CLIMATE

Rightsizing carbon dioxide removal

Betting the future on planetary-scale carbon dioxide removal from the atmosphere is risky

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Proven approaches for limiting climate change include enhancing energy efficiency, capturing wind and solar energy, decreasing deforestation, and reducing industrial and agricultural emissions. These approaches are increasingly cost-competitive, consistent with large-scale use, and largely supported by public sentiment. Yet, the current pace of their deployment is far from sufficient for holding warming well below 2°C above preindustrial levels with high probability, the goal of the Paris Agreement. Two approaches for bridging this gap are widely discussed. First, the rate of decarbonization could be accelerated based on the above approaches. Second, continuing emissions could be compensated by removing carbon dioxide from the atmosphere (*1*, *2*). Technologies for carbon removal are mostly in their infancy, yet are increasingly asserted as key to climate policy. Here, we focus on rightsizing the expectations from carbon dioxide removal (CDR).

A SUITE OF POSSIBILITIES

CDR, or negative emissions, technologies (*2*, *3*) fall into three broad categories. The most mature strategies are grounded in improved ecosystem stewardship (see the table). These approaches increase carbon stored in ecosystems through reforestation and afforestation, conservation agriculture, or coastal restoration. In many locations, improved stewardship can enhance carbon storage at low cost while also improving habitat quality or increasing agricultural yields. However, important questions remain about maximum feasible scales, effective carbon monitoring, and risks of losing stored carbon through disturbances or climate change effects.

A second group of much less mature strategies is also biomass-based but involves more engineering and more environmental or social trade-offs. Leading options include biochar additions to soil, increased use of wood in buildings, and bioenergy with carbon capture and storage (BECCS) (see the table). Each option could lead to some long-term carbon storage, but costs, potential scales, land and water requirements, and side effects are difficult to assess based on current knowledge. With BECCS, energy is extracted from biomass, and the resulting carbon dioxide is captured and stored in geological reservoirs. Among CDR technologies, BECCS is unique in generating more energy than is required to drive the carbon capture and storage.

The third technology category entails engineered, nonbiological approaches, such as enhanced weathering and direct air capture (see the table) (*4*). Although these approaches are energy-intensive and expensive, they may eventually provide useful options for CDR at scale. At this point, however, their technological immaturity means that estimates of future costs, performance, and scalability are speculative.

OPPORTUNITIES AND CONSTRAINTS

With CDR, changes in the atmosphere and climate unfold as if emissions reductions were actually more rapid and extensive. As humanity moves toward decarbonized societies, CDR could counterbalance difficult-to-control sources such as carbon dioxide from aircraft and methane from cattle. It could also, in theory, justify delaying near-term action, based on the expectation that future large-scale CDR could cool the globe, with temperatures peaking and then later declining.

The drawbacks of CDR come into sharp focus in the peak-and-decline scenarios. These scenarios bet the future on CDR technologies operating effectively at vast scales within only a few decades (*1*, *5*). Estimates of economic costs are crude for such scales, and environmental trade-offs are potentially stark. The risks are high: Massive deployments might work, but if they don't, future generations may be stuck with substantial

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Careful stewardship of forests can help to store carbon while maintaining biodiversity. The image shows Killiecrankie Gorge in Perthshire, Scotland.

climate change impacts, large mitigation costs, and unacceptable trade-offs.

Some CDR approaches already combine technological readiness, low costs, and clear co-benefits. Ecosystem stewardship and building with biomass are examples, but with unanswered questions on maximum practical scales. Other CDR strategies might eventually mature into useful parts of the climate-response portfolio, but their potential relevance depends on uncertain technology developments and the trajectory of climate policy. For instance, immense deployments of BECCS would require shifting land and water away from producing food and sustaining natural ecosystems. Direct air capture could become a major industry if the technology matures and prices drop dramatically.

Rightsizing CDR involves taking full advantage of the approaches that are available now while simultaneously investing in research and early-stage deployment, driving down the costs of the immature options, and evaluating side effects. Most important, rightsizing avoids reckless assumptions that massive-scale CDR with low costs and limited side effects will quickly materialize (*3*, *5*).

LARGE-SCALE DEPLOYMENT

Much of the recent discussion about CDR concerns deployments at vast scales. Many candidate technologies have the potential to be the foundation for strong enterprises, capturing many millions of tons of carbon dioxide per year, in locations where each approach makes sense technically and economically, with a favorable mix of co-benefits and side effects. It is at much larger scales (billions of tons of CO_2 per year) that the technologies warrant concern.

For its latest report, the Intergovernmental Panel on Climate Change (IPCC) analyzed about 900 scenarios from about 30 integrated assessment models (*6*). These models determine a cost-effective mix of technologies, based on estimated technology costs and on climate policy, including carbon pricing. Of the 116 scenarios with a 66% or better chance of limiting global warming to 2°C by 2100, 101 include CDR, mostly BECCS, in the technology mix for the second half of the 21st century (*7*). Across these scenarios, the median commitment to carbon dioxide removal from BECCS in 2100 is about 12 billion tons of CO_2 per year, equivalent to more than 25% of current CO_2 emissions (*8*).

This is truly massive use of a technology with little real-world experience and poorly known economics. The requirements for land and water are large but uncertain. Based on relatively optimistic assumptions about future yields, this BECCS commitment corresponds to 0.4 to 0.7 billion ha of productive land (*7*); more conservative assumptions yield a land requirement of 1.2 billion ha (*9*). This range is about 25 to 80% of total current global cropland or up to 8% of Earth's land area. Converting land on this staggering scale would pit climate change responses against food security and biodiversity protection. Massively expanding managed land for CDR could crash through the planetary boundary for sustainable land use (*10*–*12*).

Compared with BECCS, afforestation and reforestation would require even more land and water, and the carbon sinks might saturate or reverse (*7*). Direct air capture might require much less land but entail much higher costs and consumption of a large fraction of global energy production (*7*). The required land would operate as an immense array of industrial facilities. The other CDR technologies have questionable potential for reaching deployment at the scale of several billion tons per year.

A sampling of CDR technologies

Comparative features of three widely discussed, potentially large-scale strategies for carbon dioxide removal (*2*, *7*).

	FOREST AND SOIL STEWARDSHIP	BECCS	DIRECT AIR CAPTURE
Level of engineering complexity	Low	Medium	High
Environmental cobenefits	High	Low	Low
Land area required for large-scale deployment	High	High	Low
Risk of later carbon dioxide release	High	Low	Low
Energy status	~Neutral	Production	Consumption

THE PROBLEMS WITH PEAK AND DECLINE

Scenarios with massive CDR deployments often involve temperatures peaking and then declining. If the goal is to avoid the worst effects of climate change, such peak and decline scenarios imply substantial risks. High temperatures reached transiently may lock in permanent effects—for example, by triggering ice-sheet instabilities that cause substantial irreversible sea level rise (*13*). High peak temperatures could stimulate significant releases of greenhouse gases from the Arctic or the Amazon, further exacerbating climate change (*14*). Species, communities, or economic activities that have adapted to peak temperatures may struggle to adjust back as temperatures fall. Similarly, land and ocean sinks have absorbed substantial emissions to date. But the ramifications of reversing gears through substantial negative emissions remain poorly understood (*1*, *15*).

OUTLOOK

The meteoric rise of CDR technologies in planning for climate solutions has stirred up discomfort and debate. The dynamic is familiar. Early work on climate change adaptation controversially implied that climate change mitigation might fall to the side. Similarly, the question now is not whether to either reduce emissions or deploy CDR. Again, the answer is both, staying focused on not only climate effects but also broader planetary sustainability. Opportunities for ecosystem stewardship-based approaches can be tapped now. BECCS can be tested, developed, and deployed while keeping expectations in check. Research and development on direct air capture and other emerging options can help clarify their future relevance.

Across direct emissions reductions and CDR, a transparent and balanced approach is necessary. By avoiding cavalier assumptions of future technological breakthroughs and embracing whole-hearted near-term ambition, we can protect societies and the planet on which we depend. ■

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