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Integrated assessment of carbon dioxide removal portfolios: land, energy, and economic trade-offs for climate policy

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Abstract

Carbon dioxide removal (CDR) is crucial to achieve the Paris Agreement's 1.5 °C–2 °C goals. However, climate mitigation scenarios have primarily focused on bioenergy with carbon capture and storage (BECCS), afforestation/reforestation, and recently direct air carbon capture and storage (DACCS). This narrow focus exposes future climate change mitigation strategies to technological, institutional, and ecological pressures by overlooking the variety of existing CDR options, each with distinct characteristics—including, but not limited to, mitigation potential, cost, co-benefits, and adverse side-effects. This study expands the scope by evaluating CDR portfolios, consisting of any single CDR approach—BECCS, afforestation/reforestation, DACCS, biochar, and enhanced weathering—or a combination of them. We analyse the value of deploying these CDR portfolios to meet 1.5 °C goals, as well as their global and regional implications for land, energy, and policy costs. We find that diversifying CDR approaches is the most cost-effective net-zero strategy. Without the overreliance on any single approach, land and energy impacts are reduced and redistributed. A diversified CDR portfolio thus exhibits lower negative side-effects, but still poses challenges related to environmental impacts, logistics or accountability. We also investigate a CDR portfolio designed to support more scalable and sustainable climate mitigation strategies, and identify trade-offs between reduced economic benefits and lower environmental impacts. Rather than a one-size-fits-all scaling down, the CDR portfolio undergoes strategic realignment, with regional customization based on techno-economic factors and bio-geophysical characteristics. Moreover, we highlight the importance of nature-based removals, especially in Brazil, Latin America, and Africa, where potentials for avoided deforestation are the greatest, emphasizing their substantial benefits, not only for carbon sequestration, but also for preserving planetary well-being and human health. Finally, this study reveals that incentivizing timely and large-scale CDR deployment by policy and financial incentives could reduce the risk of deterring climate change mitigation, notably by minimizing carbon prices.

1. Introduction

According to the latest Sixth Assessment Report (AR6) of the IPCC, carbon dioxide removal (CDR) is 'unavoidable' to limit warming to the Paris Agreement's climate goals [1]. Whilst CDR cannot substitute for immediate, rapid, and deep GHG emissions reductions, all 1.5 °C–2 °C scenarios assessed in the AR6 require net removals of CO_2 from the atmosphere by either enhancing natural carbon sinks or developing new carbon negative technologies. These practices and technologies differ in terms of removal process, timescale of carbon storage, technological maturity, mitigation potential, cost, co-benefits and adverse side-effects, and governance requirements [2–9]. However, the integrated assessment modelling (IAM) literature—on which the IPCC's recommendations are based—so far limits CDR to bioenergy with carbon capture and storage (BECCS) and sequestration on land (AFOLU) [10–14], with relatively few scenarios incorporating direct air carbon capture and storage (DACCS) [15–21], and scarcely none using enhanced weathering (EW) and/or other approaches, such as biochar [2, 22–25]. Importantly, it contrasts with the current state and trajectory of the voluntary carbon removal market, which has shown some interest in DACCS, AFOLU approaches (often referred as 'nature-based removals') and biochar [26–29].

Hence, careful consideration is needed when interpreting the scale of CDR in these climate mitigation scenarios, as well as the role of each individual CDR approach. For example, large-scale deployment of BECCS leads to controversial trade-offs—notably in energy (bioenergy production for other uses) and AFOLU (food security, but also current and future carbon sinks)—raising questions about the feasibility and sustainability of these scenarios [6, 30–34], as well as the associated risk of deterring mitigation efforts [32, 35–37]. Nature-base removals (e.g. afforestation/reforestation, peatland and wetland restoration, agroforestry or improved forest management) might not be as durable because these carbon sinks will eventually saturate and are subject to disturbance events (e.g. fires, droughts, storms, diseases or deforestation) that will be exacerbated by climate change. Moreover, CDR costs are often unrealistically low in these IAM scenarios. For example, DACCS costs below \$300/tCO_2 when the systematic CDR reviews literature ranges between\$25–1000/tCO_2 [21], diminishing the credibility and reliability of recent CDR pathways in IAM scenarios.

Bottom–up techno-economic studies have shown that CDR portfolios are considerably more viable in achieving climate goals than any single CDR approach [2], yet also involve trade-offs [38]. First, their composition will depend on the availability of resources and technologies, as well as socio-political preferences [39]. The efficiency, timing and permanence of different CDR approaches will vary from one to another, but also within the same approach depending on where, how, and how long they are deployed [40]. Second, with more CDR options added to the CDR portfolio, more removals can be achieved, cost-efficiently, whilst reducing individual CDR option deployment, provided that most suitable CDR options are strategically and regionally selected [39]. Third, deploying CDR portfolios will limit negative side-effects, therefore reducing technological overreliances (by diversifying the portfolio), institutional disparities (by adapting and balancing regional deployments) and ecological damages (by limiting the deployment of single options) [2, 4, 38, 41].

Only recently, a few IAM studies have started to model CDR portfolios. Holz *et al* [25] identified a trade-off between near-term emissions reductions and future large-scale deployment of a CDR portfolio. Strefler *et al* [22] showed that a CDR portfolio can reduce the cost (i.e. lower GDP loss) of achieving the Paris Agreement's 1.5 °C target by reducing transitioning challenges (i.e. lower near-term emissions reduction), relative to any single CDR option. Fuhrman *et al* [23] conducted a disaggregated regional assessment of a CDR portfolio, with explicit impacts on energy, water and land in 2050. Finally, Morrow *et al* [24] focused on new CDR policies, such as inter-regional trade in CDR or separate targets for emissions reductions and CDR.

While these studies offer valuable insights, the literature still lacks a synthesized, holistic, and in-depth assessment of CDR portfolios deployment—a gap our study aims to address, by exploring integrated CDR impacts on land and energy, as well as on the World's economy. Crucially, we evaluate trade-offs between scalability, sustainability (proxied here by reduced environmental impacts) and policy costs (in terms of GDP), both globally and regionally. To do so, we analyse scenarios that are consistent with the Paris Agreement's 1.5 °C, wherein different CDR portfolios—consisting either of a single CDR approach or a combination of them: afforestation/reforestation, BECCS, DACCS, biochar and EW—are available. We aim to provide policymakers with insights to develop credible, resilient, and regionally-differentiated CDR portfolios. By representing CDR portfolios that reflect the carbon removal market and include realistic cost assumptions, we enhance understanding of their transformational impacts across energy systems, land use patterns, and climate change mitigation strategies.

2. Methods

We use the global multi-region and multi-sector Economic Projection and Policy Analysis (EPPA) model [42] to determine climate change mitigation pathways that align with 1.5 °C climate goals. BECCS or DACCS were recently integrated into EPPA [21, 43]. Afforestation/Reforestation is also implemented, but not directly used to offset GHG emissions, due to concerns over reversal risks of forest carbon sinks and issues of additionality—forest projects may have occurred regardless of offset credits or carbon pricing [44–48]. Uncertainties in measuring, monitoring, reporting, and verification (MRV) also pose

Table 1. Comparison of CDR costs, climate mitigation goals, and carbon prices: our study vs literature review and IAM studies.

CDR approach	This study	Literature review	IAM studies	
		Fuss et al [4]	Strefler et al [62]	Fuhrman et al [23]
BECCS	\$140–260/tCO_2	\$15–400/tCO_2	\$20–50/tCO_2	\$100–200/tCO_2
Biochar	\$70–360/tCO_2	\$10–345/tCO_2	Not modelled	-[a]
DACCS	\$380–660/tCO_2	\$25–1000/tCO_2	From\$200/tCO_2	\$185–235/tCO_2
EW	\$265–340/tCO_2	\$15–3460/tCO_2	\$200/tCO_2	\$40–200/tCO_2
Afforestation/ Reforestation	Not covered by the regional carbon prices	\$0–240/tCO_2	From \$30/tCO_2	-[b]
Climate change mitigation goal	Net-zero regional GHG targets (1.5 °C-compatible)	—	1.5 °C-compatible CO_2/temperature stabilization	Global CO_2 target (1.5 °C-compatible)
Global carbon price[c] (mid-century)	\$170–270/tCO_2	—	\$440/tCO_2	\$550–700/tCO_2

[a] Cost per tCO_2 not available, but instead a cost of \$45.93/ton of feedstock is mentioned in the associated reference Bergero et al [63].
[b] Cost per tCO_2 not available. The cost is determined by the relative cost of maintaining the forest for carbon storage and the opportunity cost of land, i.e. reflecting competition for land. The authors indicated that afforestation/reforestation is usually cheaper than any other CDR approach.
[c] This is the global carbon price for the mid-21st century. In our study, it is calculated based on regional carbon pricing data in the *CDR Portfolio* and *Constrained CDR Portfolio* scenarios. In Strefler et al [22, 62], this is the carbon price in the *Full Portfolio* scenario, and in Fuhrman et al [23], in the *Below 1.5 °C in 2100* and *Below 1.5 °C + Sectoral Strengthening* scenarios.
Note: Fuss et al [4] provides a systematic bottom–up review of the CDR literature, with in-depth assessment of CDR costs. Holz et al [25] focuses solely on the carbon cycle and climate response associated with deploying portfolios of CDR approaches in 1.5 °C scenarios, without delving into economic considerations or cost analysis. Morrow et al [24] incorporates certain cost assumptions, the authors explicitly caution against using the relative cost of any technology derived from their study. Indeed, their model, GCAM-CDR, may exaggerate the economic advantage of less energy-intensive technologies over more energy-intensive competitors, such as DACCS, due to the model's assumption of higher energy prices than those typically assumed in the CDR literature.

challenges, as accurately quantifying carbon storage in forests can be complex and costly [2, 4]. The EPPA model is updated here with two additional CDR technologies, biochar and EW. Their parametrization in EPPA follows a bottom–up approach, incorporating granular and up-to-date data, and is detailed briefly below. Agricultural co-benefits of biochar and EW are not yet featured in EPPA, owing to high uncertainties, but is intended as future work. Furthermore, it is important to note that MRV can be challenging for biochar and EW as well. Chiquier [49] demonstrated how different characterizations of permanence, and subsequently different MRV implementations, can impact CDR portfolio deployment. In future research, we plan to build upon Chiquier [49]'s findings to address this crucial aspect of CDR modelling, and aim to incorporate afforestation/reforestation as a distinct CDR option under the GHG emissions targets in EPPA. MRV can also be challenging. More details about the EPPA model, including these updates and limitations, are provided in supplementary materials (SM1–4).

Biochar is a form of charcoal produced from biomass through pyrolysis, a thermal decomposition of materials at high temperatures in the absence of oxygen [2, 3]. The pyrolysis process stabilizes the carbon in the biomass, preventing it from decomposing and releasing CO_2 back into the atmosphere for hundreds of years. Biochar is also known to improve soil quality and help crop productivity by increasing water retention and nutrient availability [50–53]. As such, biochar can substitute for fertilizers, thereby reducing N_2O emissions from agricultural soils [54]. The pyrolysis process generates not only biochar, but also syngas and bio-oil, which can be used as energy sources, for example to produce electricity [55, 56]. Here, we assume that biochar is produced via slow-pyrolysis to maximize the amount of biochar produced [57, 58], and co-produces electricity. The pyrolysis process is highly inefficient, with only 12.7% of the biomass converted into electricity [56]—in comparison, the energy efficiency assumed for BECCS is around 21% [43]. Bioenergy crops, such as miscanthus or switchgrass, are cultivated for biochar, and the competition for croplands between biochar, energy (including BECCS) and agriculture is endogenously determined by EPPA. We assume that biochar is applied once a year, with an application rate of 5tC/ha [56–60]. Following Woolf et al [58], we estimate the permanence of CO_2 removal via biochar, once applied on croplands, to be 70% over a 100-year time period. Net costs (including revenues from electricity generation) range between \$70–360/tCO_2 stored (table 1), which is consistent with the middle to upper-range of the literature [4, 61]. Note that lower-range cost estimates typically rely on optimistic assumptions, such as utilizing waste and residual biomass feedstocks with negligible economic value, minimizing biomass transportation and processing requirements, and factoring in substantial subsidies from the co-generated electricity sales at the pyrolysis plant.

EW accelerates natural weathering processes (that absorb CO_2 from the atmosphere), by finely grinding silicate rocks and minerals, such as olivine, basalt, or serpentine, and spreading them on agricultural fields or coastal areas [2, 3, 64]. Crushing rocks speed up chemical reactions by increasing their surface area. When crushed rocks come into contact with air and water, such as rainwater or groundwater, they react with CO_2 to form bicarbonate ions (HCO_3^-). The bicarbonate ions further precipitate in soils as stable carbonate minerals (for example calcium carbonate $CaCO_3$), or are further transported (through surface runoff or groundwater flow) to rivers and eventually oceans, effectively and permanently removing CO_2 from the atmosphere[64]. The weathering of rocks also releases essential nutrients such as calcium, magnesium, and potassium, which can improve soil fertility and crop productivity [65–67]. However, EW is a highly energy-intensive process that could potentially offset some of its climate benefits [40, 68]. The large-scale mining, processing, transport and spreading of rocks may also have significant environmental impacts, affecting local ecosystems, water quality, and land use [69, 70]. Here, only basalt is considered for EW to account for potential health and environmental hazards from industrial alkaline materials [71, 72], and applied on croplands. Maximum CO_2 sequestration potential of basalt is ~0.3 tCO_2/t rocks [62, 73]. Regional costs of EW vary between \$265–340/tCO_2 stored, aligning with the middle-range of cost estimates reported in the CDR literature [4]. As presented in table 1, it exceeds the estimates found in other IAM studies exploring CDR portfolios [23, 62], however many of these studies lack transparency around their cost estimates, or assume very low costs even when disclosed (see SM4 for a comparison with the IAMs literature).

We analyse six main scenarios with different CDR portfolios: one scenario including all CDR options (*CDR Portfolio*), four scenarios including only one CDR option (*Only BECCS, Only DACCS, Only Biochar*, and *Only EW*), and one scenario constraining natural resources (*Constrained CDR Portfolio*). The CDR options are assumed to be available at a commercial scale from 2025 for BECCS and biochar, and 2030 for DACCS and EW. The *Constrained CDR Portfolio* scenario is designed to evaluate the trade-offs between the economic benefits and the substantial energy and land impacts associated with deploying large-scale CDR portfolios—we impose constraints that increase the cost of resources supply chains—bioenergy crops for BECCS and biochar, and rocks for EW—, nearly exponentially, once their demands reach and then exceed specified threshold values (see SM7.1 for more details). This helps us understand how higher scalability and sustainability requirements, e.g. logistical challenges, ecological footprints, or implementational challenges of MRV, influence the scales and relative contributions of different CDR options within the portfolio. Finally, we also discuss the economic, ecological, and political challenges of two scenarios, one that focuses on the role of nature-based removals, by preventing the loss of natural lands, and a second that delays the deployment of a CDR portfolio. All scenarios are characterized by aggressive climate mitigation ambitions and policies that impose regionally-disaggregated GHG targets reaching net-zero by 2070, and align with a 1.5 °C temperature stabilization goal [74] (see SM1.3).

3. Results

3.1. Comparing single CDR approaches to a CDR portfolio

3.1.1. CDR deployment & Economic impact

Across all 1.5 °C scenarios, CDR is implemented at small scale as early as 2025, but its deployment becomes crucial around mid-century to achieve net-zero GHG emissions by 2070, and is the most extensive afterwards to offset residual emissions[4] (figure 1(A)). The scale at which CDR is deployed varies depending on the available CDR approaches, with cumulative amounts by 2100 ranging from 150 to 700 $GtCO_2$. Annually, up to 31.5 $GtCO_2$ yr^{-1} are removed from the atmosphere in 2100 in the *CDR Portfolio* scenario, owing to highest CDR availability (figure 1(B)). As shown in figure 2(B), climate mitigation strategies also vary across regions—with different levels of emissions reduction and avoidance, residual emissions, and CDR in 2100.

DACCS emerges as the least cost-competitive CDR technology—the least cumulative CDR is deployed in the *Only DACCS* scenario, due to the technology's high costs. The net-zero strategy in this scenario relies mostly on GHG emissions reduction. This has a severe detrimental impact on the global economy, as evidenced by the largest projected policy cost of 17% by 2100 relative to the *CDR Portfolio* scenario[5], which instead deploys a portfolio of CDR approaches. BECCS, biochar and EW are relatively more cost-competitive, as reflected by the limited policy costs of 2.5%–5.5% through 2100 in scenarios that solely deploy each of these options. In our *CDR Portfolio* scenario, the relative contributions and policy costs of land-based CDR approaches (BECCS and biochar), DACCS, and EW align with Strefler *et al* [22]. However, DACCS

[4] CDR is deployed to offset *all* GHG emissions, not only CO_2, hence the net-negative CO_2 emissions observed in the second half of the century.

[5] Policy costs are measured as additional percentage losses, relatively to the *CDR Portfolio* scenario, on baseline 2100 GDP.

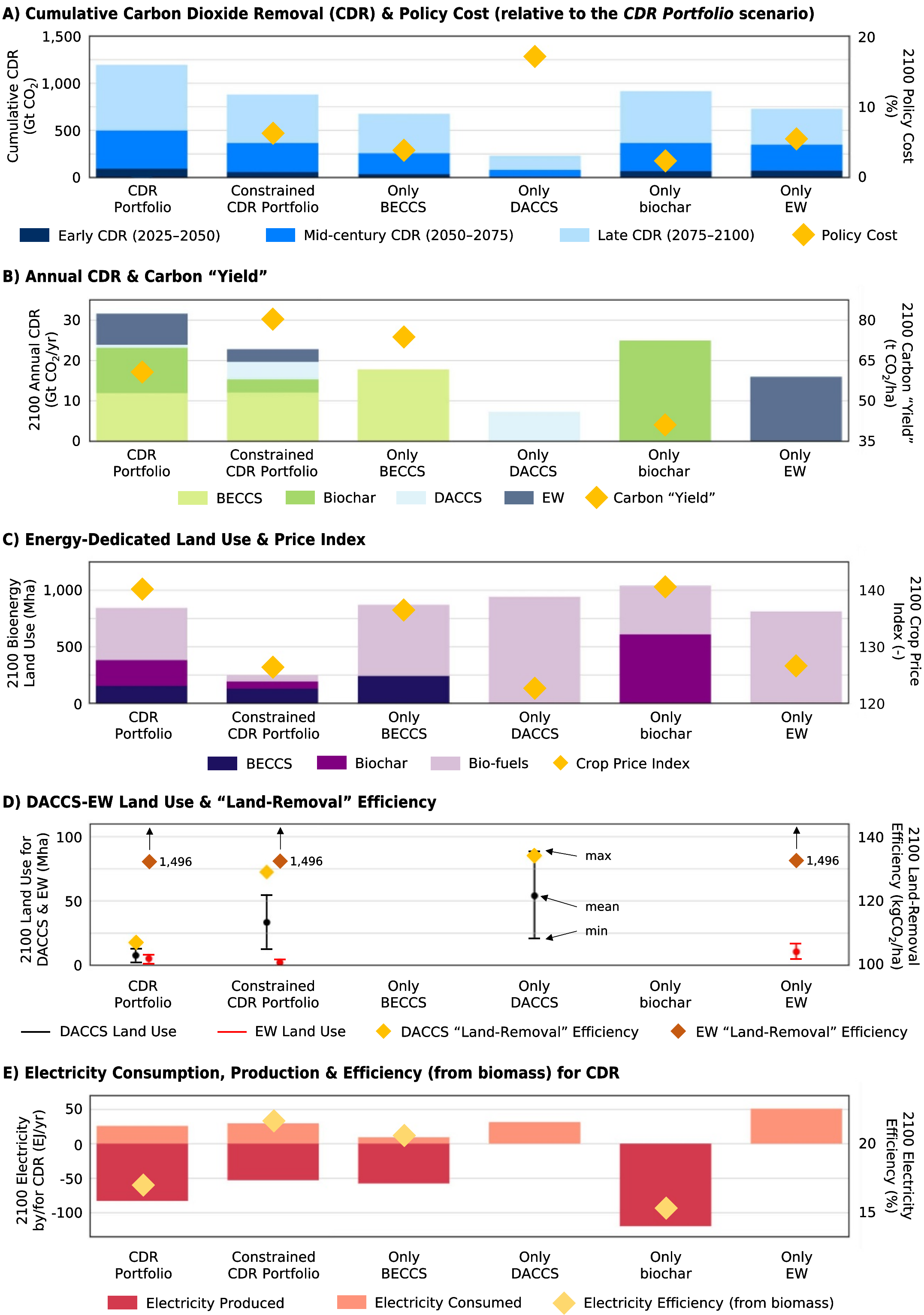

Figure 1. (A) 2025–2100 cumulative CDR deployment & 2100 policy cost, i.e. additional percentage losses, relative to the CDR portfolio scenario, on baseline GDP; (B) 2100 annual CDR deployment & 2100 carbon 'yield' of land-based CDR approaches, i.e. the amount of CO_2 removed from the atmosphere by BECCS and biochar per hectare of land used to cultivate the bioenergy crops; (C) 2100 energy-dedicated land use & 2100 crop price index (relative to 2020, with 2020 = 100); (D) 2100 land use for DACCS and EW, i.e. the direct land use of the DAC units and the indirect land use associated with the dedicated renewable energy sources required to power these units for DACCS, and the mining land use for EW & 2100 'land-removal' efficiency, i.e. the ratio of kg of CO_2 removed from the atmosphere by DACCS and EW per hectare of land used by the respective CDR option; and (E) 2100 electricity consumption/production for CDR & 2100 electricity efficiency (from biomass) of BECCS and biochar. Note that EW land removal efficiency is off the scale (D).

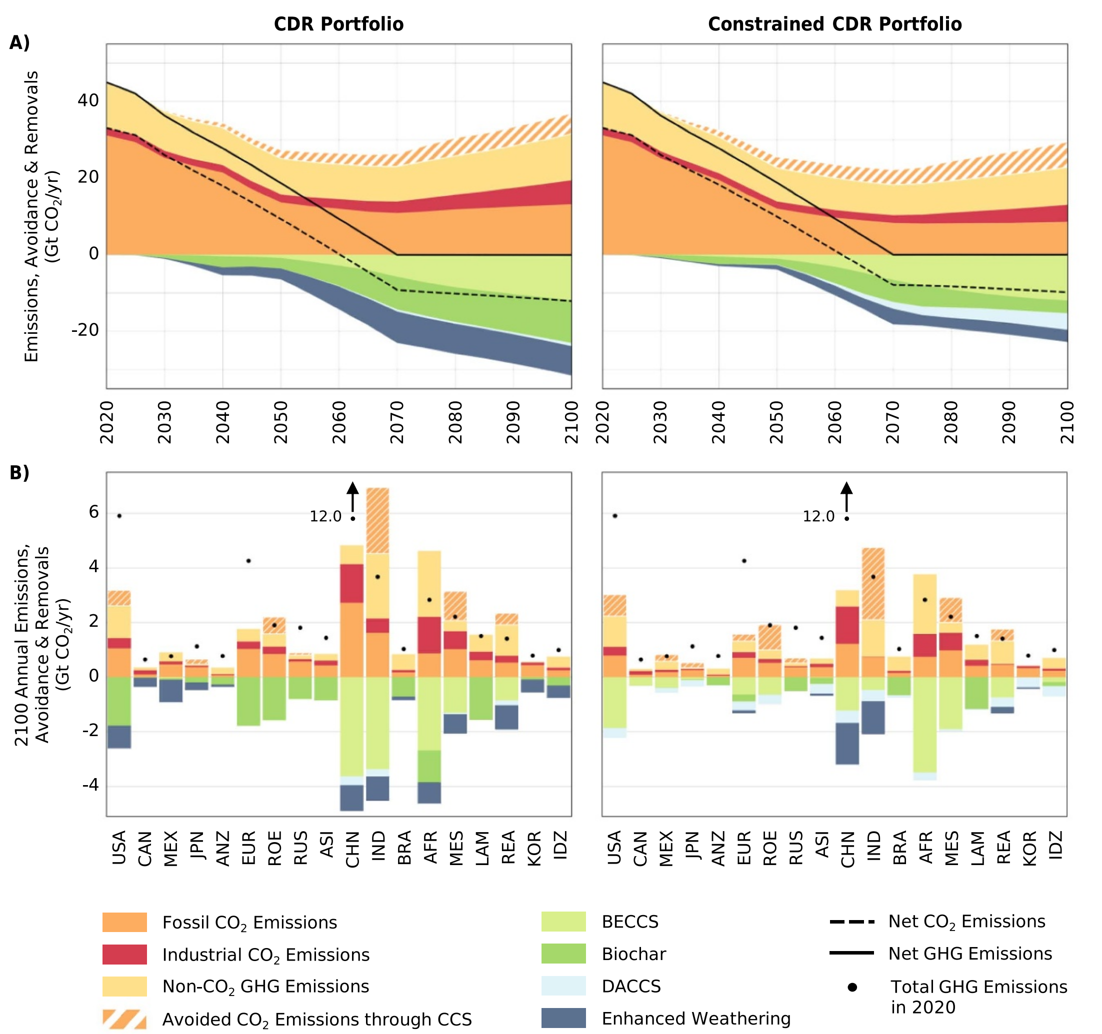

Figure 2. (A) Annual GHG emissions, avoided CO_2 emissions and CO_2 removals between 2020 and 2100; and (B) regional annual GHG emissions, avoided CO_2 emissions and CO_2 removals in 2100, in the CDR portfolio scenario and the constrained CDR portfolio scenario. Total GHG emissions in 2020 are indicated, regionally, by the black circles.

contribution is substantially reduced compared to Fuhrman *et al* [23] and Morrow *et al* [24], due to our higher cost assumptions. Note that different parameterizations of climate mitigation goals and costs of mitigation options are implemented across our study and these other IAM studies, which impact carbon prices, as shown in table 1, and ultimately impact the overall amount of CDR required for reaching net-zero goals. These varying approaches to climate targets and technologies—namely net-zero GHG emissions targets versus CO_2/stabilizing temperature, costs of non-CDR options, exogenous constraints to the deployment of CDR, and different CDR portfolio—influence economic implications, as well as the scale of CDR deployment across different modelling frameworks.

3.1.2. Impact on land

In the *CDR Portfolio* scenario, BECCS and biochar each remove 11–12 $GtCO_2$ yr^{-1} in 2100. Yet, they have very distinct impacts on land. The carbon 'yield'—here defined as the amount of CO_2 removed from the atmosphere per hectare of land used to cultivate bioenergy crops—is twice as high for BECCS than for biochar (figure 1(B)). That represents 150 Mha of cropland allocated to BECCS versus 225 Mha to biochar in 2100 (figure 1(C)). In scenarios where only BECCS or biochar are deployed, 2100 global price indices for (non-bioenergy) crops relative to 2020 are at their highest, between 136 and 141. They reflect the substantial pressure on land resources, and ultimately food security, in net-zero strategies that prioritize the deployment of land-based CDR approaches [6, 30]—here 35% of energy-dedicate croplands are used by BECCS, while up to 65% are used by biochar, respectively.

Conversely, DACCS has a significantly smaller land footprint compared to land-based CDR approaches, even when accounting for the space needed for the DAC units and the dedicated energy sources required to power these units [3, 21]. As shown in figure 1(D), the land footprint of dedicated renewables can vary significantly, due to location, configuration, tracking technology for solar installations, and shared land usage with agriculture for wind farms, or even offshore wind. For EW, the land area required to produce a ton of mineral also varies depending on factors such as location, mining type (underground or surface), geological characteristics of the mineral deposit, or the technology available for extraction. Here, we assume that the average land occupation rate for a basalt quarry is 200 ha/Mt of rock, based on the approach outlined in Rosado *et al* [75]. Even with a 50% uncertainty range, EW land footprint remains negligible compared to the substantial land requirements of BECCS and biochar. Consequently, scenarios that only deploy DACCS or EW experience significantly less competition for cropland, lowering crop price index in 2100.

3.1.3. Impact on energy

CDR options have very distinct impacts on the energy system (figure 1(E)). DACCS and EW utilize electricity to power fans and regenerate sorbents, and to crush rocks. In the *CDR Portfolio* scenario, although their electricity consumption is relatively high compared to current production levels (22% of global electricity production in 2015), it is expected to be relatively small in the future—using only 5% of electricity production by 2100 (see SM7.2).

Conversely, BECCS and biochar produce electricity. But BECCS, which combusts biomass and converts it directly and entirely into electricity, demonstrates higher efficiency than biochar. Pyrolysis plants convert half of the biomass into biochar, with the remainder turning into syngas and bio-oil. These co-products are subsequently utilized to generate electricity, introducing additional conversion losses. By 2100, considering projected advancements in electricity generation technology (see SM1.2), BECCS efficiency reaches around 21.5% in the *Only BECCS* scenario, whereas biochar efficiency is only at 15% in the *Only Biochar* scenario.

3.1.4. Scalability & Sustainability

By diversifying the portfolio of CDR approaches, more cost-effective net-zero strategies are adopted that reduce the reliance on any single approach, thereby re-distributing and mitigating adverse impacts on land-energy systems (figure 1). However, even in our *CDR Portfolio* scenario, 660 EJ yr^{-1} of bioenergy crops are projected to be produced globally by 2100, exceeding by far the highest 2050 estimates of sustainable bioenergy of 133 EJ yr^{-1} [76]. The large-scale deployment of EW, 7.7 $GtCO_2$ yr^{-1} by 2100, is also of concern, due to logistical challenges in the rocks supply chain, environmental implications of mining, and health risks associated with the application of dust on lands. This represents a total volume of 25.5 Gt of basalt rocks mined, approximately three times the current global coal production (8.5 Gt in 2022 [77]), and exceeding current-day cement production (4.2 Gt in 2022 [78]) by more than six times.

In the following section, we explore a scenario that imposes constraints on the utilization of natural resources, i.e. bioenergy and basalt rocks, to address environmental concerns, logistical challenges, and considerations related to accountability, i.e. MRV.

3.2. Constraining a CDR portfolio

3.2.1. CDR deployment & Economic impact

In the *Constrained CDR Portfolio* scenario, CDR deployment is reduced to 22.8 $GtCO_2$ yr^{-1} in 2100, resulting in 28% lower residual GHG emissions compared to the *CDR Portfolio* scenario. Economically, it penalizes the World's economy by an additional 6.2% GDP loss (figure 1(A)). The deployed CDR portfolio does not simply reduce in scale, but shifts towards different approaches, both globally and regionally (figures 2(A) and (B)). In the *CDR Portfolio* scenario, CDR is deployed in 2100 via a combination of BECCS and biochar, with 12 $GtCO_2$ yr^{-1} and 11.2 $GtCO_2$ yr^{-1} respectively, EW with 7.7 $GtCO_2$ yr^{-1}, and DACCS with no more than 1 $GtCO_2$ yr^{-1}, reaching the scale of hundreds of Mt/yr of CO_2 removal in China, India and parts of East Asia, and tens of Mt/yr in Middle-East. In the *Constrained CDR Portfolio* scenario, CDR also scales up from 2050 to keep up with the net-zero 2070 target, mostly via land-based CDR approaches. However, once net-zero GHG is achieved, biochar deployment goes down to 3.3 $GtCO_2$ yr^{-1} through 2100. EW contribution is limited to 3.2 $GtCO_2$ yr^{-1} by 2100, here—2.4 times less than in the other scenario. Instead, other CDR approaches take over, with BECCS becoming the most deployed one—as much as in the *CDR Portfolio* scenario, accounting here for half of the total CDR by 2100—, while DACCS reaches approximately 4.3 $GtCO_2$ yr^{-1}. Note that a sensitivity analysis on costs shows that lower CDR costs may enable a prolonged delay in short-term GHG emissions reductions, but do not necessarily support higher levels of residual GHG emissions in the long-term. Conversely, very high costs—twice the highest regional estimates—are observed to reduce the level of CDR deployed by 2100 by 41%. Despite the cost uncertainties, DACCS and EW are still more expensive than BECCS and biochar—owing to their high energy and/or capital intensity—and therefore remain less deployed by 2100 (see SM6).

Regionally, biochar is either less deployed or partly substituted by BECCS, a more land-efficient option, as observed in the US and Europe. Exceptions exist, though—Latin America continues to deploy biochar extensively, with little reduction in CDR levels by 2100. DACCS is partly deployed instead of EW, due to limited accessibility and large-scale utilization of basalt rocks, as seen in Korea, East Asia, or in the US. But, although land-based CDR approaches are more cost-effective for atmospheric CO_2 removal, the high competition for limited bioenergy resources in the *Constrained CDR Portfolio* scenario can make EW a more appealing mitigation option in some other regions, such as in China and India.

3.2.2. Impacts on land

Energy-dedicated cropland area reduces by 71% to only 250 Mha by 2100 in the *Constrained CDR Portfolio* scenario (figure 1(C)). Not only are biomass-based CDR options the most carbon-efficient in this scenario—with the highest carbon 'yield' of 80.5 tCO_2 ha^{-1} across all 1.5 °C scenarios (figure 1(B))—, but the competition for land is minimal (see SM7.3). The 2100 crops price index of 126 is of similar order of magnitude as in scenarios where only DACCS or EW are deployed (figure 1(C)).

3.2.3. Impacts on energy

By 2100, less electricity is produced via BECCS and biochar in the *Constrained CDR Portfolio* scenario, but most efficiently—21.5% due to BECCS predominant deployment relative to biochar. (figure 1(E)). In fact, bioenergy accounts for 75 EJ yr^{-1} in 2050, which is consistent with global sustainable bioenergy projections of 44–133 EJ yr^{-1} [76], and contributes twice less to the total primary energy compared to the *CDR Portfolio* scenario as a result of its exponential cost penalty (figures SM7.2). However, as shown in figure 3, the energy system transition differs substantially from one region to another. Latin America, Brazil and Africa still make significant investments in bioenergy—contributing to 43%–62% of their total primary energy by 2100 whereas fossil fuels + CCS represent 30%–50% in India and Middle-East, and ⩾50% in Eurasia.

3.2.4. Logistics, Accountability & Agricultural co-benefits

The total volume of basalt rocks mined is reduced to 10.5 Gt by 2100, twice less than in the *CDR Portfolio* scenario, but is concentrated in a few regions—India, China, the EU—which do not necessarily exempt from logistical challenges. Conversely, the amount of biochar that must be spread on agricultural land accounts for 2.2 Gt by 2100, and is more distributed globally. Moreover, whilst biochar and EW only account for 29% of annual CDR deployment by 2100, their MRV is not comparable to the one of geological CO_2 storage, i.e. BECCS and DACCS, and might still have a moral hazard effect deterring mitigation.

However, should agricultural co-benefits of biochar and EW be accounted for, assuming application rates of 5 tC ha^{-1} for biochar [56–60] and 20 t rocks/ha for EW [64, 73, 79], these are nearly 900 Mha, i.e. 45% of all croplands in 2100 that could benefit from improved soil quality and increased crop productivity. More research is needed to explore these potential co-benefits in IAM scenarios.

3.3. Preventing natural lands loss

Forests and other natural ecosystems contribute to mitigating climate change, safeguarding biodiversity, improving water and air quality, while also enhancing resilience to environmental catastrophes or protecting against land degradation—essential for planetary well-being, but extremely difficult to model properly. As such, the benefits provided by natural ecosystems are too often overlooked in economic analyses and decision-making processes.

Yet, as evaluated in SM8, deploying nature-based removal practices that prevent the loss of natural lands could minimally change the global strategy for climate mitigation, whilst nonetheless protecting about 100 Mha of natural forests and 25.5 Mha of natural grasslands by 2100, compared to the *Constrained CDR Portfolio* scenario, at the cost of only 0.2% of the global GDP in 2100 (figures SM8.1–2). Regions most impacted would be Africa, Brazil and Latin America (figure 4), where deforestation currently happens [80], e.g. in the Amazon rainforest [81, 82] or in the Congo Basin in Central Africa [83, 84], due to agriculture, logging, infrastructure development, and mining. Economically, these regions would be most penalized—up to 1.4% of their GDP in Africa by 2100 (figure SM8.2). Locally, the economic impact could be more substantial, and disproportionally affect populations with varying income-levels.

Nature-based CDR strategies are essential for carbon sequestration and addressing other environmental, social and economic objectives; thus, further research is needed to reflect these externalities in climate mitigation scenarios. Even small areas of protected land (relative to the total area of natural lands), as here, could yield significant economic benefits.

3.4. Delaying CDR portfolio deployment

Despite the consistent growth of the carbon removal market—the volume of CDR purchases has rocketed from 0.009 $MtCO_2$ in 2020 to 4.5 Mt CO_2 in 2023 [28]—, there are still concerns about whether CDR is scaling-up quickly enough, and whether it will be sustained to meet the Paris Agreement's climate goals [85]. If not, it is important to understand the impact this will have on the global strategy for climate action, in terms of economy, energy, emissions, land use, and more.

In a scenario (see details in SM9) where CDR deployment would be delayed for economic, political or social reasons (e.g. no policy incentive, or lack of social acceptability) until

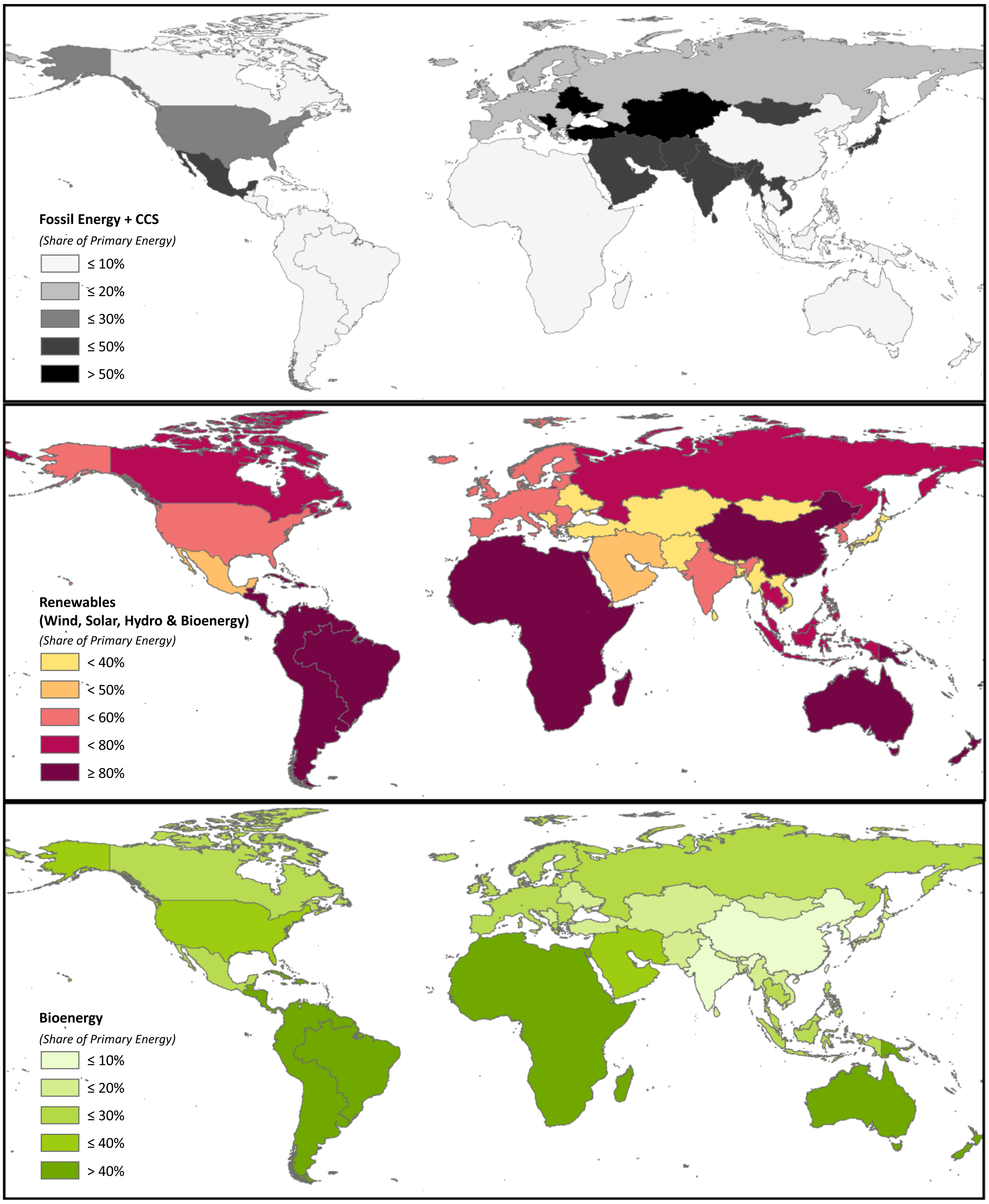

Figure 3. Shares of: top. Fossil energy (coal & gas) + CCS; middle. Renewables, including hydro, wind, solar & bioenergy; and bottom. Bioenergy, in total primary energy across the EPPA regions by 2100, in the constrained CDR portfolio scenario.

the second half of the century, regional carbon prices would increase dramatically—surpassing $800/t$CO_2$, worldwide—as global GHG emissions would decline but CDR would not be available yet (figure SM9.2).

Considering the current range of carbon prices on the different carbon markets, between $8/t$CO_2$ in China ETS and $100/t$CO_2$ in the EU ETS [86], it might be challenging to imagine the public support for the high levels of carbon prices. Moreover, notable recent events, e.g. the Yellow Vests crisis in France in 2018, Russia's invasion of Ukraine in 2022 precipitating an energy crisis, or the farmers' strikes in the EU in 2024, have demonstrated the lack of public support for aggressive carbon taxation or pricing measures. As suggested by Nemet *et al* [85], anticipating the near-term deployment of CDR, at scale, to meet future climate goals, and taking adequate policy and/or financial measures to allow it, may help in maintaining carbon prices below a certain level, thereby preventing a global social crisis down the line. It will also reduce the risk of climate deterrence.

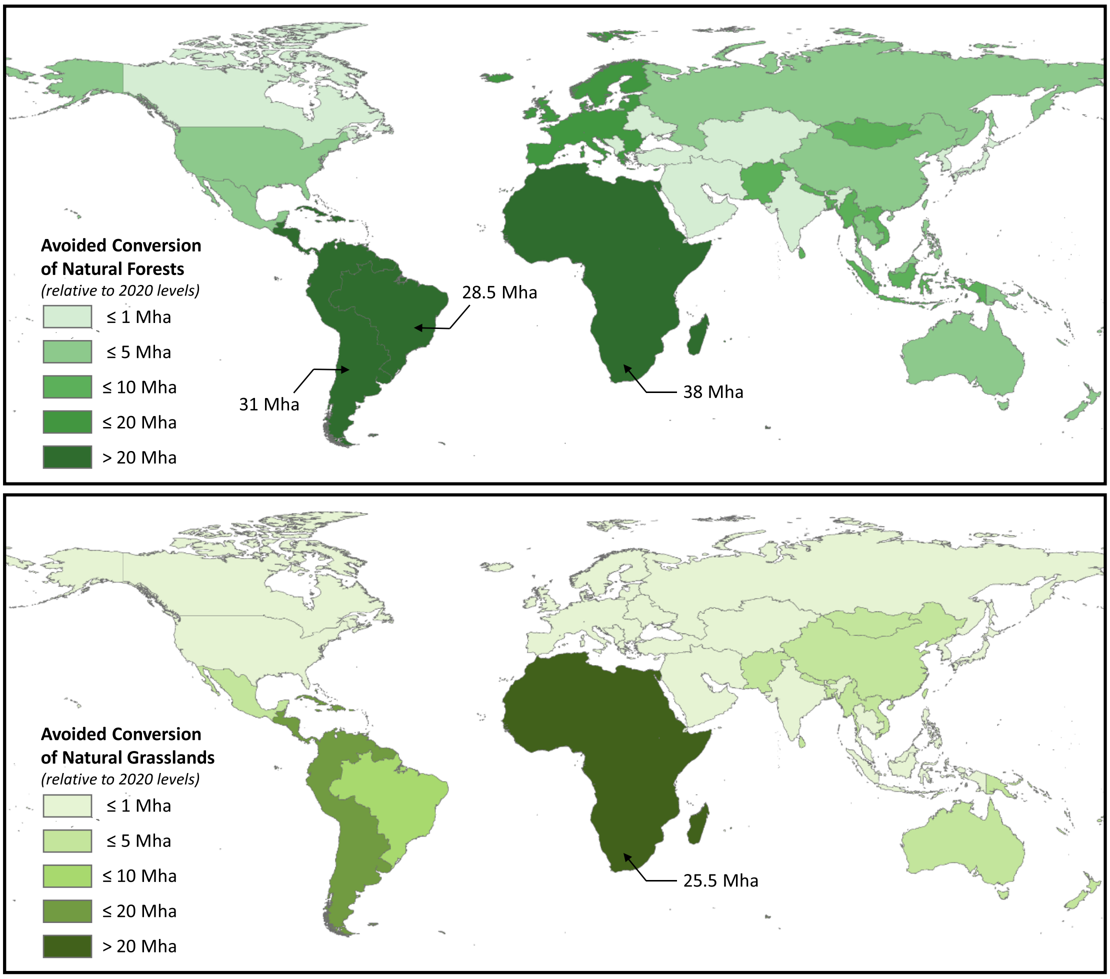

Figure 4. Top. Avoided conversion of natural forests in 2100—involves preventing the loss of natural forests (to croplands, pastures or managed forests); bottom. Avoided conversion of natural grasslands in 2100—involves preventing the loss of natural grasslands (to pastures), relative to the constrained CDR portfolio scenario. This is done by: (1) permanently dedicating land to natural forest or grassland cover, and (2) maintaining or increasing levels relative to 2020. This results from policy/governance measures, e.g. conservation/preservation initiatives.

4. Discussion & Conclusion

This study provided insights into the effectiveness of CDR portfolios for achieving net-zero goals. By diversifying across multiple CDR approaches, the highest CDR deployment of around 31.5 $GtCO_2$ yr^{-1} was achieved in 2100, while also proving the most cost-effective net-zero strategy. Specifically, BECCS and biochar were identified as most cost-competitive in removing CO_2 from the atmosphere, followed by EW, whereas DACCS emerged as being uncompetitive, due to high capital expenditure and energy requirements.

Assessing the implications of individual CDR options on energy and land also contributed to understanding the trade-offs associated with each option across other sectors. Typically, BECCS and biochar are both land-intensive CDR approaches, but we found that biochar requires almost twice more land to cultivate bioenergy crops than BECCS per ton of CO_2 removed. Despite being more cost-effective, the CDR portfolio scenario showed substantial pressure on land resources, and ultimately food security through high crops prices. Conversely, the land footprints of DACCS and EW remain negligible, even accounting for DAC units, dedicated renewables assets, or mining facilities. We also revealed contrasting energy system impacts across CDR options, with BECCS exhibiting higher electricity production efficiency than biochar, and EW and DACCS utilizing energy for crushing rocks, powering fans, or regenerating sorbents.

Diversifying CDR approaches mitigated overreliance on any single option, and thus redistributed land and energy impacts, compared to deploying just one approach, but not without environmental, logistical, or MRV-related challenges. With another CDR portfolio, designed to support a more scalable and sustainable climate mitigation strategy, we identified trade-offs between economic benefits, environmental integrity, and energy use. Crucially, as CDR deployment was reduced to 22.5 $GtCO_2$ yr^{-1} in 2100, the CDR portfolio underwent strategic re-composition, instead of uniform downsizing, entailing regionally-selected approaches based on local techno-economic conditions and biophysical characteristics. For future work, we envisage to jointly optimize the cost and environmental impacts of CDR portfolios, e.g. land and energy footprints, to explore more cost-effective, sustainable, and holistic mitigation strategies.

Importantly, non-geological CDR practices, i.e. biochar and EW, contributed to 29% of annual CDR by 2100 in this other CDR portfolio—posing remaining challenges related to logistics in some regions, and potentially accountability issues. But, biochar and EW also offer promising agricultural co-benefits that could improve soil quality and productivity across 45% of all croplands by 2100, providing additional value beyond their carbon removal potential. These co-benefits need to be modelled in IAM studies to evaluate their full potential.

We also discussed the co-benefits of natural ecosystems, essential for planetary well-being and human health, and examined the economic trade-offs of preserving them. Our results suggested that the strategy for climate mitigation may only experience a minimal negative economic impact, while protecting about 125 Mha of natural lands, predominantly in regions where deforestation is happening. However, the full extent of the positive economic impacts of these co-benefits remains highly uncertain. Thus, we call for further investigations in the preservation and restoration of natural ecosystems, for both environmental and economic reasons, as a means to mitigate and adapt from the adverse effects of climate change while also promoting sustainable economic development.

Lastly, we showed that delaying the deployment of a CDR portfolio would inevitably be economically more challenging, leading to much higher carbon prices—greater than \$800/tCO_2, worldwide. This suggests the importance of near-term policy and financial actions to reduce the risk of deterring climate mitigation.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

S C designed the research, developed the modelling tool, produced and analyzed the scenarios, and wrote the first draft of the paper. A G and H C contributed to the modelling tools. A G and S P advised on the scenarios. All authors contributed to writing the paper, and advised on the presented research.

Conflict of interest

The authors declare no competing interests.

Additional information

Supplementary material for this article is available online.

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