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# Ensuring the environmental sustainability of emerging technologies for carbon dioxide removal

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# Introduction

Some technologies developed to combat climate change have adverse side effects in other domains, from the environment to society and geopolitics, as well as on different scales and time frames. They may not fully satisfy the conditions of sustainability, defined as the ability to meet current needs without compromising the ability of future generations to meet their own needs, along with supporting the aims of environmental protection, social equity and economic viability. This paper addresses the challenge posed by the potential deployment of emerging techniques for the large-scale removal of carbon dioxide ($CO_2$) from the atmosphere (grouped under the term carbon dioxide removal, CDR). While some technologies are already mature from a development perspective, they have not yet been deployed at scale. Deployed at large scale, these techniques could cause damage to the environment or the climate itself, i.e., constituting an environmental sustainability risk. Written for the EPFL International Risk Governance Center's (IRGC) project, the paper describes some potential risks of deployment of CDR techniques alongside prospective benefits, as well as emphasizing the insufficient knowledge available today to inform policy decisions on the extent to which we should encourage or mandate deployment of some of these techniques. There are reasons to worry today because, on the one hand, CDR is likely to be critical for stabilizing and eventually reducing $CO_2$ atmospheric concentration; on the other hand, it seems it will not be possible to do so without some degree of countervailing risks elsewhere.

Increasingly tense and fraught discussions are underway around the use of emerging technological options to help address climate change and stabilize the climatic system. For instance, direct air capture with carbon storage (DACCS) utilizes very large fans to remove $CO_2$ directly from the air. Bioenergy with carbon capture and storage (BECCS) emphasizes growing and harvesting plants as a source of energy and, by capturing emissions, a means for carbon storage. Enhanced weathering works by increasing the ability of rocks to absorb $CO_2$ from the atmosphere. Biochar removes carbon by converting organic material, whether from plants or animals, into a form of high-carbon charcoal.

Based on a large sample of expert interviews undertaken for the GeoEngineering and Negative Emissions Pathways in Europe (GENIE) project, which offers an interdisciplinary, holistic perspective of CDR technologies to understand conditions under which they might be deployed at scale, an early consensus seems to be emerging wherein risks abound no matter which emergent options are supported and/or deployed by scientists, policymakers, or the public. As one of our expert respondents put it:

> “Energy system transition is like a game of poker. We won't know which technology will work; we don't have good predictive skills for technologies like solar that are already a decade ahead. Think back: for technologies in the 1950s, how much predictive skill did we really have for 2050? Imagine how actors then would have distributed their bets. It's a monumental challenge.”

Another explained that:

> “There are huge investment risks with deploying climate engineering: where to put the money, where to put the finance, where to create markets. There are risks everywhere. It comes down to how you talk about technology transitions, deal with futures, anticipate problems and integrate them into policy development.”

Our systematic analysis of these interview data revealed no fewer than 12 different baskets of risk, which we have termed “risk-risk trade-offs” to underscore that climate action undertaken to mitigate the worst impacts of climate change does not ultimately eliminate all risks. As the diagram suggests, attempts to address risk in one area can exacerbate risk in another dimension. Moreover, these risk-risk trade-offs cut across different dimensions, including institutions and governance, technology and the environment, and behavior and future generations (see Figure 1).

In this paper, we focus primarily on the environmental risks of four CDR technologies: BECCS, DACCS, enhanced weathering, and biochar, which are still “emerging” in the sense that most are at the stage of experimentation and testing, but there is no demonstration or deployment on the scale that would be required to reach the potential levels needed to help address climate change. Each of the four technologies presents potential threats that may manifest only in the long term and which remain challenging to identify and assess on the basis of what we now know – even though such knowledge is crucially needed to support informed (evidence-based) decisions. For each technology, and based on GENIE data, we identify and describe the environmental risks of deployment and some positive co-benefits, while also highlighting the possible environmental risks of not deploying, i.e., the risks of not taking action to try and mitigate climate change. This enables a broader and more comprehensive assessment of risk-risk trade-offs across space, time, and in diverse sectors.

## 1.

## Bioenergy and carbon capture and storage (BECCS)

BECCS involves harnessing specific energy crops (e.g., perennial grasses, or short-rotation coppicing) or increased forest biomass in order to replace fossil fuels and to remove $CO_2$ by capturing and storing underground the emissions that result from the burning of the biomass. Similarly, if biogenic $CO_2$ is captured (e.g., $CO_2$ captured from a biogas plant or bioenergy), negative emissions are generated given that $CO_2$ is removed from the atmosphere. Because this technique is so tightly coupled to bioenergy systems, myriad environmental risks can accompany the deployment of BECCS. In particular, to reach the scale needed to help address climate change, it would have to expand to the scale of billions of tons of additional production of fuels or building materials per year (Parson & Buck, 2020). R093[2] added that BECCS would “need land and huge amounts of water,” and R124 warned that “rivers could run dry with widespread deployment of BECCS.” Studies have confirmed both the land intensity and water intensity of BECCS (Creutzig et al., 2012, 2015). R037 articulated that “large-scale BECCS and afforestation will negatively affect food security,

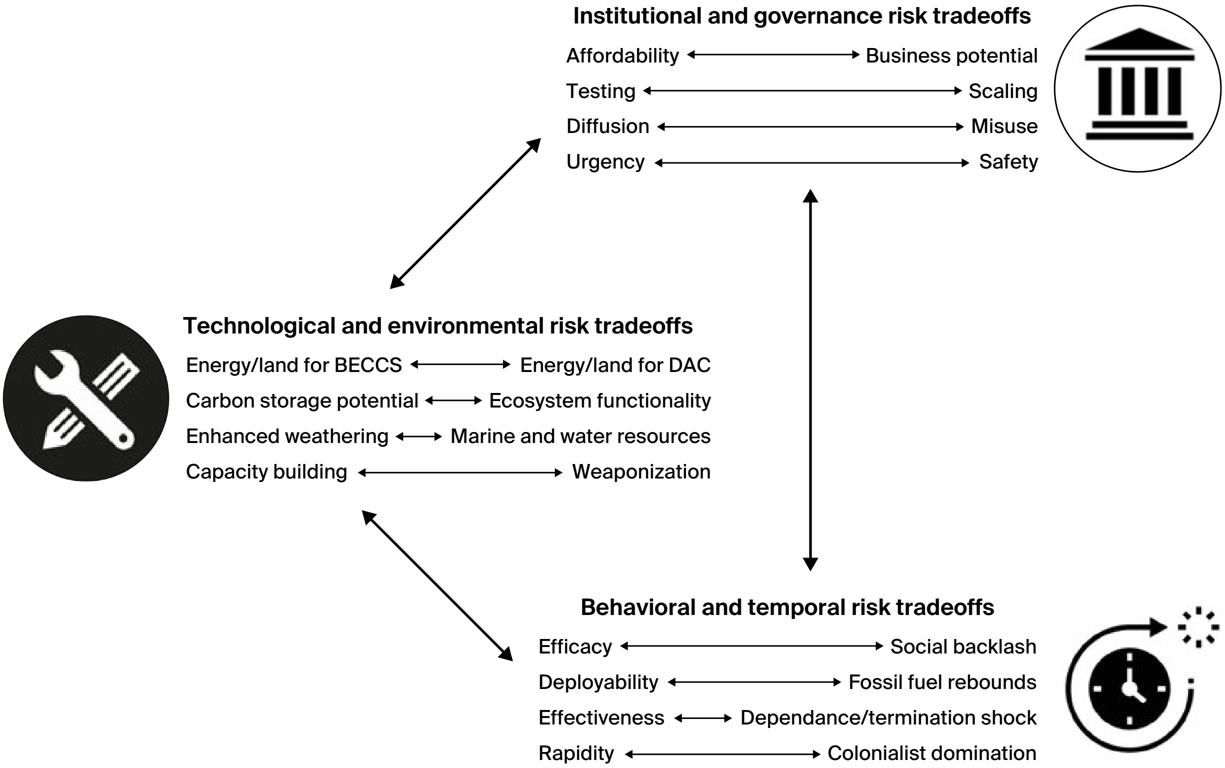

**Figure 1** | Institutional, technological and behavioral trade-offs that may emerge from climate engineering deployment (reprinted from Sovacool, Baum, & Low, 2022b). Note: rationales for clustering each of the twelve risk-risk trade-offs are based on qualitative expert interview data. Some of the trade-offs relate to solar geoengineering alongside CDR, both of which are covered by the GENIE project, though the focus of this particular IRGC report is only on CDR.

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[2] In order to ensure anonymity while also helping to link interview participants with particular quotes, the GENIE project assigns interviewees a respondent number, i.e., R093 is the 93rd expert respondent. These numbers will be used in this paper as well.

because you are taking land out of production, and negatively affecting the ability for land to be used for poverty reduction or farming.” R042 termed this as follows:

> ”I see the highest risk of carbon removal with impacts on land use. And land use is the main driver of anthropogenic mass extinction that we are currently witnessing which is arguably at the same level and scale as climate change. [...] If there are mass plantations and they are historically known to actually be led to land capture and land enclosures from societies that have traditional property rights on land, I’m skeptical that carbon removal will be able to deliver without hurting food production or agriculture.”

R121 added that another dimension to this co-impact involved the pollution flows at the back-end, which could also negatively impact land. As they noted: “growing all of these bioenergy crops will generate large amounts of pollution, which could limit access to food or at least safe and healthy food.”

Furthermore, existing supply chains for biomass are not extensive enough to move beyond the current deployment of smaller, more distributed BECCS facilities (Buck, 2019). Scaling up of both BECCS and direct air capture (see the next section) is thus limited and must confront challenges in the form of unclear standards and procedures for monitoring, reporting and verification (MRV) or high energy costs per ton of captured or avoided $CO_2$; increasing conflicts over land use or biodiversity; and competition from wind and solar as sources of renewable energy, which undercuts the need for storage (i.e., because mitigation is cheaper) or the need for bioenergy (since biomass is more expensive as an energy source) (Creutzig et al., 2019).

This is not to say that BECCS deployment is without positives, or that it cannot help mitigate the potential for other environmental risks. Multiple respondents discussed BECCS as an important part of a diversification insofar as it could help promote a portfolio approach to climate protection. R026 stated that:

> “CDR could consist of co-deployed options. For example, with enhanced weathering and genetically modified crops, enhanced weathering with BECCS, or enhanced weathering with clean coal, there are neat land-based couplings and interactions that can arise.”

Indeed, R060 identified the co-deployment of various technologies as necessary, given not only the desire to avoid or mitigate certain negative co-impacts that would attend to scaling the use of any one option on a grand scale (also noted by R025, R043, R081, R083, R085) but also the scale of the problem itself:

> “The thing I always come back to is that there is no silver bullet. In practice [...] it’s going to be a portfolio of things because some things will probably never scale to a global scale. [...] I think, practically, it's going to be more of a local to regional operation if it can get to that scale, and not a global solution, for all sorts of reasons.”

In this vein, R055 spoke about how “obviously, BECCS needs massive upscaling of the bioeconomy, and it could revolutionize the biofuel, biomass, and biogas markets, along with transport networks and supply chains connected to them.”

## 2.

## Direct air capture with carbon storage (DACCS)

DACCS refers to the capture of $CO_2$ from the air via engineering or mechanical systems, and then using solvents or other techniques to extract it before storing it underground. However, DACCS technology faces important risks. The first of these risks is cost, which also affects environmental sustainability. Potential cost estimates for direct air capture are contested in the literature, ranging from $30 per ton $CO_2$ captured to $600 at the high end, with most estimates falling in the multiple hundreds (Godin et al., 2021; Gür, 2022). It should be noted that this is in addition to sequestration and transportation costs. Under optimistic assumptions, if direct air capture follows the cost-reduction trajectories of comparable technologies such as solar power, there would be significant economies of scale as well as the development of follow-up innovations, which could bring prices down and make direct air capture economically viable. In arguing for the merits of such a comparison, Lackner and Azarabadi (2021) contend that direct air capture, like solar power, is likely to be scaled up through the increasing production of small-scale modules and efficiency improvements instead of increasing size, as is the case with larger power plants. However, for such a "buy-down" to happen, a significant financial entry barrier beyond initial profitability would still need to be overcome. It is unclear where the money to sequester gigatons of $CO_2$ could come from under the current global economic structure, specifically the incentives available for carbon removal. Scaling up carbon storage, especially in saline aquifers or at other underground geological sites, will also face extreme limits; they need to grow at no less than 10% per year every year from 2020, and yet the National Academies of Sciences, Engineering, and Medicine (2019) warned that "scale-up could be limited by materials shortages, regulatory barriers, infrastructure development (i.e., $CO_2$ pipelines and renewable electricity), the availability of trained workers, and many other barriers."

The second major risk is the energy requirements of the technology (Madhu et al., 2021), which could give rise to severe environmental risks. Sequestering gigatons of $CO_2$ using direct air capture will require enormous amounts of electricity, some of which may have to come from fossil fuels. High energy needs and/or the need to compete for currently scarce amounts of renewable energy have the potential to reduce the carbon-capture efficiency of direct air capture projects, put pressure on efforts to decarbonize the electricity supply, and also put constraints on the location of direct air capture plants. The list of places in the world that are in close proximity to both good sources of renewable energy and to suitable injection sites is much smaller than the list of places in the world that have access to carbon sequestration sites alone. Fuss et al. (2018) identify four core challenges: capital investment costs, energy costs for capture, energy costs for regeneration, and costs related to sorbent (i.e., the materials used to absorb $CO_2$) loss and expensive maintenance.

A third environmental risk is the permanence and security of the long-term storage and sequestration of $CO_2$. Indeed, as concluded by one of our other studies, "issues of long-term storage intersect with other aspects of risk, including permanence, leakage, liability, and the pursuit of a more circular economy" (Sovacool, Baum, Low, et al., 2022). For example, if the cap rock that seals the top of reservoirs fails, the gas could leak — possibly at a rate that would be dangerous to anyone or anything on the surface — and aquifers may transport brines and $CO_2$ to the surface, necessitating monitoring and thorough hydrogeological assessments. R003 expanded on this topic as follows:

> "The entire system of direct air capture or storage of carbon presents geological risks. You're essentially trying to mine air, a very low-grade, low-value product: not gold, but $CO_2$. And once you've got it, you've got to compress it, you've got to pump it maybe hundreds or thousands of kilometers, and you've got to compress it down into rock strata which doesn't want to accept anything more, so you've got to use huge amounts of energy. Once it's down there, you're never quite sure whether a fault is going to happen and it's going to vent again and you're going to kill lots of people around about where it's venting because $CO_2$, you know, if you remember those lakes in Africa [the Lake Nyos disaster in Cameroon] which vented their $CO_2$ and they wiped out five villages worth of livestock and people."

There are also risks of seismic effects, not to mention questions around how this might affect the social acceptance of these projects. R027 explained that:

> "Lack of social license is a real risk for many techniques [...] we might not even know that these knock-on consequences are happening because the systems are so complex and so interconnected. We still don't fully understand how they work."

Nevertheless, DACCS does have benefits for environmental sustainability. DACCS technologies could, in principle, be installed almost anywhere, would require relatively little land (less than 0.001 ha per ton carbon per year, compared to 0.1-1.7 ha for BECCS plants, depending on the fuel stock; Sovacool, Baum, Low, et al., 2022) and, according to its advocates, would have only relatively small environmental side-effects, all while producing a verifiable, high-purity stream of carbon dioxide that can be permanently sequestered using existing carbon-storage technology. Fuss et al. (2018) add that DACCS could even be deployed proximate to storage facilities, and it could be co-located with attractive sites for renewable energy, thus minimizing transport and grid costs. The National Academies of Sciences, Engineering, and Medicine (2019, p. 8) identified DACCS as one of the few realistic technical options that "could be scaled up to remove very large amounts of carbon". Fasihi and colleagues (2019) project that if DACCS systems are commercialized in the 2020s, they could see “massive implementation” by the 2040s and 2050s, when they could be of a magnitude equal to existing sources of climate change mitigation, such as wind energy or solar energy.

A second benefit is potentially positive couplings with renewable energy, in particular between direct air capture and solar energy. R005 framed this by noting that “because solar power is very cheap, especially in deserts, it makes good sense to run DACCS on it.” R010 identified “a positive potential synergy between DAC and solar energy, given DAC could create demand for solar even more.” R051 also concurred that “solar [...] is the cheapest form of energy that can be used to power future DAC facilities, and solar thermal in particular could provide water at 100°C and offers a very low-carbon, economic solution.”

## 3.

## Enhanced weathering

Enhanced weathering, also referred to as enhanced rock weathering, employs alkaline materials (such as basalt or lime) which naturally interact with carbon in order to drawdown and provide long-term sequestration of $CO_2$ (in the form of solid carbonate minerals). Given that such processes when left to occur naturally (e.g., under exposure to natural processes like rain, wind, or the action of waves) work very slowly, on the scale of centuries to millennia, enhanced weathering aims to speed things up. Notably, by deploying physical, chemical, or even biological mechanisms to grind the rocks, the surface area that is exposed and which can react with $CO_2$ is increased — along with, potentially, the carbon-sequestration potential of the rocks. Enhanced weathering has gained prominence in light of recent estimates that it might be able to store $CO_2$, at a relatively low cost, on the magnitude of 2.9 to 8.5 billion tonnes per year by 2100 (Beerling et al., 2020; Hartmann et al., 2013; Strefler et al., 2018).

Regarding environmental sustainability, there are a few reasons for concern. First of all, there is the sheer quantity of rocks which would probably be required, especially if we aim to remove multiple billions of tons per year. Instead of simply making sufficient use of available resources or the by-products of the mining sector, it is highly probable that existing mining would need to be intensified and/or new mining sources would need to be excavated. Beyond the impact of the requisite mining on landscapes and local communities (let alone the questions of where such mines would be sited), notably on water and land resources as well as biodiversity, there is also the attendant demand for energy, e.g., for the crushing of rocks. A recent synthetic review of the literature (Sovacool, 2021; based on McLaren, 2012) has established that in order for enhanced weathering and BECCS to achieve significant carbon reductions, as much as 12% of total global energy consumption could be required. As stressed by one of the experts in our interview exercise, enhanced weathering would thus “have a very high energy demand” and, as such, calling it a “low-carbon” option was “disingenuous.” Around 10% of experts surveyed were concerned as a result about the extent to which this technology would be “material intensive” and with supply chains quite extended over large areas (Sovacool, Baum, & Low, 2022a).

Elsewhere, Cox et al. (2020) conclude that the level of effort envisioned could be “equivalent to the size of the current oil and gas industry” once all the impacts in terms of mining, extraction, processing and transport are considered. Among the experts we surveyed, one (R002) similarly stated enhanced weathering “will likely rival mining operations”, while another (R041) less optimistically predicted “a doubling of global mining activities”. The extent to which enhanced weathering can source its rock resources without dramatically expanding the need for mines thus emerges, in Cox et al. (2020) and elsewhere, as one “red line”. After all, if one of the aims of carbon removal is to foster a transition away from our reliance on oil and gas, not to mention the heavy impacts of the mining sector on biodiversity, then these linkages would seem to undercut any improvements here.

When done in marine environments, as is the case for ocean alkalinity enhancement, there are additional issues with how this might (adversely) impact oceans, life below water and/or water security. Although less of a concern than for BECCS and its high water demands, this trade-off between carbon-sequestration potential, water availability and water quality emerges as central (Sovacool, Baum, & Low, 2022b). Specifically, the risk may be that by adding additional nutrients to lands or coastal regions (or generally increasing acidity levels), this might unintentionally influence the balance of species within ecosystems, for instance, by stimulating and favoring the growth of certain organisms rather than others. In our large-scale expert-interview exercise

(Sovacool, Baum, & Low, 2022a), such risks were highlighted by more than one of every six experts questioned – making it one of the most frequently mentioned, non-general risks for a CDR technology. As an example, R036 reflected on the public's response if a "nice beach vacation" were spoiled by the leakage of "alkaline waters" or, in the words of R026, if the effects of enhanced weathering were perceived to infringe on this "last pristine environment".

Similarly, through surveys and focus groups centering on enhanced weathering, a group of co-authors have established over a few studies (Cox et al., 2020; Pidgeon & Spence, 2017; Spence et al., 2021) how perceived risks increase substantially, and public acceptability drops, as soon as the question of ocean impacts is mooted. Cox et al. (2020) specifically identified this as a "red line" for the public, in view of the emotional resonance of oceans for so many individuals as well as the ocean's status as a "fragile, interconnected ecosystem". The experts (e.g., R072, R080, R087) in our extensive expert-interview exercise were cognizant and critical of the specific risks of ocean-based approaches, notably, how this may lead to "the dissolution of other materials, potentially other bioactive materials from the rock" (R072) or "biomagnification through the food web where you have increasing concentrations of a toxin, or a metal, or what have you".

More positively, the prospective co-benefits for the environment and agriculture have also received attention. In this respect, enhanced weathering is increasingly viewed as a potential package (along with soil carbon sequestration and biochar) that can be jointly deployed to improve food yields, enrich soils and increase carbon stocks, foster biodiversity, and increase the health of ecosystems. This constellation of enhanced weathering, biochar and soil carbon storage already features in several early-stage climate-intervention trials (Low et al., 2022). Going one step further, many of the experts even envisioned a "triple win" (R125) if such practices were used to substitute for the use of costly industrial fertilizers, a strategy which would make use of the capacity for enhanced weathering to slowly release minerals over time, when they are then available for soils and their constituent micro-organisms (see also Cox & Edwards, 2019). Notably, enhanced weathering could serve as a kind of "slow-release fertilizer" (R015) in suitable climates and regions, such as the humid tropics, which have "poor soils because of the high rainfall and temperature [... and] are totally depleted." Given that it is farmers in such regions that struggle most to purchase expensive fossil-based fertilizers, enhanced weathering could thus provide assistance to those most in need.

Having looked at the attendant environmental risks and benefits of enhanced weathering, it is helpful to set this in relation to climate change. While the potential for materials to dissolve into water sources is a reason for concern for how it might impact ecosystem functioning, this has also been pointed to as a key benefit of enhanced weathering, namely, to help to tackle ocean acidification. Indeed, the experts interviewed were unanimous about how ocean alkalinity enhancement and enhanced weathering could help return oceans closer to their pre-industrial state. The fact that other methods, such as solar radiation management, cannot deal with ocean acidification renders enhanced weathering particularly important. A couple of experts even went so far as to adjudge this approach as synonymous with ecosystem restoration, though one (R060) still highlighted how much remains uncertain, particularly the extent to which the alkalinity level can actually be increased in this manner.

In any case, alongside its substantial potential to sequester carbon, there is much to speak for enhanced weathering as a way to address climate change. The above discussion makes clear, though, that the how, where and how much of enhanced weathering is crucial. First and foremost, if enhanced weathering can only be done at scale through a massive expansion in mining activities and/or through heavy reliance on non-renewable energy, the resulting environmental risks are likely to substantially offset (at a minimum) any gains that are achieved. On this point, several experts did however observe that, by using a combination of the various methods (e.g., enhanced weathering with soil carbon sequestration and biochar), the inevitability of the trade-offs might be mitigated somewhat. Otherwise, as reflected by questions over whether the co-benefits for local farmers and fisheries would exceed the potential damages to local ecosystems and the ecological balance of oceans, there is a definite need for more research here.

## 4.

# Biochar

Biochar is a form of carbon removal which works by managing the thermal degradation (i.e., heating it) of organic material, such as tree branches or cornstalks, inside a container with no oxygen. The resulting black material is very similar to charcoal, thus the name. If we grind it up and add it to the soil, it is possible to remove $CO_2$ from the air and store it in soils for decades or longer, thereby increasing soil carbon stocks and improving soil fertility. Like its counterpart, enhanced weathering, biochar has received attention as a possible amendment to soils that could substitute for fertilizers and/or improve agricultural productivity. Pointing to the stability of biochar, i.e., as it tends not to interact with other forms of soil carbon — or, for that matter, processes of enhanced weathering — one expert (R019) described it as “safe, scalable shovel-ready, it’s durable [and] it can keep forests healthy and reduce bio risks”.

Having touched upon the prospective environmental benefits of biochar for carbon sequestration in terrestrial ecosystems (i.e., in concert with enhanced weathering), we focus instead on some of the other applications of biochar, e.g., as an input for concrete, steel, cement, animal feed and compost (Honegger et al., 2021; Sovacool, Baum, & Low, 2022a). Drawing on our expert-interview exercise, one out of every eight experts noted the relevance of biochar for net-zero and sustainable forms of concrete and cement production and, more broadly, for decarbonizing industrial processes (e.g., nuclear-reactor designs, buildings, or “green coal”) and thus for the emergence of the bioeconomy. Another application receiving increasing attention is the potential of biochar to facilitate remediation. Whether in storm drainage systems, water-treatment plants, or even potentially for hospital waste, many of our experts also highlighted the role that biochar could play in addressing the issue of landfilling.

Turning to the environmental risks, a primary risk– and common to those carbon-removal methods that rely on biomass – is that of adverse impacts on terrestrial ecosystems and land management. In particular, there is the potential for trade-offs and competition for scarce biomass resources. Indeed, for biochar to play a scaled-up role in addressing climate change, lots of organic material would be required. Depending on how this is sourced, there is the risk that this could undermine food security or increase pressures on land use (e.g., to cultivate on more marginal lands or watersheds), that is, by literally burning potential food. As a result, it is crucial that circular principles such as cascade usage be adhered to, whereby high-value uses (such as food) are prioritized before those such as biochar, where the biomass would be burned and potentially locked away in soils. Here, one of our experts (R039) made explicit reference to how little attention is paid at the moment to the ultimate consequences of biochar for soils, land and oceans: “We have voluntary carbon market actors paying producers of biochar just for the production of biochar and for selling it, with entire disregard for whatever happens with it afterwards.”

Similar to enhanced weathering, but again worth emphasizing, there are potential handling and disposal risks, such as the fact that biochar could potentially catch fire. Though discussed more in relation to industrial processes, these risks are worth monitoring in order to avoid leakage and impermanence of biochar when applied to agricultural purposes. Also, as one of our experts (R026) stressed, there are always the risks of chemical contamination, specifically, “if you take the wrong rocks or wrong materials [...] spread them on agricultural land, can contaminate food, pollute local rivers; they are also linked to ocean pollution.” Lastly, the fact that biochar is fundamentally dependent on heating organic materials indicates that energy use, mainly how such energy is sourced, is a crux issue. If, for instance, renewable energy is available in sufficient amounts such that biochar is not a drain on scarce energy resources or produces a rebound effect – i.e., where, like direct air capture, the attempt to remove carbon becomes coupled with continued reliance on oil and gas – then the energy requirements of biochar become less problematic. At present, however, limited availability of renewable energy represents a notable constraint for biochar employing energy sustainably.

Again, as is the case for all the carbon-removal methods here considered, the main takeaway is that the balance of risks and benefits depends on how and where they are applied. Among other things, in the case of biochar, this entails ensuring that the organic materials are of a sufficiently high quality that they do not have contaminants or harmful ingredients. On the flip side, this could mean that there is a constraint on what can be used for biochar, and thus the scale that can be attained. As is generally true for many of the carbon-removal methods, there is a trade-off between how much carbon can be captured and sequestered and the kinds of impacts that can be expected, i.e., on land use and ocean ecosystems. The fact that biochar also lends itself to a number of other uses, such as water remediation and the decarbonization of industrial processes, simultaneously provides alternate avenues through which it might help address climate change. Accordingly, even if one avenue is closed down on account of being too environmentally risky or too demanding of scarce energy or biomass resources, there are potentially others that can still be pursued.

## 5.

## What could be done to address the risks to environmental sustainability?

The question of "how to ensure" that emerging CDR technologies, if deployed on a large scale, would not lead to adverse consequences for environmental sustainability is a vexing one. Indeed, there are various reasons for concern at present, whether because existing instruments (such as LCAs) are insufficient to assess and encapsulate the full range of risks that exist, or because there are concerns about other potential risks to environmental sustainability, which have so far been ignored or neglected (Terlouw et al., 2021). This has two implications for research and policy.

First, we call for more sophisticated modeling, policy analysis, and even research designs that are capable of understanding and capturing the risk-risk trade-offs of carbon removal. This holds particularly true for some of the social and political risks, which are more prosaic and difficult to quantify or measure. And yet, the degree to which the views and perceptions of the public as well as insights from political science have been integrated into models remains minimal (Peng et al., 2021; Shen, 2021). This finding becomes even more pertinent when such risks have varying temporal timeframes, work on separate spatial scales, involve different actors, and have distinct effects on incumbency and democracy. As such, we confirm the findings arising from Ürge-Vorsatz et al. (2014) and Bhardwaj et al. (2019), notably, that the analysis of co-benefits, whether for energy or climate policy, demands a multiple-objective and multiple-impact framework.

Secondly, the complementarity and interoperability of some CDR options imply that risks may accumulate when multiple innovations are linked together in ways that improve their functionality, attain economies of scale, or when they are co-deployed by the same firm, programme, or actor. The implication is that future deployment is likely to require complementary innovations across an array of technologies, thereby further complicating the task of risk management. Examples here include:

- The reliance of BECCS and DACCS on intricate carbon capture and storage systems that must sequester carbon safely for thousands of years;
- The potential coupling of enhanced weathering and biochar as part of an emerging land-based bioeconomy;
- The dependence on intellectual property regimes or the use of inputs (fertilizers, materials) that could lend themselves to monopoly market structures or pose different environmental risks themselves.

Such complementarities between CDR options suggest the need to move beyond analyzing individual technologies towards entire systems. Yet, this would only be possible with highly sophisticated research designs that also utilize whole systems or sociotechnical approaches.

## 6.

## Conclusion

The four forms of carbon removal identified here — BECCS, DACCS, enhanced weathering and biochar — could become instrumental parts of the transition to a net-zero, more carbon-resilient society. Our results indicate, however, that deployment of such options would involve a diffuse collection of risks as well as benefits (which could themselves represent risks for the climate if the technology is not deployed). As Table 1 below summarizes, no single technology is risk-free. BECCS could lead to negative impacts on land and food while also catalyzing more resilient local bio-economies. DACCS may have high resource and energy requirements which could be (partly) offset if coupled with renewable energy. Scaling-up of enhanced weathering would likely depend on large mining operations and their environmental impacts but could help address the pressing problem of ocean acidification. Biochar poses handling and disposal risks but could also contribute towards more carbon-rich soils and more sustainable forms of building materials.

Table 1 | Summarizing the potential environmental risks and benefits of four emergent carbon removal technologies

| | Estimates for carbon removal and sequestration | Risks of deployment | Benefits of deployment |
|---|---|---|---|
| BECCS | 0.5 – 11 $GtCO_2$/year | Negative impacts on land use, competition with food security, pollution from reliance on fertilizers | Diversification and an integral part of a portfolio approach to net-zero, positive transformation of local bioeconomy |
| DACCS | 5 – 40 $GtCO_2$/year | High cost, need for energy inputs, risks around sequestration and storage | Modularity, ability to be scaled up quickly, positive couplings to renewable energy |
| Enhanced weathering | 2 – 4 $GtCO_2$/year | Need for mining and large quantities of rock, negative impacts on oceans and marine life, concerns over public acceptability | Co-benefits to agriculture including enhanced crop yields, reduction of ocean acidification |
| Biochar | 0.3 – 6.6 $GtCO_2$/year | Handling and disposal risks including fires, intensity of land use | Potential to contribute to green buildings or more sustainable soils |

Source: Authors, with estimates for carbon removal and sequestration from Table TS:7 from the IPCC AR6 WG3 technical summary report (IPCC AR6 WG III, 2022). Note: BECCS = bioenergy with carbon capture and storage, DACCS = direct air capture with carbon storage. Gt = Gigaton

We highlight the particular importance of considering the following three aspects:

1. There could be significant impacts on long-term environmental sustainability if and when large-scale climate interventions, including some CDR techniques, affect biological and Earth systems.
2. It would be useful to develop guidelines, criteria, and instruments to evaluate the outcomes for environmental sustainability of emerging CDR technologies, especially for those with high sequestration potential.
3. Equally needed are methods to evaluate and arbitrate between trade-offs and thereby facilitate decision-making about these trade-offs, in a manner compatible with legitimate democratic processes and acceptable to business and society.

Consequently, analysts and policymakers should recognize the difficulty in predicting risks and embracing the intersectionality and coupled nature of risks and benefits. No benefits come without risks, and vice versa, especially for novel climate-intervention technologies. From this perspective, the value of comprehensively entertaining and wrestling with the prospective risks of CDR is entangled with not only the potential of identifying which options can be co-deployed, or deployed in particular contexts, but also to vouchsafe, as much as possible, the very sustainability of the technologies themselves.

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