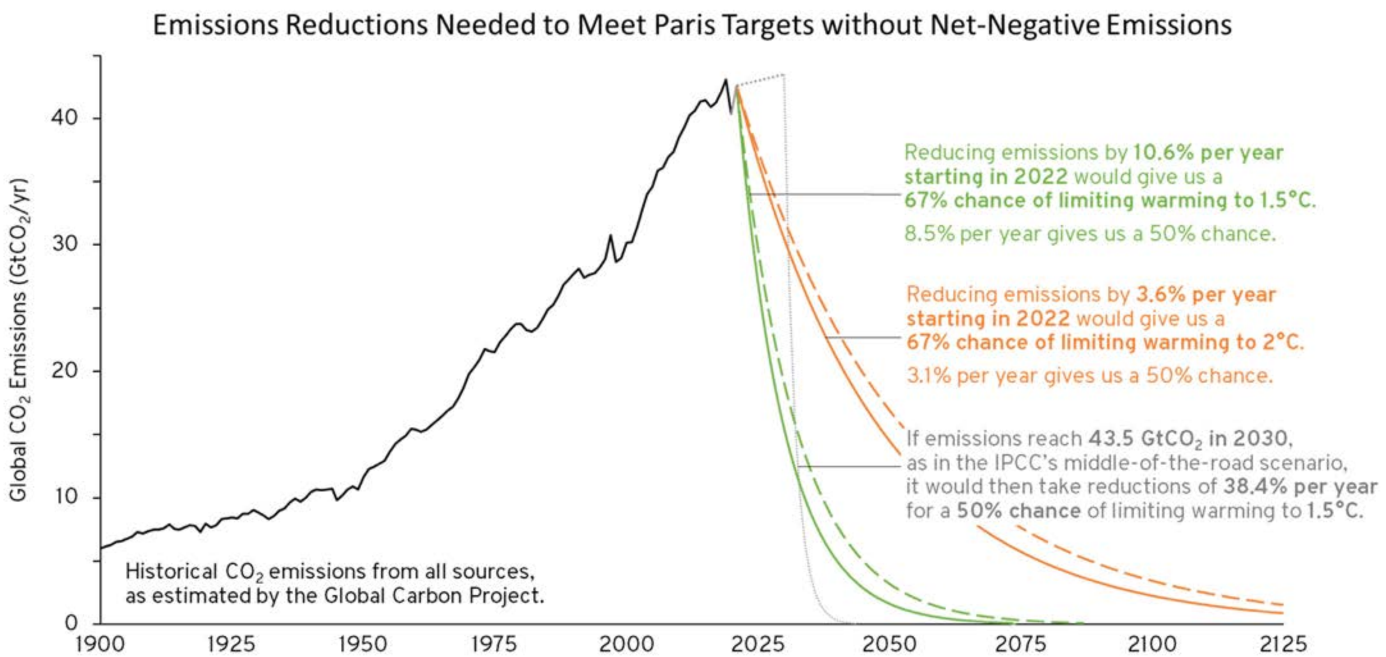

Figure 1. Global carbon dioxide (CO_2) emissions will need to plunge precipitously to reach the Paris Agreement targets of limiting warming to 1.5°C or 2°C. These simplified trajectories illustrate how quickly CO_2 emissions would have to fall to achieve those targets with varying degrees of certainty, if the world never goes below net-zero CO_2 emissions. Solid lines indicate emissions reductions needed for a 67% chance of limiting warming to 1.5°C (green) or 2°C (orange). Dashed lines indicate reductions needed for a 50% chance of meeting those same targets. Source: Authors' calculations based on historical data from the Global Carbon Budget Project, projections for 2021 from the International Energy Agency, and mitigation scenarios and carbon budgets from the IPCC's Sixth Assessment Report. Inspired by a chart by Zeke Hausfather.

Net-Zero and Net-Negative Emissions

The key to understanding carbon removal's role in climate policy is to understand the much abused notion of net-zero emissions. CO_2 emissions warm the planet because some of the CO_2 stays in the atmosphere, where it traps heat that would otherwise escape into space. Global warming will stop soon after humanity stops increasing the amount of CO_2 in the atmosphere. More precisely, it will stop soon after humanity stops adding more CO_2 than we remove over relatively short time periods, such as a year.[4] This is the point at which humanity achieves net-zero CO_2 emissions: when the amount of CO_2 it emits each year is completely counterbalanced by the amount it removes in that same year.

It is absolutely essential to the concept of net-zero emissions, however, that emissions are counterbalanced by genuine, durable removal of CO_2 that happens close enough in time to the original emissions. Traditional offsets that merely avoid emissions (for example, paying for someone else to keep forests intact or to switch from fossil fuels to renewable energy) do not count. Nor do removals that only come far in the future. If you plant a tree that will absorb CO_2 over many decades, you cannot count those future removals against emissions today; only the carbon that the tree absorbs this year counts toward this year's net emissions. Similarly, promising to clean up CO_2 later does not eliminate the warming caused by emissions today. The climate does not care about accounting tricks; it responds only to the real-time flows of CO_2 and other greenhouse gases into and out of the atmosphere.

To get to real net-zero emissions, the world will have to rely primarily on emissions reductions. This is mainly because it is almost always easier, cheaper, and more effective to avoid emitting CO_2 in the first place than it is to clean it up afterward. Trying to use carbon removal to avoid a transition away from fossil fuels would therefore be difficult and enormously expensive, to say nothing of the foregone environmental and health benefits that would come from phasing out fossil fuels. Therefore, traditional approaches to mitigation, such as switching to renewable energy production and reducing energy demand, must remain at the core of climate policy.

Still, to get all the way to net-zero CO_2, we are likely to need some amount of carbon removal to clean up emissions from the hardest-to-decarbonize sectors, at least until humanity can develop and roll out carbon-neutral technologies across all of those sectors. Furthermore, supplementing emissions reductions with carbon removal can help achieve the deep, rapid reductions depicted in Figure 1, getting the world to net-zero emissions sooner than we would without carbon removal.[5] Approaches that do not require large amounts of energy, such as reforestation and regenerative agriculture, as well as technologies that supply carbon-negative energy, such as biochar production or bioenergy with carbon capture and sequestration (BECCS), could play an especially important role in getting to net-zero faster.

Getting to net-zero faster matters because it means that temperatures will stabilize sooner and at a lower level, reducing the impacts of climate change and decreasing the risk of crossing critical thresholds for ecosystems and geophysical systems.

Once the world does reach net-zero CO_2 emissions, carbon removal could be used to go even further. By removing additional CO_2 each year to counterbalance the warming from other greenhouse gas emissions, such as methane and nitrous oxide from agriculture, carbon removal could get the world to net-zero greenhouse gas emissions. At that point, the world would begin to cool gradually.[6] Going even further than that, carbon removal could be used to clean up "legacy carbon" left in the atmosphere from past emissions, achieving net-negative emissions that would accelerate the decline in CO_2 concentrations and global average temperature.[7] If the world cannot curb emissions quickly enough, net-negative emissions would become essential to bringing global average temperature below 2°C or 1.5°C. Even if the world does meet the Paris targets, achieving net-negative emissions could be worthwhile because climate change is already harming people and ecosystems around the globe, and it will get worse by the time we get to net-zero emissions. Carbon removal offers us, conceivably, a way to reverse that warming and restore a safer climate.

Some approaches to carbon removal

There are many ways to remove CO_2 from the atmosphere and many ways to sequester or store it. Some of the most discussed approaches include:

Biochar. A carbon-rich solid made by heating biomass, biochar can be buried as a soil amendment or used in building materials.

BECCS. Combining bioenergy with carbon capture and storage takes CO_2 captured by biomass and compresses it for use or sequestration.

DACCS. Electrochemical systems capture CO_2 directly from the air and compress it for use or sequestration.

Enhanced mineralization. Grinding silicate minerals accelerates the natural chemical reactions by which they capture CO_2 from the air.

Forestation. Since forests capture CO_2 and store carbon, planting and/or restoring forests removes CO_2.

Ocean-based methods. A variety of methods, from kelp farming to ocean liming, can increase the vast amount of carbon stored in the ocean.

Soil carbon sequestration. A range of agricultural practices can increase the amount of carbon captured and stored in soils.

See Appendix A for more details on these approaches.

2. Sustainable Carbon Removal

The need to consider carbon removal options is clear. Carbon removal is, though, far more than a technical challenge. To make a noticeable difference in meeting the Paris targets or reversing warming, carbon removal would need to scrub billions of tonnes of carbon from the atmosphere every year for many decades. What would it take to make such a massive undertaking not just operational, but sustainable?

While sustainability, in its most literal sense, just means "able to be sustained or continued indefinitely," the term has taken on a more specific meaning for many environmentalists: it denotes the successful balancing of economic, social, and environmental goals to ensure that an activity can continue indefinitely.[8] When used in this way, sustainability becomes an "essentially contested concept," which means that people use it to denote a certain complex kind of success but disagree endlessly about exactly how to understand that success.[9] In the case of sustainability, people disagree about which economic, social, and environmental goals matter for sustainability; how to measure the achievement of those goals; and about what counts as striking the right balance between them.

Defining sustainable carbon removal means identifying what economic, social, and environmental goals matter for carbon removal and figuring out how to measure and balance them.

One way to approach these questions is to look to the Brundtland Commission's famous definition of "sustainable development" as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[10] On this definition, the social and economic goals of sustainability have to do with meeting the needs of the present, while the environmental limits on development have to do with enabling future generations to meet their own needs.

Sustainable carbon removal turns the Brundtland Commission's conception of sustainability on its head: sustainable carbon removal is carbon removal that meets the needs of the future without compromising the ability of current generations to meet their own needs. Carbon removal could help societies achieve their long-term environmental goal of limiting climate change, thereby helping to secure the needs of future generations, but doing it sustainably means doing it without compromising societies' ability to meet their current economic, social, and environmental needs. This also ties back to the most literal meaning of sustainability: no one will sustain carbon removal over the long run if its economic costs, social impacts, or environmental side effects become unbearable, especially because the climate benefits will be gradual and diffuse. Achieving sustainable carbon removal, therefore, requires balancing competing goals, both now and in the future.

Sustainable carbon removal is carbon removal that meets the needs of the future without compromising the ability of current generations to meet their own needs.

Before turning to the crucial questions about how to decide which goals to balance and how to balance them, it is worth reflecting on reasons to care about whether carbon removal gets done sustainably.

Why Sustainability Matters for Carbon Removal

Given the urgency of reaching net-zero emissions, some proponents of carbon removal see concerns about sustainability as a distraction from the "real business" of scaling up carbon removal and emissions abatement. Here we consider three reasons to take sustainability seriously.

First, pursuing sustainability is a matter of justice; it is the right thing to do. Adverse sustainability impacts involve real harms and risks to people, communities, and ecosystems, and favorable sustainability impacts involve real benefits. Furthermore, negative impacts may tend to be unjustly distributed, especially because injustices in existing systems will tend to push harms and risks onto already vulnerable communities. These harms, risks, and benefits matter. Ignoring them and their distribution is simply unjust.

Second, caring about sustainability is a matter of intellectual consistency. People are accustomed to caring about cost-effectiveness: one of the key questions about any approach to carbon removal is how much it costs to sequester a ton of CO_2. Commercial actors, of course, need to keep cost-effectiveness in focus to ensure they remain economically viable and competitive. From a public policy perspective, however, the main reason to care about cost-effectiveness is because choosing cost-effective methods of carbon removal leaves societies with more resources to spend on other things they want. That is, cost-effectiveness matters because it enables people to have and do more of what they value. The very same reason justifies concern for sustainability: the environmental and social aspects of sustainability also reflect things that people value, and so this justification for seeking cost-effective methods also justifies seeking sustainable methods. Another reason to care about cost-effectiveness is because there may be limits to how much societies are willing to pay for carbon removal, and so finding cost-effective methods increases the amount of carbon pollution that can be cleaned up. This leads directly to the next reason to care about sustainability.

Third, concern for sustainability is a matter of pragmatism. Just as there are limits to the economic burdens that societies will bear for the sake of carbon removal, there are limits to the social and environmental burdens they will bear. Pursuing carbon removal without concern for its economic, social, and environmental impacts or their distribution—in other words, without concern for its sustainability—risks provoking backlash from affected publics and concerned policymakers. From energy to public health to agriculture, examples abound of technologies and practices that have run aground on public concerns about their economic, social, and environmental risks, either real or perceived. Thus, dismissing sustainability concerns because the world cannot go without carbon removal may well backfire: unless societies take sustainability seriously in developing and deploying carbon removal, the world may end up with less carbon removal rather than more.

Is There Enough Sustainable Carbon Removal?

Some carbon removal advocates fret that imposing sustainability requirements on carbon removal, especially at this early stage, would prevent societies from removing enough carbon to meet the Paris targets. Research on the potential for sustainable carbon removal remains sparse, in part because the concept has yet to be adequately operationalized. The US National Academy of Sciences, however, estimates a global potential to remove 9.13–10.83 billion metric tons of CO_2 per year in ways that would avoid "large potential adverse societal, economic, and environmental impacts,"[11] even though they exclude direct air capture and enhanced weathering for economic reasons and omit almost all ocean-based approaches to carbon removal. Given the large potential contribution from those approaches,[12] that estimate suggests that the global potential for sustainable carbon removal exceeds the roughly 5–15 billion tons of CO_2 projected annually in most of the Paris-compliant scenarios that the IPCC examined in their *Special Report on Global Warming of 1.5°C*.[13]

3. Identifying Sustainable Carbon Removal

To integrate sustainable carbon removal into public policy and private decision making, we need ways to identify sustainable carbon removal. Operationalizing the concept of sustainable carbon removal requires answering two questions:

1. How should we measure the economic, social, and environmental impacts of carbon removal?

2. How should we decide when carbon removal strikes the right balance between future and present needs?

Measuring sustainability

Measuring the impact of a multifarious activity, such as carbon removal, on a vaguely defined outcome, such as sustainability, requires a range of methodological choices. By analogy, suppose that you wanted to measure the impact of exercise on health. Health is a vague outcome in the sense that it can be measured in many different ways. To measure the impact of exercise on health, you will need to choose specific metrics for health. Which metrics you choose—and, just as importantly, which metrics you ignore—will affect your conclusions about the connections between exercise and health. Exercise is a multifarious activity, meaning that there are many ways of exercising. These vary not just in terms of the types of exercise people do, such as swimming or soccer or manual labor, but also in the intensity, duration, and frequency of exercise. Even the context of exercise matters: long-distance running in pristine alpine air produces different effects than running in highly polluted cities, and an exercise regimen that improves a young athlete's health could injure an older, more sedentary person. To measure the impact of exercise on health, therefore, you will need to think carefully about the kinds and contexts of exercise you want to investigate.

Similar issues arise in measuring the impact of carbon removal on sustainability. Thus, questions arise both about how to define the level of analysis and about the metrics for sustainability.

Level of analysis

Just as medical or public health researchers can learn different things by investigating the effects of exercise at different levels of analysis, from broad categories like aerobic exercise or strength training down to detailed analyses of specific exercise regimens on specific populations, researchers can learn different things by studying carbon removal at different levels of analysis.

To date, most evaluations of carbon removal for sustainability have been conducted at the level of broad categories of carbon removal options, such as reforestation, direct air capture, or bioenergy with carbon capture and storage. Yet, each of these categories contains a wide range of different approaches, and each approach could have different sustainability implications in different contexts. Therefore, high-level or "coarse-grained" analyses might yield different results than more "fine-grained" analyses that look at more specific approaches. In this section, we identify and discuss a spectrum of levels of analysis, from a very coarse-grained division of carbon removal approaches down to the most specific. Analyses at different levels serve different purposes and have distinct advantages and disadvantages.

Sabine Fuss and colleagues' excellent synthesis of the scientific literature captures the dominant approach of coarse-grained assessment. Their assessment estimates the cost and carbon sequestration potential of seven types of carbon removal: afforestation & reforestation, BECCS, biochar, enhanced weathering, DACCS, ocean fertilization, and soil carbon sequestration. For each category, Fuss and colleagues

Table 1. Examples of different levels at which to analyze various approaches to carbon removal, using direct air capture (DAC) as an example. The most abstract level in the table treats direct air capture as a single category, to be contrasted with other broad categories of technologies and practices, such as bioenergy with carbon capture and storage (BECCS), enhanced weathering, forestation, or soil carbon sequestration. Each subsequent row of the table becomes more and more specific, until we arrive at the most specific level of analysis, that of specific projects.

Level of Analysis	Example(s)
Coase-grained technologies	Direct air capture (DAC)
Fine-grained technologies	Liquid solvent DAC, solid sorbent DAC, electroswing DAC, carbonate looping DAC
Sociotechnical systems	A privately financed, green hydrogen-fired, liquid solvent DAC facility in a technologically advanced capitalist democracy with strong labor unions, with CO_2 sequestered in offshore geological reservoirs
Specific projects	Carbon Engineering facilities in Texas or Scotland; Climeworks' Orca facility in Iceland

also identify potential social and environmental risks and co-benefits, albeit in a rather vague way.[14] From a sustainability perspective, this level of analysis produces useful qualitative conclusions about the kinds of co-benefits and side effects that deserve attention when considering each kind of carbon removal. For instance, Fuss and colleagues conclude that BECCS could pose a risk to biodiversity and food security: clearing forests to plant bioenergy crops impacts biodiversity and converting arable land from food production to bioenergy production impacts food security. Any assessment of BECCS as a general approach to carbon removal must wrestle with this crucial point.

At the same time, the example of BECCS illustrates the limitations of the standard coarse-grained approach. While it is true that some ways of implementing BECCS pose serious risks to biodiversity and food security, other ways of implementing it could avoid those problems. For example, BECCS that exclusively uses existing waste biomass, such as municipal waste or agricultural waste, as its feedstock would not require diverting natural lands or existing agricultural lands for bioenergy crops. Just because some approaches to BECCS could have dire consequences does not mean we should reject all approaches to BECCS.

One alternative to this coarse-grained approach is to assess more narrowly defined technologies. To see how this works, consider the case of DAC, which uses chemical engineering to capture CO_2 from the atmosphere. To count as carbon removal, DAC needs to be coupled with technologies to store the captured CO_2 (e.g., by injecting it into geological formations) or sequester it in long-lived products (e.g., carbon-negative cement). Even without taking those sequestration technologies into account, there are many different ways to implement DAC, each with different economic, social, and environmental impacts.

Consider some of the established and emerging approaches to DAC. The two best developed approaches both technologies use fans to force air through a carbon-capturing device, and both use heat to release the CO_2 from the chemicals that captured it, but they differ in crucial ways. In particular, one of the technologies requires much higher levels of heat than the other—approximately 900°C (1,650°F) versus approximately 100°C (212°F). Currently the only viable means of producing 900°C heat for this purpose is by burning natural gas or hydrogen. The lower-grade heat for the second technology can be procured not only from natural gas or hydrogen, but also from industrial waste heat or high-temperature geothermal sources. The need to produce and burn natural gas or hydrogen for one of the technologies leads to clear differences in the economic, social, and environmental impacts of these two kinds of DAC: extracting, transporting, and burning natural gas all have important economic, social, and environmental consequences, as do processes for producing and transporting hydrogen. DAC that requires high-grade heat cannot currently avoid those consequences, whereas DAC that requires only low-grade heat can avoid them where viable alternatives are available. Some emerging DAC technologies, by contrast, operate at room temperature, with different sustainability implications.

As this example illustrates, analysts could draw ever more fine-grained distinctions between technologies to tease out different implications. Not only does "high-heat" DAC differ from "low-heat" DAC, but high-heat DAC that burns natural gas differs from high-heat DAC that burns hydrogen, and the implications of hydrogen-fueled DAC would differ depending on how the hydrogen is produced (e.g., by processing natural gas or by using renewable energy to split water molecules). Projections of carbon removal's long-run impacts require some imagination about the variety of ways it could be implemented in decades to come. The DAC technologies of 2050 may or may not resemble those that are available today.

At the limit, assessing a technology would require sketching what scholars of science and technology call a sociotechnical system of use. A sociotechnical system of use includes not just the physical equipment used to achieve some goal, but all of the people and social, legal, political, and infrastructural systems that affect how the equipment operates.[15] As an example, consider cars. The economic, social, and environmental impact of cars depends not just on aspects of the physical car, such as whether it is powered by gasoline, diesel, or electricity, but also on an elaborate system of laws, regulations, driver education, social norms and expectations, and supporting physical and social infrastructure. In the context of natural gas-fueled DAC, relevant parts of the sociotechnical system of use include where and how natural gas is extracted, who profits from that extraction, how the natural gas is transported, regulations on methane leakage, legal liability for environmental damage from these processes, whether and how the CO_2 is transported, who pays whom for capturing and sequestering carbon, and so on. In places where large parts of that system differ, gas-fired DAC will have different economic, social, and environmental consequences. Even more importantly for long-term thinking about DAC or other approaches to carbon removal, the impacts of carbon removal will change as the sociotechnical systems around them change.

Describing complete sociotechnical systems, of course, is difficult and time-consuming. While doing so would enable more accurate analyses of economic, social, and environmental impacts, taking a narrower view of technologies as types of physical equipment will often prove more practical. There is, however, a straightforward alternative that captures many of the benefits of assessing entire sociotechnical systems: assessing specific carbon removal projects.

Evaluating specific carbon removal projects makes it possible to focus on specific combinations of technologies in a specific context, without having to conjure up hypothetical sociotechnical systems. As an example, consider a Canadian bio-asphalt project being developed by a company called Ensyn. The project would take "sawdust and other woody debris" from specific lumber mills that "process forest or managed plantations" in Canada; deliver that debris by truck to specific pyrolysis facilities that are, on average, about 55 miles away; heat the debris into biochar using Ensyn's fast pyrolysis technology; and then transport the biochar to asphalt factories to be incorporated into asphalt, which would be used for paving roads and other surfaces in eastern Canada.[16] The details of this project make it possible to investigate not only the lifecycle emissions and costs of the process, but also the social and environmental implications of using this debris from these particular lumber mills that source lumber from particular forests and plantations and use the resulting biochar

Assessing Carbon Removal at Multiple Scales

Another dimension of assessment cuts across the levels of analysis discussed here: it is important to evaluate carbon removal approaches at multiple scales, since many of the effects of an approach depend on the scale at which it is implemented. For example, a small BECCS plant might run sustainably using waste biomass from nearby farms, but that doesn't necessarily mean that a large BECCS plant could do so. Even afforestation could push into inappropriate areas if scaled up far enough.

To assess carbon removal at multiple scales, analysts must attend to two competing forces. On the one hand, scaling up a particular approach often means being able to take advantage of economies of scale and learning by doing. On the other hand, scaling up a particular approach could mean exhausting the sustainable supply of one or more inputs. The most obvious examples here involve carbon removal using waste products, such as enhanced weathering from industrial byproducts, but similar concerns arise for land, non-waste biomass, clean electricity and hydrogen, and so on.

One final point concerns the efficacy of natural climate solutions at scale. Natural climate solutions will likely sequester different amounts of carbon in different places. Analysts cannot safely extrapolate from studies in specific locations to infer the overall potential of an approach. Estimating the regional or global potential for natural climate solutions is therefore especially difficult.

in particular ways. Notably, many of the social and environmental implications of this biochar project differ from the more commonly discussed projects that use biochar as a soil amendment, and so conclusions about biochar in general may not apply to this project or vice versa.

Different levels of analysis—from coarse-grained analysis of technological categories to very fine-grained analysis of individual projects—offer different advantages and disadvantages. Coarse-grained analyses require less information and enable high-level comparisons between approaches. They also illuminate the kinds of risks and co-benefits that can come from various approaches, which can guide developers, regulators, and analysts toward the most beneficial approaches within a particular category. By blurring together different technologies, practices, and sociotechnical systems, however, they cannot be used for detailed or conclusive sustainability assessment. More fine-grained analyses, by contrast, enable more detailed sustainability assessments and more decisive comparisons, but they require more information and do not always provide generalizable insights. In short, coarse-grained analyses can provide broad insights and general guidance, while fine-grained analyses can provide more actionable information about particular projects or technologies.

Regardless of the level of analysis, however, the second outstanding question about identifying sustainable carbon removal concerns which metrics to use.

Metrics for sustainability

Many assessments of carbon removal focus on dollars and tons: they ask how many tons of CO_2 can be removed and how much money it would cost per ton to remove it. These are important metrics, of course, but they capture only the economic aspect of sustainability (and only one part of that aspect). Rigorous assessment of sustainability in carbon removal requires identifying additional metrics by which to measure other economic aspects of sustainability, such as the impacts of carbon removal on poverty, as well as the broader social and environmental impacts.

The question is which metrics we should use. One possibility, which is currently being explored by some scholars, is to use the Sustainable Development Goals (SDGs) as a way to assess carbon removal's economic, social, and environmental impacts. The SDGs comprise seventeen broad goals, such as eliminating poverty and promoting responsible consumption and production, that were endorsed by all United Nations member states in 2015. To operationalize the broad goals, negotiators translated each goal into a set of more detailed targets and then identified specific indicators with which to measure progress toward individual SDGs. The targets specify desired outcomes by 2030, which is not immediately relevant to most

Figure 2. Icons and titles for the Sustainable Development Goals. (Source: United Nations)

approaches to carbon removal because of how long it will take to research, develop, and scale most approaches. The indicators, however, provide metrics that can be used on any timeframe. Thus, the SDGs and their respective indicators represent a publicly negotiated global consensus on what matters most for social and environmental sustainability. This makes them appropriate benchmarks for scientific assessments of the sustainability of negative emissions technologies.

Figure 2 shows the seventeen SDGs. Because these seventeen high-level goals are measured along 232 unique indicators underlying dozens of targets, the relationship between goals, targets, and indicators is best illustrated by example. Consider SDG 2, which is to "end hunger, achieve food security and improve nutrition and promote sustainable agriculture." Target 2.3 is to "double the agricultural productivity and incomes of small-scale food producers" by 2030. This, in turn, is to be measured by looking at two indicators: the "volume of production per labour unit by classes of farming/pastoral/forestry enterprise size," and the "average income of small-scale food producers, by sex and indigenous status."

Many of the SDG indicators are directly relevant to various kinds of carbon removal. Others have no clear connection, although it is worth noting that because climate change negatively impacts most SDGs,[17] the climate benefits of carbon removal indirectly affect many indicators in ways that do not depend on the approach being used. Sticking with the indicators listed above, fo spreading crushed basalt on cropland can boost agricultural yields while capturing carbon through mineralization, large-scale afforestation could reduce food security through competition for arable land, and agroforestry can boost income of small-scale food producers while capturing carbon in trees.[18] To illustrate the range of connections, Tables 2 and 3 describe the potential impacts of different approaches to carbon removal on a half dozen relevant SDG indicators. Table 2 describes potential impacts of two different approaches to forestation: monoculture carbon farms, in which a single tree species is planted and managed in ways that maximize carbon uptake, and forest restoration, in which recently deforested lands are allowed or encouraged to regrow into biodiverse forest ecosystems. Table 3 describes the potential impacts of two different approaches to BECCS: large-scale BECCS using dedicated energy crops, such as switchgrass, and the burning of agricultural wastes for centralized energy production, such as the burning of palm kernels at the Mikawa power plant in Japan. Neither table exhaustively catalogs the SDG impacts of either approach, but they illustrate the variety of connections between carbon removal and the SDGs and the importance of fine-grained analyses.

As metrics for sustainability, the SDG indicators are certainly not exhaustive. In particular, the indicators attached to SDG 13 ("Climate Action") focus almost entirely on procedural inputs to climate action and do not include any metrics of climate change or its immediate drivers: neither global average temperature nor greenhouse gas concentrations nor emissions appear as indicators. In general, though, the SDG indicators provide useful metrics for sustainability and illustrate the kinds of concrete metrics that can be used to measure different aspects of sustainability.

Researchers have begun to explore the connections between the SDGs and various approaches to carbon removal. This research remains mostly qualitative at this point: it can tell us which approaches have positive or negative impacts on which SDGs, but they say little about whether those impacts are large or small, either in absolute terms or relative to an approach's other impacts. The existing studies analyze each approach at a very coarse-grained level, but they do imply that different ways of implementing each approach and different kinds of policy can improve the overall sustainability of each approach. In other words, the existing research can give us a general picture, but little detail.

Table 2. Potential impacts of two different approaches to forestation on selected indicators for the Sustainable Development Goals (SDGs).

SDG Indicator	Monoculture Carbon Farms	Forest Restoration
1.1.1. Proportion of population below the international poverty line	Could impoverish some people by displacing marginalized people or denying them access to land; but could also help bring some people out of poverty by providing a source of employment	Could impoverish some people by displacing marginalized people or denying them access to land; but it could also help bring some people out of poverty by providing income, food, or fuel
1.4.2 Proportion of total adult population with secure tenure rights to land	Could force people off of lands that they use	Could force people from lands that they use; but could be done in ways that strengthen land rights for, e.g., indigenous groups
2.1.2 Prevalence of moderate or severe food insecurity in the population	Could increase food insecurity by competing for arable land; but could also reduce food insecurity for some by providing a source of employment	Could increase food insecurity by competing for arable land; but could also provide a source of food
6.1.1 Proportion of population using safely managed drinking water services	Could decrease water quality through fertilizer run-off	Would improve quality of surface water
8.5.2 Unemployment rate, by sex, age and persons with disabilities	Tree nurseries and farm management could provide jobs in rural communities; loss of farmland could reduce employment	Loss of farmland could reduce employment; employment opportunities related to forest restoration depend on implementation
15.1.1 Forest area as a proportion of total land area	Would increase forested area using standard metrics, but not in ways that promote sustainable forestry or biodiversity	Would increase forest area in ways that enhance sustainable forestry and biodiversity

Table 3. Potential impacts of two different approaches to bioenergy with carbon capture and storage (BECCS) on selected indicators for the Sustainable Development Goals (SDGs).

SDG Indicator	Large-Scale BECCS Using Dedicated Bioenergy Crops	BECCS Using Agricultural Wastes
2.1.2. Prevalence of moderate or severe food insecurity in the population	Could increase food insecurity by competing for arable land, thereby limiting access to land for growing food and/or increasing food prices	Could reduce food insecurity by boosting incomes in rural communities
2.3.2 Average income of small-scale food producers, by sex and indigenous status	Could increase income for food producers by increasing food prices and providing additional revenue streams	Could provide an extra source of income to small-scale food producers
6.4.2. Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	Increase in water stress due to additional water demand for irrigating bioenergy crops	No direct effect, although increase in overall value of a crop could induce some extra demand for irrigation
7.2.1. Renewable energy share in the total final energy consumption	Add bioenergy to the overall energy supply	Add bioenergy to the overall energy supply
9.4.1. CO_2 emission per unit of value added	Reduce carbon intensity of the economy by providing carbon-negative energy	Reduce carbon intensity of the economy by providing carbon-negative energy
12.3.1. (a) Food loss index and (b) food waste index	No direct effect; possible indirect effects caused by increase in food prices	Reduces food loss by repurposing agricultural wastes for productive use

The rough outline of that picture is that natural climate solutions tend to support sustainable development, with one important caveat, and that the sustainability implications of more technological approaches to carbon removal tend to be mixed, with each approach having some positive impacts and some negative impacts. Many of these impacts depend crucially on the details and context of implementation, sometimes even flipping from positive to negative or vice versa. The caveat about natural climate solutions is that very large scale forestation would involve trade-offs with certain SDGs because it would require so much land. Appendix B summarizes the recent research on this topic in more detail.

Weighing risks and benefits

Estimating the social, environmental, and economic impacts of a carbon removal technology or practice does not, by itself, answer the question of its sustainability. We also need to weigh the risks and benefits to see whether the technology's long-term and near-term benefits justify the burdens it imposes on current generations. The diversity of risks and benefits make this difficult. In this section, we discuss three approaches to weighing risks and benefits: an intuitive approach, benefit-cost analysis, and multicriteria decision analysis.

The intuitive approach involves compiling the risks and benefits of an approach, perhaps with the aid of data visualization techniques, and then making intuitive judgments, in light of distributional concerns, about whether the near-term and long-term benefits of a technology justify the burdens it imposes. This is the simplest approach, but it suffers from obvious shortcomings: different people might make different judgments about the same case, and the approach offers no systematic way to resolve such disagreements. The approach imports subjective preferences and biases without forcing anyone to articulate them, which can make it hard to identify the sources of disagreements, much less debate them. In some cases, however, the weight of risks over benefits (or vice versa) could be clear enough that most people would agree, especially when comparing two different technologies rather than making an overall judgment about one approach.

Benefit-cost analysis involves converting all of the benefits and costs of an activity to a common unit of measurement, weighting the benefits and costs to capture concerns about equity and the timing of costs and benefits, and then determining whether the benefits exceed the costs. This is more time-consuming than the intuitive approach, and it requires analysts to make difficult choices about equity weighting, discounting future costs and benefits, and deciding how to quantify seemingly unquantifiable things and compare seemingly incommensurate things. It does, however, provide a more systematic approach that makes key assumptions explicit, making it easier to diagnose disagreements (but not necessarily to resolve them). It gives a satisfyingly concrete, numerical answer to the question of whether the benefits outweigh the costs, but that concreteness should not be mistaken for value-neutrality or indisputability. The choices needed to quantify and compare the diverse costs and benefits of carbon removal require value judgments that can significantly affect the results of the analysis.

Multicriteria decision analysis (MCDA) offers a way to evaluate and compare alternative solutions to a problem, especially when the solutions differ in ways that are hard to compare. This makes it especially suitable for sustainability assessments. Roughly, MCDA involves several steps: identifying the alternatives, identifying criteria by which to evaluate alternatives, weighting those criteria according to some set of preferences, and then ranking the alternatives based on their performance on the weighted criteria.[19] Compared to benefit-cost analysis, MCDA involves more explicit statements of the judgments used in comparing alternatives. Since choosing and weighting criteria is ultimately a political activity, making these value judgments explicit enables more transparent public debate about carbon removal.

A recent MCDA of carbon removal by Oscar Rueda and colleagues illustrates the process and its relevance to sustainability assessments. Rueda and colleagues compared seven approaches to carbon removal on nine criteria. Some weightings focus on feasibility, some on effectiveness, some on sustainability, some on risk, and so on. Based on each approach's performance on those nine criteria, they designed seven "optimal" portfolios based on different ways of weighting the criteria. These portfolios differ significantly. Rueda and colleagues conclude, for instance, that focusing primarily on economic feasibility leads to a portfolio composed mainly of forestation, soil carbon sequestration, and biochar, with some enhanced weathering; focusing mainly on effectiveness in reducing climate change yields a portfolio composed entirely of DACCS, enhanced weathering, and BECCS; and focusing on sustainability leads to a mix of forestation, soil carbon sequestration, biochar, and DACCS.[20] The upshot is that different approaches offer different risks and benefits, and that the optimal mix of approaches to carbon removal will differ markedly depending on how societies weight those risks and benefits. It is worth noting that Rueda and colleagues use broadly defined technologies and rely on qualitative judgments about sustainability. Their study demonstrates the value of MCDA for carbon removal and provides important insights about the pros and cons of different baskets of approaches to carbon removal. Complementing such high-level analyses with MCDAs of fine-grained technologies would provide even greater value and guidance for policymakers and civil society.

Finally, it is worth noting that these approaches can also be used to compare cases that involve carbon removal to ones that does not. In which cases, if any, do the climatic benefits of carbon removal, plus any co-benefits from carbon removal, justify the downsides? Making this comparison allows analysts to consider whether carbon removal really improves the prospects for future generations without unduly burdening current generations.

5. Conclusion

Farmers, foresters, ecologists, and engineers have identified a wide range of ways to permanently remove CO_2 from the atmosphere. These technologies and practices can help us halt global warming sooner, meet the goals of the Paris Agreement, and gradually restore a safer climate. The challenge now is figuring out how to implement carbon removal in environmentally, socially, and economically sound ways—that is, figuring out how to implement sustainable carbon removal.

Identifying and developing sustainable approaches to carbon removal means refining the ways that we evaluate carbon removal. In particular, evaluations need to move beyond broad technological categories to examine the impacts of more specific technologies and take account of the social conditions in which they get implemented. Furthermore, evaluating carbon removal involves weighing the climatic benefits of cleaning up carbon pollution together with the co-benefits and downsides of each approach. Given the complex trade-offs involved, assessments of carbon removal can benefit from approaches that make their assumptions and value judgments explicit.

Appendix A. Introduction to Carbon Removal

What is carbon removal?

Carbon removal, also known as carbon dioxide removal (CDR) or carbon drawdown, is the process of capturing carbon dioxide (CO_2) from the atmosphere and locking it away for decades or centuries in plants, soils, oceans, rocks, saline aquifers, depleted oil wells and other geological reservoirs, or long-lived products like cement. Scientists have proposed many different methods of carbon removal. Some of these are already in use at relatively small scales, whereas others remain in the early stages of research and development. Technologies and practices for implementing carbon removal are often called negative emissions technologies (NETs).

Carbon removal is not the same as carbon capture

Although they are often conflated, carbon removal is importantly different than fossil carbon capture and use or storage (fossil CCUS). Carbon capture and storage (CCS) captures CO_2 from a smokestack or flue, such as in a gas-fired power plant or a cement factory, and then sequesters that CO_2 underground. Processes that capture CO_2 and use it to produce commercial products, such as methanol or cement, are known as carbon capture and use. CCUS includes either process. We use the term "fossil CCUS" to identify processes where the carbon in the captured CO_2 comes from fossil fuels or carbonate minerals.

The distinctions between carbon removal and CCUS are easily blurred—and are sometimes deliberately blurred—because both involve capturing CO_2 and because a few approaches to carbon removal incorporate some of the same equipment and process steps as fossil CCUS. Nonetheless, neither fossil CCUS nor the use of captured CO_2 in short-lived products, such as synthetic fuels, counts as carbon removal. This is not just a semantic point: maintaining a clear distinction between carbon removal and CCUS matters because, unlike carbon removal, fossil CCUS cannot actually draw down atmospheric CO_2 levels. To say this more simply: carbon removal removes CO_2 from the atmosphere, while fossil CCUS can only reduce the amount of CO_2 entering the atmosphere. Proponents argue that fossil CCUS could play a valuable role in climate policy, but it is crucial to recognize that fossil CCUS and carbon removal would play very different roles in long-term climate strategies.[21]

Carbon removal brings co-benefits and concerns

There are many different ways to remove CO_2 from the atmosphere, and each method comes with its own co-benefits and concerns. Many of these co-benefits and concerns depend on the social and environmental context in which carbon removal is carried out.

There are, however, two general concerns that people have about carbon removal. The first is the prospect of a “moral hazard effect” in which policymakers or other actors might use the prospect of carbon removal—especially the prospect of large-scale carbon removal in the distant future—as an excuse to avoid cutting CO_2 emissions now. Second, some people worry that counting on large-scale carbon removal in the future amounts to a high-stakes gamble with future generations’ welfare: if we emit more CO_2 now with the intention of removing it later, but carbon removal proves infeasible for any reason, then we will have saddled future generations with a worse climate than necessary. The converse is also true, however. It will take decades to scale up carbon removal technologies and practices to the point where they can significantly affect the climate. So, if we put off research and development, but we end up eliminating greenhouse gas emissions more slowly than hoped, we will also saddle future generations with a worse climate than necessary.

Carbon removal technologies and practices

This section describes several of the most widely discussed approaches to carbon removal.

Biochar

Biochar is a kind of charcoal produced by heating biomass in a low-oxygen environment. When buried or ploughed into soils, it locks carbon away for decades or centuries while enhancing soil quality. Biochar can also be used in building materials. The amount of carbon ultimately removed with biochar depends on what kind of biomass is used, how it is sourced and heated, whether the soils are eventually disturbed, and other details of the process.

Bioenergy with carbon capture and storage (BECCS)

Bioenergy with carbon capture and storage (BECCS) involves growing or collecting biomass, processing it, converting it to biofuels or energy, capturing the resulting CO_2, and storing it underground or in long-lasting products. There are many different ways to implement BECCS, depending on whether the biomass is purpose-grown or collected from agricultural wastes, forest residues, or other sources; whether it is converted to liquid or gaseous fuels or pelletized and burned to generate heat or electricity; whether it is sequestered in depleted oil fields, saline aquifers, basalt formations, or long-lasting products; and so on, all with major implications for BECCS' climate impact and sustainability.

Direct air capture with carbon storage (DACCS)

Direct air capture with carbon storage (DACCS) refers to processes that capture CO_2 with purpose-built machines and store the CO_2 in the same kinds of geological reservoirs or long-lasting products used for BECCS. These machines capture CO_2 from ambient air using various chemical processes and then separate the CO_2 for sequestration. Whereas other forms of carbon removal take various kinds of natural materials, such as biomass or rocks, as their primary inputs, the primary input in DACCS is energy. The most mature direct air capture (DAC) technologies require both heat and electricity, but several companies are developing DAC technologies that only require electricity.

Enhanced mineralization

Enhanced mineralization involves accelerating the natural processes by which various minerals absorb CO_2 from the atmosphere. The process begins by mining specific kinds of rock, such as olivine or basalt. One prominent proposal for implementation would involve grinding those rocks into powder and spreading the powder over soils, where it would react with the air to form carbonate minerals. Other options include exposing powdered rock to CO_2-rich fluids or spreading it over the ocean. Enhanced mineralization remains at the very early stages of research and development, but the long-term potential may be quite large.

Forestation

Forestation involves planting trees over large areas or allowing forests to regrow naturally. Growing trees on land that was recently covered in forest is called reforestation; growing trees on land that has not been recently covered in forest is called afforestation. Forest restoration refers to helping degraded forests recover their natural forest structure and rebuild ecological processes and biodiversity. Agroforestry, in which farmers integrate trees into agricultural practices, is sometimes counted under the heading of carbon removal, too. These new or restored forests would absorb carbon in both the trees and the soil as they grow, with the rates and side effects depending on the mix of trees being planted and whether the forest regains its natural ecological functions. Forests would sequester the captured carbon for as long as they remain standing, which means that, as with other biological methods of carbon removal, the climate benefits of forestation are reversible.

Ocean-based approaches

Scientists are exploring a wide variety of ocean-based approaches to carbon removal. These include the restoration of ocean and coastal ecosystems, such as mangroves, oyster reefs, kelp forests, and open-ocean ecosystems; fertilizing the ocean with micro- or macronutrients; artificial upwelling and downwelling; electrochemical approaches, such as processes that react seawater with limestone to produce hydrogen and bicarbonate; adding alkaline materials, such as lime, to the ocean; and cultivating seaweed for bioenergy or to sink into the deep ocean. Aside from restoration of coastal habitats, most of these approaches remain in the early stages of research.

Soil carbon sequestration

Soil carbon sequestration refers to a number of different practices for increasing the amount of carbon stored in soils, especially agricultural soils. Prominent examples include no-till agriculture, manuring, and cover crop rotation. Because they improve soil quality, these practices can contribute to improved crop yields and help protect fields against both floods and droughts. Soil carbon sequestration methods are already in use and ready to scale up, but major challenges remain, including encouraging widespread adoption and ensuring long- term maintenance of the practices to keep the carbon in the ground.

Appendix B. Research on Carbon Removal and the Sustainable Development Goals

Several recent studies have examined how carbon removal could affect the Sustainable Development Goals (SDGs). Strictly speaking, each study examines how carbon removal affects the kinds of social, environmental, and economic goods at stake in the SDGs. The studies do not address whether any of these approaches could contribute to the specific, time-sensitive targets established as part of the SDGs.

Pete Smith and colleagues consider how six different approaches to land-based carbon removal could affect the SDGs.[22] Specifically, they examine afforestation/reforestation, wetland restoration, soil carbon sequestration, biochar, terrestrial enhanced weathering, and bioenergy with carbon capture and sequestration (BECCS). For each approach, they proceed one-by-one through the top-level SDGs, identifying specific positive or negative impacts that approach could have on each SDG. Their analysis is entirely qualitative; they make no attempt to quantify the impacts or to weight them. Only occasionally do they distinguish between different ways of implementing a particular approach, as when they distinguish the impacts of agroforestry from the impacts of other kinds of forestation on SDG 2 ("Zero Hunger").

Smith and colleagues conclude that all of the approaches have positive impacts on at least some SDGs, but that most of them could also have some negative impacts. All of the approaches, they note, would positively impact SDG 13 ("Climate Action"). The other impacts differ from approach to approach and vary with the details of implementation, although one common theme is that approaches that require a lot of land, such as many varieties of BECCS afforestation/reforestation, would have serious negative impacts if implemented at large scales. They identify wetland restoration and soil carbon sequestration as "no-regrets options" that offer "almost exclusively positive impacts" for sustainability and ecosystem services.[23]

In a similar project, Matthias Honegger and colleagues surveyed recent authoritative reports, scientific papers, and relevant experts to identify SDG-relevant impacts of carbon removal.[24] They lump approaches to carbon removal into six categories: BECCS, direct air capture with carbon sequestration (DACCS), afforestation/reforestation, soil carbon sequestration and biochar, terrestrial and marine enhanced weathering, and ocean fertilization. For each category, they identify effects that would have positive or negative implications for each relevant SDG. For instance, in discussing enhanced weathering and its implications for SDG 1 ("No Poverty") and SDG 2 ("Zero Hunger"), Honegger and colleagues note that enhanced weathering could boost crop production and fisheries, although excessive application could reverse those effects. Thus, they conclude that enhanced weathering would have a positive or theoretically ambiguous—that is, either positive or negative—effect on SDG 1 and SDG 2. Like Smith and colleagues, Honegger and colleagues do not attempt to quantify these impacts.

In general, Honegger and colleagues find quite varied effects for each category of carbon removal on the SDGs. They note that carbon removal, as a whole, "is overall expected to contribute substantially to SDG-13 [Climate Action] by complementing deep and fast reductions in [greenhouse gas] emissions," but they also warn that carbon removal "might underperform compared to expectations."[25] For every category of carbon removal they consider, they identify negative impacts on some SDGs, but they also identify positive impacts or ambiguous impacts that could be positive or negative. In most cases, those ambiguities arise because the impact depends on the details of how carbon removal gets implemented. In other cases, the ambiguities arise because an impact would be good for some people or regions but bad for others. For instance, they note that biomass production for BECCS or reforestation would affect water runoff, increasing water storage upstream but reducing water runoff downstream.[26] Finally, some ambiguities arise from scientific uncertainty about impacts. Honegger and colleagues provide useful tables summarizing their conclusions about each approach.

Jay Fuhrman and colleagues offer similar analyses, but they also go a step further to try to rate the overall impact of an approach on each SDG as positive, negative, or ambiguous.[27] Based on Smith and colleagues' research and additional impacts identified in the scientific literature, Fuhrman and colleagues evaluate seven broad approaches to carbon removal in terms of their potential for "tradeoffs" and "synergies" with the SDGs. With respect to each relevant SDG, they assign a score to each approach, ranging from "high potential for tradeoffs" through "no or uncertain impact" to "high potential for synergies." The supplemental information that they published online with their paper provides a useful table summarizing the bases for their judgments.[28] In cases where an approach involves both synergies and tradeoffs, this scoring requires the authors to make subjective, implicit estimates and weightings of those impacts. Their conclusions about the SDG impacts of carbon removal largely align with those of Smith and colleagues, in part because they lean heavily on Smith and colleagues' analysis.

Looking across all three studies, several themes and lessons emerge.

First, natural climate solutions tend to be most closely aligned with the SDGs in the sense that, at a purely qualitative level, their impacts tend to promote sustainable development with only limited trade-offs, though the studies do not tell us whether the benefits would be large or small. One crucial exception to this generalization about natural climate solutions, however, is that large-scale afforestation or reforestation could negatively impact a number of SDGs, especially SDG 1 ("No Poverty") and SDG 2 ("No Hunger"), depending on how and where forestation is done. This follows from the general principle that approaches that require large amounts of dedicated arable land come at significant social cost and potentially high environmental cost.

Second, more technological approaches to carbon removal have more mixed implications for sustainable development. For each of these approaches, each author team concluded that the approach would have positive impacts for some SDGs and negative impacts for others. In many cases, the same approach could have positive and negative impacts on the same SDG. This could happen, for instance, because different parts of the process have different effects or because the effects would benefit some people but harm others. In many cases, the effects depend on the particular ways in which each approach gets implemented.

Third, the studies generally make no attempt to quantify or weight the various impacts within each SDG, much less between them. Fuhrman and colleagues offer subjective scores that try to balance positive and negative impacts, where necessary, but they have a fairly limited amount of evidence on which to base those evaluations. Much more research is needed to quantify the impacts, especially in different contexts and at different scales, and to evaluate each approach in light of different weightings of those impacts. Crucially, these analyses do not take into account any attempt to quantify the climate benefits of the different approaches. Some approaches have the potential to remove much more carbon from the air than others do, yielding both a much stronger impact on SDG 13 ("Climate Action") and stronger indirect effects on the other SDGs. Coastal blue carbon might be more closely aligned with the SDGs than DAC, for instance, but its carbon removal potential is comparatively tiny. This needs to be taken into account when evaluating different approaches.

Finally, all three studies consistently find that different ways of implementing these approaches would have different implications for sustainable development. In other words, assessing carbon removal using coarse-grained technological categories provides a blurry picture of carbon removal's social, environmental, and economic impacts. Sharpening that picture requires analyzing sustainability impacts in a more fine-grained way.

Notes

1. Pierre Friedlingstein et al., "Global Carbon Budget 2020," *Earth System Science Data* 12, no. 4 (2020): 3269–3340, https://doi.org/10.5194/essd-12-3269-2020
2. The science behind this claim is more complicated than one might expect. Once humans stop adding CO_2 to the atmosphere, CO_2 levels will begin to fall as the land and ocean naturally absorb some of that CO_2. The oceans, however, absorb not just CO_2, but also much of the excess heat trapped by greenhouse gases, and this process will slow down as the oceans warm, leaving more heat in the atmosphere. These two processes—declining amounts of heat-trapping CO_2 and declining amounts of heat absorbed by the oceans—will more or less balance each other for a long time, so that global average temperature will remain more or less stable. For an accessible explanation, see: Zeke Hausfather, "Explainer: Will Global Warming 'Stop' as Soon as Net-Zero Emissions Are Reached?," *Carbon Brief*, April 29, 2021, https://www.carbonbrief.org/explainer-will-global-warming-stop-as-soon-as-net-zero-emissions-are-reached
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5. Whether the world can avoid 1.5°C or 2°C of warming without carbon removal remains a fraught question, as does the question of whether we can still avoid 1.5°C even with carbon removal. There are some conceivable scenarios under which reforestation and traditional mitigation—switching to renewable forms of energy, low-carbon agriculture and lifestyles, and fossil fuel-free forms of transportation—will be enough on their own to keep the world below 2°C or even 1.5°C of warming. These scenarios, though, rest on heroic assumptions about social and

technological change and become less likely day by day as greenhouse gas concentrations in the atmosphere continue to rise. While our position is that some significant amount of carbon removal will be necessary to meet the Paris targets, the fact that carbon removal can help stop warming sooner makes it worthwhile regardless of whether it is necessary to meet certain political targets.

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Abbreviations

BECCS	Bioenergy with carbon capture and storage
CCS	Carbon capture and storage (also: carbon capture and sequestration)
CCUS	Carbon capture and use or storage
CDR	Carbon dioxide removal
CO_2	Carbon dioxide
DAC	Direct air capture
DACCS	Direct air capture with carbon storage
IPCC	Intergovernmental Panel on Climate Change
MCDA	Multicriteria decision analysis
SDG	Sustainable Development Goal

Institute for Carbon Removal Law and Policy

As a supplement to cutting greenhouse gas emissions, the world could further reduce climate risk by actively removing carbon dioxide from the atmosphere. The Institute for Carbon Removal Law and Policy is dedicated to assessing the social, legal, ethical, and political implications of carbon removal technologies and practices and to facilitating engagement on these issues by key stakeholders and the public. The Institute is an initiative of the School of International Service at American University in Washington, DC.

Sustainable Carbon Removal

Carbon Removal Briefing Paper No. 3
October 2021

www.american.edu/sis/carbonremoval

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