POLICY FORUM

CLIMATE POLICY

Sustainability limits needed for CO$_2$ removal

The true climate mitigation challenge is revealed by considering sustainability impacts

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Many governments and industries are relying on future large-scale, land-based carbon dioxide (CO$_2$) removal (CDR) to avoid making necessary steep greenhouse gas (GHG) emission cuts today (*1*, *2*). Not only does this risk locking us into a high overshoot above 1.5°C (*3*), but it will also increase biodiversity loss, imperiling the Kunming-Montreal Global Biodiversity Framework (KMGBF) goals (*4*). Such CDR deployments also pose major economic, technological, and social feasibility challenges; threaten food security and human rights; and risk overstepping multiple planetary boundaries, with potentially irreversible consequences (*1*, *5*, *6*). We propose three ways to build on the Intergovernmental Panel on Climate Change (IPCC) analyses of CDR mitigation potential by assessing sustainability risks associated with land-use change and biodiversity loss: estimate the sustainable CDR budget based on socioecological thresholds; identify viable mitigation pathways that do not overstep these thresholds; and reframe governance around allocating limited CDR supply to the most legitimate uses.

Achieving the Paris Agreement climate goals primarily depends on deep, rapid, and sustained reductions in GHG emissions, including steep reduction in fossil fuel production and use (*3*, *7*). Yet some CDR will also be needed in coming decades to reach "net zero" (by counterbalancing hard-to-abate residual GHG emissions), and then "net negative" emissions (to help reverse any temperature overshoot above 1.5°C) (*3*). A crucial question is how much CDR can be deployed sustainably. The mitigation potential for CDR reported by the IPCC has been primarily constrained by technical and economic considerations but has been lacking the assessment of sustainability risk across the range.

We assess risks to biodiversity and other impacts of land-use change arising from bioenergy with carbon capture and storage (BECCS) and afforestation and reforestation (A/R), the two CDR approaches most used in climate mitigation scenarios (*3*); and "nature-based" CDR (which includes various ecosystem restoration approaches). From this, we highlight ways forward for scientists at the start of the IPCC's seventh assessment cycle and for policy-makers and economic actors to heed the call at the December meeting (COP28) of the United Nations Framework Convention on Climate Change (UNFCCC) for deep emission cuts to keep the 1.5°C goal in reach.

SUSTAINABILITY LIMITS

The latest IPCC Working Group III (WGIII) report estimates the upper "technical mitigation potential" of BECCS and A/R at 11.3 and 10 gigatonnes of CO$_2$ per year (GtCO$_2$/year), respectively (*3*). Together, this could require converting up to 29 million km^2 of land—over three times the area of the United States—to bioenergy crops or trees, and potentially push over 300 million people into food insecurity [see supplementary materials (SM)]. The upper end of the IPCC's BECCS technical potential does not take into account socioeconomic barriers or the transgression of planetary boundaries, but the A/R potential takes into consideration food security and environmental impacts. The IPCC report does not provide details or quantitative evaluation of how sustainability risks vary with increasing levels of A/R or BECCS deployment (*3*).

We compare IPCC mitigation potentials with recent studies that give greater attention to the ecological, biological, and societal impacts of land-based CDR (see SM), to provide quantified sustainability limits. Comparison of CDR potential between various estimates within the IPCC report and across recent studies is complicated by differences in methods and units, and assumptions that are not always clearly enumerated. To address these issues, we have harmonized indicators and clearly identified assumptions (see SM). For example, assumptions for BECCS include projected future bioenergy and food crop yields; available land and impacts of land conversion; conversion efficiency of biomass to energy; and capture efficiency of emitted CO$_2$ (see SM).

Accounting for biodiversity losses and other land-use impacts, we find that high risk levels for BECCS and "nature-based" CDR start well below the IPCC's mean technical potential, and the A/R threshold from medium to high risk is at the level of IPCC mean technical potential (see the figure and SM). We find that the upper bounds of low risk for BECCS from dedicated bioenergy crops and residues are 0.7 and 1.2 GtCO$_2$/year for low and medium conversion and capture efficiencies, respectively (see the figure and SM). Corresponding upper bounds of medium risk are 1.3 and 2.8 GtCO$_2$/year for low and medium conversion and capture efficiencies. We consider that these upper bounds of medium risk indicate the limit between acceptable and unacceptable impacts; if exceeded, there are high risks to biodiversity, water availability, biogeochemical cycles, and competition for food production, which occur when around 1.5 million km^2 of land is dedicated to bioenergy crops (*5*) (SM).

Hence, upper bounds of both low and medium risk for BECCS are far lower than the mean IPCC mitigation potential (see the figure and SM). Low risk thresholds are even below what is considered feasible at reasonable cost. Sustainability issues such as biosphere integrity, freshwater use, and food security should therefore be guiding limits to deployment rather than the currently assessed technical and economic potentials (*4*–*6*). To be sustainable even at low or medium risk levels, limited BECCS deployment would also require additional bioenergy policy reforms and safeguards that confine biomass feedstock to those with short "carbon payback period" (fast-grow-

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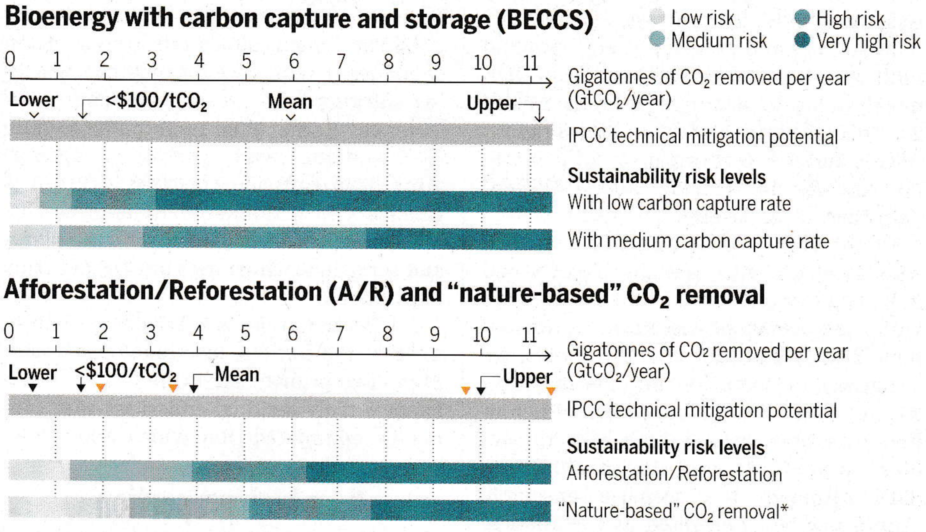
ing crops or residues, not standing forests); address current accounting gaps that consider bioenergy "carbon neutral" even when harvest emissions remain unaccounted for (*8*); and ensure careful siting, to prevent the risk of major additional biodiversity losses from deforestation (*4, 6, 8*).

Sustainability limits to land-based carbon dioxide removal (CDR)

Technical mitigation potential reported by the Intergovernmental Panel on Climate Change (IPCC) (*3*), and economic potential [<\$100 per tonne of CO_2 (tCO_2)] (*3*), must be considered in light of associated sustainability risk, based on analyses of precautionary land footprints and recent literature. Triangles indicate numerical values of specific features. Transitions between risk levels are more gradual than indicated by the color changes. See supplementary materials for details.



Bioenergy with carbon capture and storage (BECCS)

Afforestation/Reforestation (A/R) and "nature-based" CO_2 removal

▼ Mitigation potentials for A/R only; ▼ Mitigation potentials for A/R, improved forest management, and agroforestry CO_2 removal in combination [from left to right: lower, <\$100/tCO_2, mean, and upper (21.5 $GtCO_2$/year)]; *ecosystem restoration practices including limited reforestation, forest restoration, reduced forest harvest, and agroforestry.

GRAPHIC: D. AN-PHAM/SCIENCE

To assess the sustainability of A/R and "nature-based" CDR, we primarily evaluated three recent publications (including a meta-review of 33 studies) that focus on ecological, biophysical, socioeconomic, and feasibility constraints (*1, 9, 10*) (see SM). Constraints include impacts of large-scale land-use change on biodiversity, food security, and rights of Indigenous and local peoples. They also account for feasibility challenges of halting tropical deforestation (the main driver of the 4 to 7 $GtCO_2$ annual land-use emissions) and the risks of weakening or reversal of terrestrial carbon sinks—namely, owing to climate change. These studies confirm that restoring degraded terrestrial ecosystems is beneficial across a wide range of sustainability criteria and poses far fewer feasibility challenges and risks than other approaches, such as afforestation (particularly monoculture), that seek to sequester carbon well beyond historical bounds (*1, 4, 9, 10*).

We estimate low risk levels for "nature-based" CDR to be up to about 2.6 $GtCO_2$/year, including up to 1.3 $GtCO_2$/year from reforestation. These are considered low risk levels because they focus on restoration and involve very limited land-use change (see the figure and SM). Our evaluation of medium risk allows for land-use change up to levels that studies concluded are unlikely to substantially infringe upon sustainability limits. The upper bound of medium risk is about 5.1 $GtCO_2$/year for "nature-based" CDR, including up to 3.8 $GtCO_2$/year from reforestation. These are far below the upper bounds of technical mitigation potential and even below the more tightly constrained economic potential identified by IPCC WGIII (see the figure).

We are concerned that the sustainable supply of other CDR methods may also be poorly evaluated, causing "mitigation deterrence" by diminishing the sense of urgency of deep emission cuts (*2*). For example, ocean-based CDR is being increasingly explored, with reported potential removal of 0.1 to 1 $GtCO_2$/year each for ocean fertilization, artificial upwelling or downwelling, seaweed cultivation, ecosystem recovery, alkalinity enhancement, and electrochemical techniques (*11*). Yet the feasibility and sustainability of deployments at such scales is highly uncertain. Direct Air Carbon Capture and Storage (DACCS) is also considered to have high CDR potential but has high costs and energy demands (*3*), with sustainability implications that are relatively unexplored. This makes it premature to assume that ocean-based CDR or DACCS can make substantial contributions to sustainable CDR.

The relatively low cost of land-based CDR and rapid initial deployment (*12*)—especially A/R—explains why they are overwhelmingly emphasized in countries' climate plans (*1*) and IPCC scenarios for future action (*3*). We recommend that research on a sustainable and realistic CDR budget across all CDR methods be prioritized, building on previous calls to "right-size" CDR [e.g., (*5, 6, 9*); see also SM]. This sustainable CDR budget should (i) assess ecological and biophysical risks and limits, as well as social feasibility constraints; (ii) account for competing land-use demands (food production, the bioeconomy, biodiversity protection); (iii) safeguard human rights and sustainable development priorities (food security, respecting land tenure); (iv) determine realistic timescales for deployment and climatic benefits (*8*); (v) address concerns regarding the permanence of nongeological storage (*9*); and (vi) scrutinize bioenergy accounting rules and capture rate assumptions (*5, 6, 8*).

IDENTIFY VIABLE 1.5°C PATHWAYS

Mitigation scenarios included in IPCC assessment reports (ARs) are highly influential in molding perceptions of the scale and type of future CDR needs. Among the IPCC AR6 scenario database—which collects more than 3000 mitigation pathways based on Integrated Assessment Models (IAMs)—five "Illustrative Mitigation Pathways" (IMPs) provide different combinations of mitigation options to achieve the Paris Agreement objectives (*3*) (see table S2.1). Despite well-founded admonitions that the IMPs and the IPCC AR6 scenarios database should not be overinterpreted (*13*), these scenarios are highly performative: They shape the collective understanding of the Paris-aligned "solution space" (*2*).

The IPCC AR6 WGIII Report does not comprehensively provide the land footprints, corresponding resources, and impacts of CDR use in modeled pathways. As a result, policy-makers do not have a clear view of the potentially dangerous consequences that delaying deep emission cuts has on shifting the mitigation burden onto land. To fill this gap, we have examined the contribution of CDR to mitigation in the IMPs and the IPCC AR6 scenarios database, estimated land-area requirements for CDR in the five IMPs, and compared these with the sustainability limits in the figure (see SM).

Unpacking the data behind the IMPs (see table S2.1) illustrates trade-offs between rates of emission cuts, reliance on CDR, and corresponding CDR land footprints. For example, a slower transition away from fossil fuels in the "IMP-Neg" scenario results in substantial CO_2 emissions in 2050; high overshoot above 1.5°C; and very large CDR deployment that greatly exceeds our estimates of sustainable BECCS and A/R levels. The corresponding CDR land footprint in this scenario is up to 7.2 and 13.3 million km^2 in 2050 and 2100, respectively—well above high sustainability risk thresholds. By contrast, steeper cuts to fossil fuels and reducing energy demand limit overshoot above 1.5°C and keep CDR mostly at low to medium risk levels: 1.7 and 2.6 $GtCO_2$/year in 2050 (with bioenergy for BECCS and A/R covering up to 2.1 to 4 million km^2 for the "IMP-SP" and "IMP-Ren" pathways, respectively).

Of the scenarios included in the IPCC AR6 database with available BECCS and A/R data, 58 and 29% of 1.5°C pathways with high overshoot exceed our estimated high BECCS and A/R risk thresholds, respectively, in 2050 (97 and 62% in 2100); 70 and 39% of 1.5°C pathways with limited overshoot exceed high risk thresholds in 2050 (84 and 45% in 2100) (see SM). Although the scenario ensemble should not be interpreted as a statistical sample in terms of likelihood or of agreement in the literature (*13*), it is concerning that such a high proportion of scenario development relies on risky levels of CDR that are not constrained by sustainability limits. Analysis of existing climate commitments [nationally determined contributions (NDCs)] reveals that countries collectively plan to produce by 2030 twice the amount of fossil fuels consistent with 1.5°C pathways (with no to limited overshoot) (*7*), and by 2060 use 12 million km^2 for land-based CDR—slightly less than current global cropland (*1*).

To inform the upcoming renewal of NDCs and biodiversity action plans, there is urgent need for analyses that make the CDR land footprint and resource use of net-zero pathways transparent and characterize "viable" pathways that do not overstep CDR sustainability thresholds. These analyses should include a comprehensive risk and cost comparison of overshooting 1.5°C, overstepping CDR sustainability thresholds, and the additional emissions-reduction burden if CDR fails to deliver as expected (*2*). We recommend that governments and the IPCC support research to clarify the land footprint of mitigation pathways and define pathways that do not overstep sustainable CDR thresholds. This would encourage development of a new generation of scenarios that give greater attention to steep and rapid declines in fossil fuel production and use, and other mitigation options such as demand reduction, and that do not trespass biodiversity, social, and planetary boundaries.

REFRAME EMERGING CDR GOVERNANCE

Reframing CDR governance to target limited sustainable supply over the coming decades only to the most legitimate uses is essential so that CDR supplements—rather than substitutes for—the necessary deep and immediate emission cuts (*3*). This reframing is even more vital in the aftermath of COP28, which called indiscriminately on countries to scale up CDR, without providing safeguards to prevent "mitigation deterrence." Rather than promote large-scale CDR without clearly calling for accelerating deep emission cuts [e.g., (*12*)], it is necessary to examine the assumptions behind these scenarios and countries' plans, and scrutinize which uses of CDR are truly unavoidable.

A CDR hierarchy is therefore needed to allocate the limited sustainable CDR supply to two priority uses. One is to counterbalance truly residual emissions that cannot be eliminated. But which and whose emissions are truly "residual"? Many developed and G20 countries are projecting large-scale "residual" emissions by mid-century. The international community will need to strictly define residual emissions and grapple with the challenging climate equity issues they raise (*14*). Bounded CDR also places additional onus on the importance of averting overshoot (*3*)—not just to avoid likely irreversible impacts, but also to guard against becoming locked into large-scale CDR, which would likely overstep sustainability thresholds.

> **"...a high proportion of scenario development relies on risky levels of CO_2 removal..."**

Amid the ramifications for CDR governance, we see three immediate priorities. First, set high integrity standards and regulations for CDR providers and purchasers, and across carbon markets and other sources of finance, to limit CDR use for counterbalancing truly residual emissions—not offsetting current fossil fuel emissions. Second, call on countries in their 2025 NDC renewal, net-zero targets, and domestic policy to not just set separate emission reduction and CDR targets (*2*) but also maximize emissions cuts; minimize CDR while detailing what it is used for; and provide transparency of, and strive to limit, land-based CDR footprints (*1*).

Third, harmonize climate and biodiversity governance by deploying clear bioenergy safeguards; developing a political package to finance the protection of existing forests and ecosystems (and their carbon stocks); and prioritizing the most sustainable CDR (e.g., restoration-based CDR versus monoculture afforestation). Land-based CDR in NDCs should be coherent with states' biodiversity conservation plans under the KMGBF. A "CDR tracker" that scrutinizes the social and environmental impacts of current and planned CDR by states and non-state actors, and their end use, would greatly contribute to accountability and integrity. Unpacking and questioning CDR assumptions is key for getting closer to—rather than further away from—successfully addressing the intertwined climate and biodiversity crises. ■

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SUPPLEMENTARY MATERIALS

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