COMMENT

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ROGELIO V. SOLIS/AP

Carbon-capture plants provide one way to reduce the amount of atmospheric carbon dioxide.

Scrutinize CO_2 removal methods

The viability and environmental risks of removing carbon dioxide from the air must be assessed if we are to achieve the Paris goals, writes **Phil Williamson**.

In Paris last December, the 196 parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to balance the human-driven greenhouse-gas budget some time between 2050 and 2100. This commitment is intended to limit the increase in global average temperature above pre-industrial levels to "well below 2 °C" — and preferably to 1.5 °C.

A balanced greenhouse-gas budget either requires that industry and agriculture produce zero emissions or necessitates the active removal of greenhouse gases from the atmosphere (in addition to deep and rapid emissions cuts). In most modelled scenarios that limit warming to 2 °C, several gigatonnes of carbon dioxide have to be extracted and safely stored each year[1]. For more ambitious targets, tens of gigatonnes per year must be removed[2].

Many CO_2-removal techniques have been proposed. Whether any of them could work at the scale needed to deliver the goal of the Paris agreement depends on three things: feasibility, cost and acceptability. A crucial component of all of these approaches is the non-climatic impacts that large-scale CO_2-removal could have on ecosystems and biodiversity.

Until now, the UNFCCC's scientific advisory body, the Intergovernmental Panel on Climate Change (IPCC), has paid relatively little attention to such impacts. It has fallen to other groups to review insights and gaps in our understanding of the influence of CO_2-removal techniques on ecology[3–5]; to make broad assessments of climate-engineering schemes[6]; and to carry out comparative modelling studies[7].

It is time for the IPCC, governments and other research-funding agencies to invest in new, internationally coordinated studies to investigate the viability and relative safety of large-scale CO_2 removal.

FRONT-RUNNERS

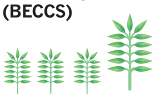
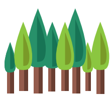
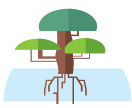
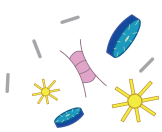
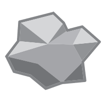
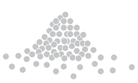
Since its establishment in 1988, the IPCC has predominantly involved physical scientists and modellers, rather than ecologists. This, combined with the only relatively recent evidence that emissions reduction alone is unlikely to avert dangerous climate change, could account for why the IPCC's roughly 5,000-page Fifth Assessment Report, released in 2013 and 2014, leaves out one crucial consideration: the environmental impacts of large-scale CO_2 removal.

This omission is striking because the set of IPCC emissions scenarios that are likely to limit the increase in global surface temperature to 2 °C by 2100 (the aim of the RCP2.6 'representative concentration pathway', the IPCC climate-change-response scenario that achieves the lowest emissions) mostly relies on large-scale CO_2 removal.

These scenarios assume that two techniques could be developed to balance the carbon budget later this century: bioenergy with carbon capture and storage (BECCS), and afforestation. BECCS involves growing bioenergy crops, from grasses to trees; burning them in power stations; stripping the CO_2 from the resulting waste gases; and compressing it into a liquid for underground storage. Afforestation — planting ▸

TAKE YOUR PICK

A plethora of schemes have been proposed to extract carbon dioxide from the atmosphere. Here are nine, some more speculative than others.

TECHNIQUE	HOW IT WORKS
Bioenergy with carbon capture and storage (BECCS) 	Crops grown for the purpose are burnt in power stations (providing energy), and the resulting CO_2 is captured for secure long-term storage.
Afforestation and reforestation 	Large-scale tree plantations increase natural storage of carbon in biomass and forest soil.
'Blue carbon' habitat restoration 	The recovery of degraded or over-exploited coastal ecosystems that have a high potential for carbon storage, such as saltmarshes and mangroves.
Biochar 	Carbon from partly burnt biomass is added to soil, with potential for agricultural benefits.
Enhanced ocean productivity 	Marine photosynthesis and CO_2 drawdown from the atmosphere is increased, either by adding nutrients to promote phytoplankton growth in the open ocean or through seaweed cultivation in shallow seas.
Enhanced weathering (using silicate rock) 	Crushed olivine or other silicate rocks are added to soil surfaces or the ocean for chemical absorption of CO_2. (Could help to reduce ocean acidification.)
Direct air capture (DAC) 	Chemicals (or possibly low temperatures) are used to extract CO_2 from ambient air. Safe CO_2 transport and storage are subsequently required.
Cloud treatment to increase alkalinity 	Alkaline rain resulting from cloud treatments reacts with, and removes, atmospheric CO_2.
Building with biomass 	A massive increase in the use of biomass (straw and timber) as a building material removes carbon for decades or centuries.

trees — also relies on photosynthesis to initially remove CO_2 from the atmosphere. Storage is achieved naturally, in timber and soil.

Limiting the global temperature rise to 2 °C, with any confidence, would require the removal of some 600 gigatonnes of CO_2 over this century (the median estimate of what is needed)[8]. Using BECCS, this would probably require crops to be planted solely for the purpose of CO_2 removal[9] on between 430 million and 580 million hectares of land — around one-third of the current total arable land on the planet, or about half the land area of the United States.

Unless there are remarkable increases in agricultural productivity, greatly exceeding the needs of a growing global population, the land requirements to make BECCS work would vastly accelerate the loss of primary forest and natural grassland. Thus, such dependence on BECCS could cause a loss of terrestrial species at the end of the century perhaps worse than the losses resulting from a temperature increase of about 2.8 °C above pre-industrial levels[10].

A more fundamental concern is whether BECCS would be as effective as it is widely assumed to be at stripping CO_2 from the atmosphere. Planting at such scale could involve more release than uptake of greenhouse gases, at least initially, as a result of land clearance, soil disturbance and increased use of fertilizer. When such effects are taken into account, the maximum amount of CO_2 that can be removed by BECCS (under the RCP2.6 scenario) is estimated to be 391 gigatonnes by 2100. This is about 34% less than the median amount assumed to be needed to keep the temperature rise below 2 °C. If less optimistic but not unrealistic assumptions are made about where the land for bioenergy crops would come from, a net release of 135 gigatonnes of CO_2 could occur by 2100 (see 'Future unknown')[8].

Incomplete understanding throws other assumptions of the BECCS-based scenarios into question[9]. For instance, little is known about the effect of future climatic conditions on the yields of bioenergy crops; what the water requirements of such crops may be in a warmer world; the implications for food security if bioenergy production directly competes with food production; and the feasibility (including commercial viability) of the associated carbon capture and storage infrastructure.

Less is expected of afforestation in terms of its ability to take CO_2 out of the atmosphere. Yet there is a near-universal assumption that increased forest cover is environmentally desirable. This is true in most cases of reforestation, particularly if a mixture of native trees is planted or re-planted, rather than an exotic monoculture. But afforestation can also involve the loss of natural ecosystems. And planting swathes of forest will cause complex changes in cloud cover, albedo (reflectance) and the soil–water balance (through changes to evaporation and plant transpiration), all of which affect Earth's surface temperature.

Counter-intuitively, afforestation at mid-latitudes and in northern, boreal forests may have a net warming effect, despite increasing the storage of carbon[7]. Also, as with bioenergy crops, it is difficult, if not impossible, to reliably quantify the effects of future climate change during 2050–2100. Increased fires, droughts, pests and disease could jeopardize the stability of carbon storage in newly planted forests.

OTHER OPTIONS

There is no shortage of other ideas for CO_2 removal by biological, geochemical and chemical means (see 'Take your pick'). For all such schemes, modelling the theoretical potential of a proposed approach can give a completely different picture from that obtained when environmental impacts — not to mention practicalities, governance and acceptability — are considered.

The roughly 25 years of discussion, research and policymaking on ocean fertilization, another CO_2-removal technique, is a case in point. Since the link was first made between natural changes in the input of dust to the ocean, ocean productivity and climatic conditions, there has been a dramatic scaling-down of expectations of how effective ocean fertilization might be as a way to avoid human-driven global warming[11].

During the 1990s, researchers postulated that for every tonne of iron added to seawater, tens of thousands of tonnes of carbon (and hence CO_2) could be fixed by the resulting blooms of phytoplankton. This quantity has been whittled down over the years with the realization that most of the CO_2 absorbed by such blooms — stimulated either by adding iron or other nutrients to seawater, or by enhancing upwelling through mechanical means — would be released back into the atmosphere when the phytoplankton decomposed. Moreover, a large-scale increase in plankton productivity in one region (across the Southern Ocean, say) could reduce the yields of fisheries elsewhere by depleting other nutrients, or increase the likelihood of mid-water deoxygenation. Such risks have resulted in the near-universal rejection of ocean fertilization as a climate intervention, through bodies such as the Convention on Biological Diversity (CBD)[3].

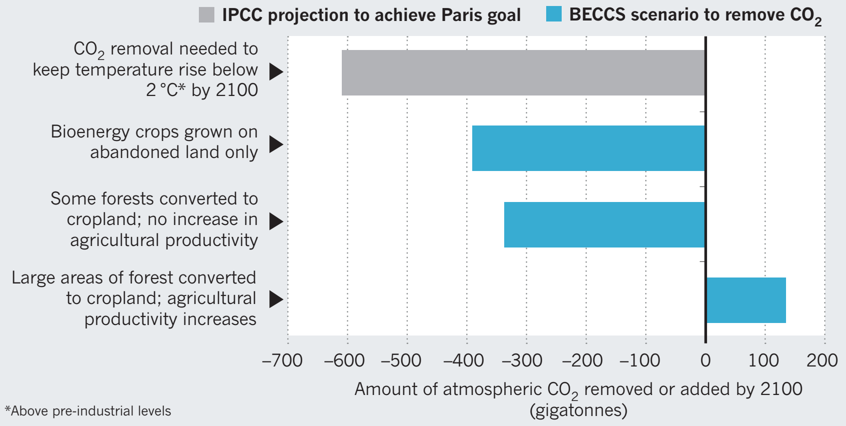
> ***"Action should focus on urgent emissions reductions."***

More recently, other, potentially more controllable, ocean-based CO_2-removal techniques have been suggested, such as the

SOURCE: REF. 8

FUTURE UNKNOWN

Projections of how much carbon dioxide could be removed from the atmosphere using bioenergy with carbon capture and storage (BECCS) between 2020 and 2100 vary drastically depending on where the land for growing bioenergy crops comes from.



*Above pre-industrial levels

cultivation of seaweed to cover up to 9% of the global ocean[12]. The specific environmental implications of this method have yet to be assessed. Yet such an approach would clearly affect, and potentially displace, existing marine ecosystems that have high economic value. (Shallow and coastal waters currently provide around 90% of global fish catches.)

Back on land, other techniques include those to increase the amount of carbon sequestered in the soil, for example by ploughing in organic material such as straw, reducing ploughing (to limit soil disturbance) or adding biochar (a form of charcoal). Another idea is to enhance weathering, which involves the absorption of CO_2 from the atmosphere by certain silicate rocks. Existing insights from agriculture, geoscience and mineral extraction enable more informed assessments of the feasibility and acceptability[3–6] of these approaches. Yet it is crucial to know more about the permanence of carbon storage for biologically based methods, and the environmental impacts that might result if such approaches are used at vast scale[4–6].

For example, the use of biochar raises land-use issues. In addition, millions of hectares of soil darkened by the application of biochar would decrease albedo, increasing heat absorption. The addition of pulverized rock to the soil surface, by contrast, would increase reflectivity. Yet to reduce the amount of CO_2 in the atmosphere by around 50 parts per million (a roughly 12% decrease from current levels), 1–5 kilograms per square metre of silicate rock would need to be applied each year to 2 billion to 6.9 billion hectares of land (15–45% of Earth's land surface area), mostly in the tropics[13]. The volume of rock mined and processed would exceed the amount of coal currently produced worldwide, with the total costs of implementation estimated to be between US$60 trillion and $600 trillion. And the chemistry and biology of rivers and adjacent ocean areas would be radically altered.

The most environmentally benign option for large-scale CO_2 removal may be direct air capture (DAC). This can be done by passing air through anion-exchange resins that contain hydroxide or carbonate groups, which, when dry, absorb CO_2, and release it when moist. The extracted CO_2 can then be compressed, stored in liquid form and deposited underground using carbon capture and storage technologies[6].

The operational costs for DAC cover a similar range to those estimated for enhanced weathering. The extraction process would also need land and probably water, and, as for BECCS, there is a risk of CO_2 leaking out of geological reservoirs. Such risks can be minimized by storing the liquid CO_2 beneath the sea or by using geochemical transformation, which involves *in situ* reactions between CO_2 and certain rock types. In theory, cooling (rather than chemistry) to liquefy out the CO_2 could also be used to remove CO_2 from ambient air[14]. The technical feasibility, costs and potential environmental impacts of this approach — which could involve setting up plants in remote places such as Antarctica — have yet to be investigated.

URGENT ACTION

As well as a major step up in research, urgent attention must be given to clarification at the UN level of what is considered geoengineering and what is climate mitigation. Once considered distinct approaches, the meaning of these terms has become fuzzier in recent years. CO_2 removal is frequently included in both categories, generating confusion and contradiction.

This is crucial to resolve because mitigation and geoengineering have very different psychological connotations. Mitigation is universally considered to be a good thing that reduces risk or damage. Geoengineering frequently elicits suspicion, or is dismissed as a 'high-risk, high-tech' approach that may itself be harmful.

CO_2 removal was not specifically discussed in Paris. However, the large-scale extraction of CO_2 does seem to be a requirement to meet the goal of the Paris agreement. The CBD considers most, if not all, techniques for CO_2 removal to be climate geoengineering, which it has repeatedly rejected as a policy option for addressing climate change. With a few exceptions, the same 195 or so governments make up both the UNFCCC and the CBD.

One solution would be to abandon the term climate geoengineering and simply assess the various methods for mitigating climate change on a case-by-case basis.

The Paris agreement shows where we want to go — the brave new world of a balanced carbon budget — but not how to get there. For now, action should focus on urgent emissions reductions and not on an unproven 'emit now, remove later' strategy. But the unwelcome truth is that, unless a lot more effort is made to cut emissions, significant CO_2 removal will need to begin around 2020, with up to 20 gigatonnes of CO_2 extracted each year by 2100 to keep the global temperature increase "well below 2 °C"[2].

Is that feasible? What environmental risks and constraints are involved? We need to know. ■

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