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Review

Understanding land-based carbon dioxide removal in the context of the Rio Conventions

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SUMMARY

Carbon dioxide removal (CDR) is increasingly recognized as essential for achieving the Paris Agreement's climate goals. Current CDR strategies primarily involve land-based measures, such as afforestation, reforestation, and soil carbon enhancement. These approaches, often labeled as nature-based solutions (NBS) or natural climate solutions (NCS), have sparked debate due to their potential adverse effects on biodiversity and uncertainty around the scale and durability of potential climate benefits. This paper introduces a framework for evaluating trade-offs in land-based CDR activities following the recent United Nations Environment Assembly definition of NBS. This framework emphasizes ecosystem integrity, human rights, and sustainable development, aligning with the objectives of the three Rio Conventions, which provide a guardrail to inform pathways toward feasible and equitable implementation. By applying this framework, we provide a more comprehensive understanding of the environmental and social constraints on CDR, ensuring that climate mitigation efforts do not compromise biodiversity, ecosystem services, or human well-being.

INTRODUCTION

Given current trends in climate warming and the slow progress of initiatives to reduce greenhouse gas (GHG) emissions, it is now clear that carbon dioxide removal (CDR) will be necessary to counterbalance residual emissions and achieve net-negative CO_2 emissions,[1] although the scale, type, and timing of the required CDR remain debated.[2] Currently, almost all CDR in national policies or future climate pledges comes from land-based measures (i.e., afforestation, reforestation, forest management, soil carbon).[3,4] While these interventions have come to be known variously as nature restoration, natural climate solutions (NCS), or nature-based solutions (NBS), many of these activities can in fact be detrimental to nature,[5–7] particularly when they focus on carbon at the expense of biodiversity and other environmental objectives.[8] Despite agreement that land carbon stocks should be restored, there are differing interpretations of what constitutes nature restoration. A growing body of literature has begun to assess the complexities of CDR deployment within sustainability constraints,[9,10] but these efforts are not yet reflected in global quantifications of CDR potentials, which do not systematically evaluate trade-offs with environmental objectives and broader sustainability goals.

Recent papers have raised the need for a research agenda on quantifying the sustainable, or feasible, potential of CDR.[11,12] While concerns that CDR may divert attention from the near-term urgency of phasing out fossil fuel emissions are well known,[13,14] equally concerning is the potential for CDR to divert attention from the need to end emissions from deforestation and land degradation.

Here, we propose and apply a framework for evaluating trade-offs in CDR activities founded on a politically agreed-upon definition of NBS. We argue that this framework provides a comprehensive view of the environmental and social constraints and enablers of land-based CDR that can be used to align assessments of CDR (e.g., Prütz et al.[15]) with recent political consensus. This draws specifically from the fifth session of the United Nations Environment Assembly (UNEA), which agreed to a resolution that defines NBS as those that deliver human well-being, ecosystem services, resilience, and biodiversity benefits while respecting social and environmental safeguards in line with the three Rio Conventions.[16] The United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD), and the Convention to Combat Desertification (UNCCD) were all established at the Rio Earth Summit in 1992. Evaluating CDR through the lens of the Rio Conventions builds on hard-won political agreements to provide a framework based on ecosystem and climatic integrity, human rights and the rights of Indigenous peoples, and sustainable development, including adequate climate finance.

CONTESTED APPROACHES TO CDR

The Paris Agreement inadvertently introduced the concept of net-zero as a climate goal via the language of "a balance between anthropogenic emissions by sources and removals by sinks," widely interpreted as net-zero GHG emissions.[17] The same language of balancing sinks and sources was used to introduce land use into the Kyoto Protocol, amid much controversy over the potential of the land sector to weaken ambition and undermine targets to reduce emissions from energy and

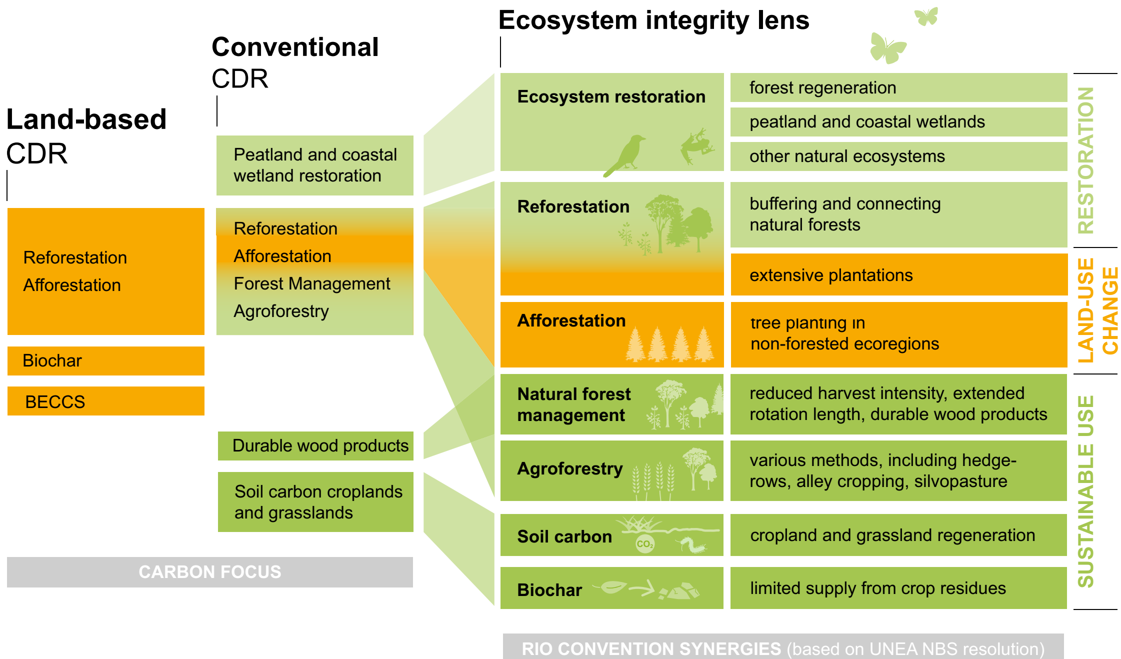

Figure 1. Ecosystem integrity lens on land-based carbon dioxide removal
A narrow carbon-focused lens sees "land-based" CDR as a simplified categorization that does not differentiate approaches to land management. Conventional CDR[4] broadens the focus to land management activities already deployed for climate mitigation. Viewing these through an ecosystem integrity lens further differentiates approaches as restoration, sustainable use, and those that drive land-use change (the latter, marked in orange, more likely to cause ecosystem degradation and increase risk profiles for carbon loss).

industrial GHGs.[18–20] However, a key difference is that while the Kyoto Protocol defined and limited land-use activities, the language of the Paris Agreement has moved land-based sinks from a politically contested add-on to occupying a central role in the long-term mitigation goal.[21]

The land sink is a key component of Earth's carbon cycle and continues to play a major role in removing carbon dioxide from the atmosphere, along with the oceans. The interaction between the climate and land encompasses a range of physical, chemical, and biological processes, one of the most crucial being the exchange of carbon dioxide between the atmosphere and land. Land-based CDR refers to the leveraging of natural processes that enhance the uptake and storage of carbon in terrestrial ecosystems (including coastal and wetland areas), while technological CDR refers to removing carbon dioxide from the atmosphere and sequestering it geologically, both resulting in a net removal of CO_2.[22]

This review delineates land-based CDR (see Figure 1) and, therefore, does not cover the wider range of technological CDR approaches, such as direct air capture, enhanced weathering, and marine sinks.[22] Land-based CDR has typically focused on afforestation and reforestation (A/R), bioenergy with carbon capture and storage (BECCS), and, more recently, biochar.[23,24] However, categorization of CDR has proved difficult—there are overlaps between land-based and technological approaches to CDR, for example, with BECCS, which encompasses both. This has led to a (re)positioning of what could be considered more conventional forms of land management that contribute to climate mitigation as "conventional" CDR, while BECCS and other, more nascent technologies that capture carbon geologically, in marine sinks or products, are referred to as "novel" CDR.[4] Conventional CDR thus encompasses and unpacks the broad category of A/R to also describe forest management, soil carbon enhancement, and other land management approaches that enhance carbon sinks. These approaches are a subset of land use, land use change, and forestry (LULUCF), as reported by countries in national GHG inventories, which include emission reduction and removal activities in the land sector.[25]

Parallel to discussions around defining land-based CDR, there has been growing recognition of nature-based or "natural" climate solutions, with efforts to quantify various protection, restoration, and land management pathways. NBS, a term that emerged in the late 2000s, refers to actions that protect and restore natural ecosystems while simultaneously addressing social, economic, and environmental challenges, of which climate is one.[26] NBS that contribute to climate mitigation include carbon removal via enhancing sinks, but also reducing CO_2 emissions through avoided land clearing and degradation, and activities that reduce agricultural (or marine) GHG emissions, such as methane and nitrous oxide.[27] The quantification of this climate abatement potential in carbon dioxide equivalents has also been differentiated from NBS as NCS.[28] It has been claimed that such activities could contribute up to 30% of the mitigation efforts (emission reductions and removals) necessary for meeting 2°C[28] and 1.5°C[29] temperature goals.

However, such proposed climate solutions remain incomplete without a consideration of the effect of the activity on other climate-relevant factors, particularly surface albedo, evaporative cooling,[30] atmospheric chemistry,[31] and circulation (i.e.,

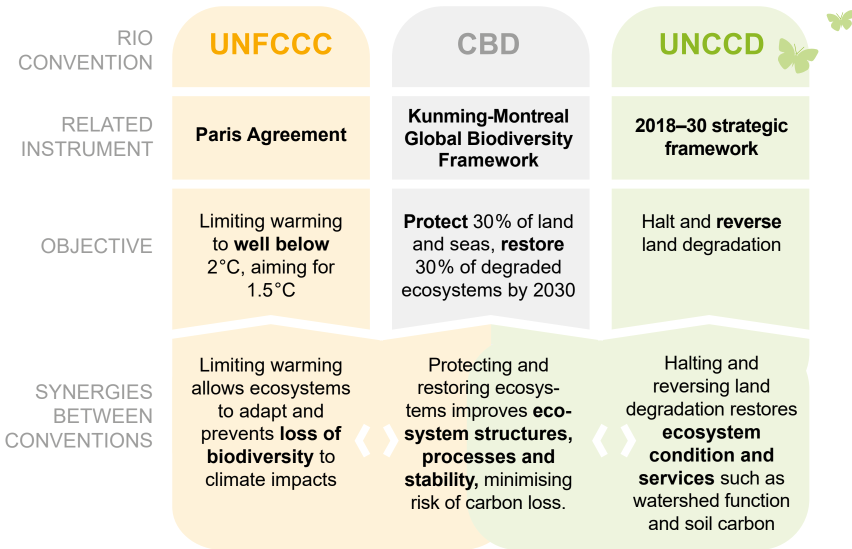

Figure 2. Synergies between Rio Convention objectives and ecosystem integrity

Drawing on Rogers et al.'s[39] framework for ecosystem integrity, which encompasses biodiversity, ecosystem structure, processes, and stability and the resulting ecosystem condition and services.

"non-local effects").[32,33] Moreover, natural, or nature-based, climate solutions have been criticized because the term is sometimes used to refer to measures that have had a negative impact on biodiversity and human rights.[34] The Intergovernmental Panel on Climate Change (IPCC) concluded in its synthesis report for the sixth assessment cycle (AR6) that human-rights-compatible climate actions that prioritize equity, social justice, and inclusivity lead to more sustainable outcomes.[1]

The term NBS has also been disputed in international policy settings. For example, "ecosystem approach" is a long-established term that serves as a foundational strategy for the CBD. However, some countries, including Norway, the United Kingdom, and the European Union, wanted to also include "NBS" during negotiations on the new 2030 global biodiversity framework under the CBD, while many developing countries, including Brazil, Argentina, Bolivia, and the African Group, opposed the inclusion of new language.[35] In discussions under the UNFCCC, Brazil, for example, had also rejected the use of "NBS" as having no internationally agreed-upon concept or definition and pointed instead to "ecosystem approaches" and "ecosystem-based approaches" as accepted terminology under the CBD.[36] This was resolved following the adoption of a resolution on "nature-based solutions for sustainable development" at UNEA 5 in 2022 (UNEA Resolution 5/5), which represented a multilaterally agreed-upon definition that recognized concerns about the potential misuse of the concept and emphasized parallels with ecosystem-based approaches.[16] Subsequently, "NBS" was quickly adopted into several multilateral environmental agreements in 2022, including the Sharm-el-Sheik Implementation Plan under the Paris Agreement[37] and the Kunming-Montreal Global Biodiversity Framework (KM-GBF) under the CBD.[38]

Importantly, UNEA Resolution 5/5 emphasizes biodiversity and the rights of Indigenous peoples, specifies that actions should have no negative impact on the climate, and that safeguards of the three Rio Conventions must be met.[16] Following this, we draw on the safeguards and objectives of the three conventions to develop a framework to guide conventional CDR implementation in ways that are compatible with politically agreed-upon climate, biodiversity, and social goals. The objectives of these conventions—preventing dangerous climate change, protecting biodiversity, and halting and reversing land degradation—converge in terms of the critical role of ecosystem integrity in achieving all three. Ecosystem integrity is a multifaceted concept that integrates across many properties of ecosystems, including ecosystem condition, stability, processes, energy dynamics, biodiversity, and services.[39] The system, with interrelated elements of structure, function, and composition, must have the capacity for self-organization and regeneration in the context of prevailing local environmental conditions. Ecosystem integrity has been utilized in ecological monitoring and assessment frameworks and, more recently, at the nexus of biodiversity and carbon stocks.[40]

The importance of ecosystem integrity to the stability and resilience of carbon stocks tends to be overlooked in the framing of both land-based CDR, which does not consider the range of land management approaches, and conventional CDR, which encompasses existing climate mitigation approaches in the land sector that are seen through a carbon-focused lens. This carbon-focused approach can result in CDR that is detrimental to nature, such as through relying on extensive tree plantations. Viewing CDR through an ecosystem integrity lens gives a fuller picture of restoration possibilities and considers the different aspects and qualities of these approaches that are important (Figure 1). Building on Rogers et al.,[39] who emphasized that ecosystem integrity should be seen as a guiding framework rather than a co-benefit, we propose that ecosystem integrity encapsulates the synergies between the Rio Conventions, which in turn provide guardrails to inform pathways toward feasible and equitable approaches to NBS (Figure 2). Literature on landscape management approaches point to the need for strong governance systems and effective planning processes in addition to ecosystem integrity.[41]

CONSIDERING ECOSYSTEM INTEGRITY IN CONVENTIONAL CDR POTENTIALS

Techno-economic assessments currently dominate the literature estimating CDR potentials.[12] The technical potential for land-based CDR determines what is possible given technological and biophysical constraints.[42] This potential is then adjusted according to economic constraints and safeguards. A number of papers call for the need to quantify the feasible potential to constrain the reliance of mitigation scenarios on CDR in the

Box 1. Current deployment and modeled projections for CDR

Current deployment of CDR is reported by the global carbon budget as the removal component of the net anthropogenic land flux, which averaged −1.8 (−2.9 to −0.7) Gt CO_2 $year^{-1}$ (averaged over 2013–2023).[108] However this is occurring in the context of emissions of 6.9 (5.5–8.8) Gt CO_2 $year^{-1}$ from deforestation, leading to a global net flux that is a source of emissions at 4.8 ± 2.6 Gt CO_2 $year^{-1}$.[108] In addition, a small sink has been estimated to be transferred to harvested wood products (HWPs) in 2022 (of 0.2 Gt CO_2 $year^{-1}$), with an even smaller amount of 0.002 Gt CO_2 $year^{-1}$ reported in geological removals via BECCS projects.[109] Carbon removal in coastal wetlands is less than 11,000 tonnes CO_2 $year^{-1}$ globally.[109] Hence, reforestation and afforestation constitute the vast majority of all current CDR, suggesting that CDR overall, but particularly conventional CDR, must be viewed in the context of land management, where halting emissions from the degradation and clearing of ecosystems is a necessary precondition to achieve a noticeable climate benefit from terrestrial sinks. Considering only the total human-induced removal of land management without considering also the human-induced emissions overstates the climate mitigation potential of CDR.

Estimates for future CDR potential scale up significantly from current deployment. Across scenarios limiting warming to 2°C with greater than 67% likelihood (C1–C3, $n = 407$),[24] modeled cumulative land-based CDR from the year 2020 reaches up to 365 Gt CO_2 by 2050 and 1,486 Gt CO_2 by 2100 (Figure S1).[110] These scenarios primarily rely on BECCS for novel CDR and A/R for conventional CDR, yet activities comprising A/R are typically not defined, making assessment from an ecosystem integrity lens impossible (see Figure 1). Given the extent to which conventional CDR dominates land-based removals, it is crucial to improve the granularity of modeled activities within this broad category to properly assess ecosystem integrity considerations. Governments and corporations are also heavily relying on CDR to reach net zero. Removals of up to −5.0 Gt CO_2 $year^{-1}$ are included in government climate pledges for 2050, the majority of which is conventional CDR on land.[111] The potential demand for additional land to achieve CDR in these 2050climate pledges is estimated at 990 million hectares, with 479 million hectares of this for A/R.[112]

next assessment round.[11,12] A previous review of 42 estimates of nature-based CDR found that cumulative potentials ranging from 100 to 800 Gt CO_2 were constrained to 100–200 Gt CO_2 based on implementation challenges and biogeochemical constraints.[43] The true climate benefit of projected technical mitigation potentials depends on what biophysical factors estimates do and do not consider, while the feasible potential relies on a comprehensive assessment of socio-cultural, environmental, and institutional factors (Box 1).[44]

In this review, we assess recent estimates for conventional CDR using our proposed framework to better understand feasible CDR potential, approaches, and implementation constraints. We reviewed literature from the past 5 years that present estimates for conventional CDR at the global or regional level, only including studies that provide quantified estimates. We first compare and evaluate the different activities and quantifications of conventional CDR presented across the assessed studies using the proposed ecosystem integrity lens. Next, we assess the extent to which biophysical considerations are represented, as efforts to quantify conventional CDR potential must account for these factors to provide a more realistic evaluation of climate mitigation potential. Finally, we assess the consideration of benefits and safeguards as discussed in the Rio Conventions referenced by UNEA Resolution 5/5. Critically, we find limited consideration of biophysical aspects and assessments of safeguards drawn from the Rio Conventions, where the latter include several socio-economic and institutional elements such as rights, finance, and sustainable development. We conclude that an ecosystem integrity lens approach to conventional CDR quantification recenters co-benefits and fosters alignment with important politically determined safeguards.

Estimates of future CDR potentials from recent sectoral studies

Our assessment considers mostly global studies that include a range of nature-based removal activities but also some studies that focus only on one intervention (such as reforestation) or one region (tropical). We standardized the estimates of CDR, which are provided in differing units and over different time periods, to estimate consistent removal paths over the period 2020–2100 (Figures S2–S4). This enabled a comparison of cumulative estimates at the global or regional level and a comparison of estimated annual peak removals between activities (Figure 3). Across different approaches to CDR, our standardized comparison shows a very high removal potential from one outlier study on afforestation[45]; outside of this outlier, the highest potentials are found in restoration (Figure 3A). Across global studies, we observe a cumulative range of 57–1,052 Gt CO_2 from 2020 to 2100, which, when including cost-effectiveness considerations, reduces to 57–385 Gt CO_2 (Figure 3B). Cost effectiveness is the only quantitative constraint currently included in the literature, although several studies exclude CDR based on activity or location on the basis of food security concerns.[46,47]

Before considering carbon removals through restoring ecosystems, it is important to acknowledge that protecting primary forests and other intact ecosystems delivers climate mitigation benefits through avoiding emissions and maintaining existing carbon stocks in primary forests, which also have the highest levels of ecosystem integrity.[39] The hierarchy of protecting, restoring, and sustainably managing the forest and land-use sector is well established in the literature[48–50] and relevant policy guidance.[34,51] Protecting existing ecosystems avoids releasing these carbon stocks to the atmosphere and maintains the ongoing sink capacity of forests and other ecosystems.[52] However, protecting primary, or largely intact, ecosystems does not result in additional sequestration of carbon beyond the natural sink capacity and so is not considered CDR. The importance of stopping the destruction of ecosystems worldwide is quantified in some studies as avoided or reduced emissions.[27,49,50,53,54]

Restoring degraded ecosystems, on the other hand, through halting deforestation and degradation (e.g., wood harvest)

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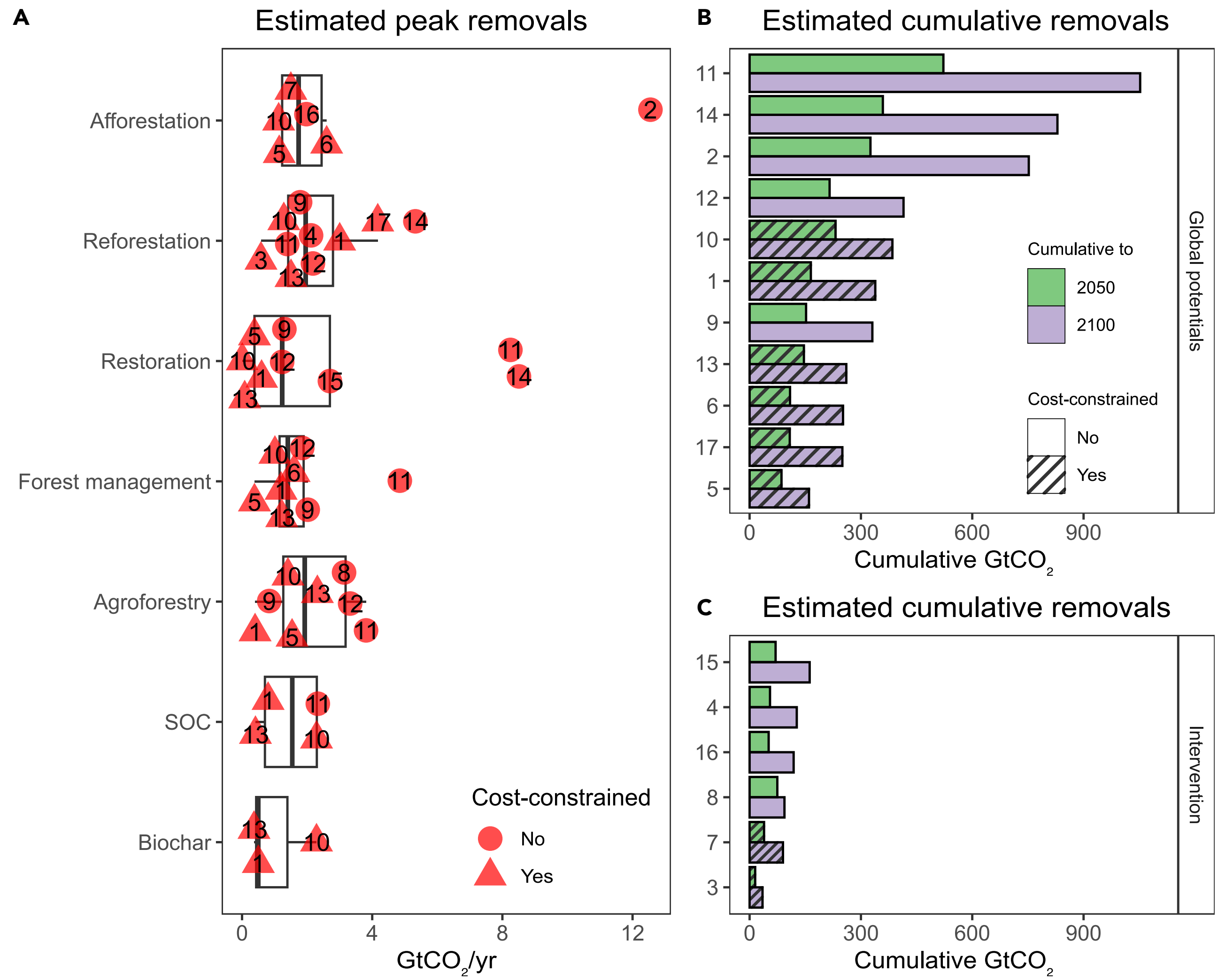

Figure 3. Conventional CDR potentials across the reviewed sectoral estimates

(A) Activity-based estimated peak removals in Gt CO_2 $year^{-1}$ derived by standardizing heterogeneous units and periods in the reviewed literature (Figures S3 and S4). The labels indicate the paper from which the potentials are drawn (Table S1), and the shapes describe whether the reported value comes from a cost-constrained analysis.

(B) Cumulative conventional CDR potential reported in the reviewed literature, aggregating all activities contained in each paper after standardizing these into consistent Gt CO_2 $year^{-1}$ paths from 2020 to 2100 (see Figure S4).

(C) The same removals for studies that we consider "single interventions" and distinct from the "global potentials" shown in (B).

provides an immediate mitigation benefit in terms of reducing emissions from these activities but also a longer-term mitigation benefit as carbon stocks recover (beyond the regrowth following harvest cycles), representing "the single most important action for sustaining and increasing the forest carbon sink."[55] This potential is illustrated through our review. While estimates show notable variation across CDR approaches, restoration stands out for its significant CDR potential across multiple studies (Figure 3A). Restoration contributes to CDR by enhancing the capacity of the biosphere to sequester and store atmospheric carbon and can contribute to goals across all Rio Conventions when natural ecosystems are allowed to regenerate. Restored ecosystems have higher levels of ecosystem integrity, lending increased resilience and stability to carbon removals, biodiversity, and ecosystem services.[34,39]

While many studies quantify the restoration potential of mangrove, coastal, and wetland ecosystems,[27,49,50,53] fewer explicitly consider forest restoration, which involves removing sources of forest degradation, such as timber harvest, to allow secondary forests to recover. Only in the more recent estimates is the sequestration potential of allowing degraded forests to recover to full maturity being considered.[46,47,56,57] The technical, or maximum, removal potential of allowing forests and other ecosystems to recover to natural carbon carrying capacity is large, estimated to peak at up to 8.5 Gt CO_2 $year^{-1}$ (Figure 3A).

However, the persistent misinterpretation of the term "forest restoration" as forest expansion or tree planting[58] has meant that the CDR potential of allowing degraded natural ecosystems to recover their natural carbon stock potential has often been overlooked. Labeling activities such as tree planting in agricultural lands or native grasslands as restoration has led to negative social and environmental impacts, including loss of biodiversity when native grasslands are forested,[58] livelihood displacement,[5] and overestimation of climate benefits.[59] The regeneration of degraded forests and other natural ecosystems (restoration) needs to be clearly differentiated from A/R.

Compounding the problem of mislabeling reforestation as restoration is a frequent lack of distinction between afforestation and reforestaion. Reforestation is understood as fostering natural succession or tree planting in deforested areas.[60] Afforestation, by contrast, is defined as "the direct human conversion of land to forests"[61] where they did not historically occur.[60] Land-based CDR included in modeled scenarios typically does not make any distinction, referring to A/R as one set of activities,[24] and several studies that find large areas for forest expansion follow suit.[27,49,54,59,62] Studies that differentiate A/R define reforestation as expanding and regenerating recently cleared forests,[56,57,63] occurring in forest ecoregions,[53] or just excluding afforestation.[64] Given the lack of clear distinction between A/R in some papers, excluding estimates that are or could be afforestation constrains reforestation potentials, with a maximum of 5 Gt CO_2 year^{-1} compared to 12 Gt CO_2 year^{-1} for afforestation (Figure 3A). Cost-effective potentials for reforestation are further constrained to 1.2–1.5 Gt CO_2 year^{-1}.[49,50]

Enhancing carbon removal in production forests is variously treated as restoration or forest management. Changes to forest management, including reduced harvest intensity and increased rotation length, can increase forest carbon stocks,[56,57] while harvested wood products are also considered a carbon sink.[27,46,49,50,53,54] However, with only 10% of carbon in harvested timber found in long-lived wood products, finding alternatives to short-lived wood products such as fuel wood or paper is also critical.[55] The extent to which improved forest management can contribute to CDR varies, as the distribution of carbon between aboveground and belowground stocks differs across forest biomes. There is evidence that in tropical and some temperate forests, where carbon is concentrated in aboveground biomass in larger trees, continued harvest will reduce carbon stocks regardless of management practices.[52,65] Reducing harvest intensity necessitates a trade-off with timber production. Some studies specify intensifying harvest in timber plantations to spare natural forests[57] or increasing production and use efficiencies, along with reducing wasteful consumption.[56,66]

Carbon removal on agricultural lands can be achieved via agroforestry (increasing trees in cropland or grazing lands)[27,46,49,50,53,56,57,66] or increased soil carbon sequestration in croplands and grasslands and via biochar (carbonized biomass sequestered in soils).[27,49,50] Agroforestry, which aims to increase trees in grazing lands and croplands without reducing livestock or crop yields, is widely thought of as delivering multiple benefits across climate, biodiversity, and livelihood goals.[67,68] However, the risk of agroforestry for restoration purposes is that non-native species are often used, which can become invasive and lead to the suppression of fire in fire-dependent ecosystems or the exclusion of other land uses.[58] In non-forested ecosystems, appropriate restoration includes resting land from grazing, seeding with native grasses, and clearing woody encroachment.[58] Biochar can contribute to CDR as well as other sustainability goals when derived from crop residues,[69] recognizing the limited availability[70] and competing uses of residues and wastes such as cover cropping and animal feed.[49]

Biophysical considerations for conventional CDR

Conventional CDR pathways impact climate not just through carbon removal but also via surface albedo, evaporative cooling, other GHGs, aerosols, and atmospheric circulation changes.[30] These factors can enhance or counteract the climate mitigation potential of CDR. Empirical evidence shows that forest expansion can impact climate patterns on local to regional scales,[71,72] while Earth system modeling suggests that the climate benefits from a future reforestation pathway can be negated by up to a third due to albedo and changes in non-CO_2 GHGs and aerosols.[31]

These interventions also occur against a backdrop of natural and uncontrolled variations in environmental conditions and disturbance regimes. Environmental conditions include CO_2 concentration, nitrogen deposition, temperature, precipitation, and vapor pressure deficit. Disturbances include wildfire, windthrow, and pest and pathogen outbreaks. These all have major impacts on the strength and stability of the land carbon cycle and ecosystem processes. Importantly, such changes will be superimposed onto CDR activities, leading to potentially complex effects on realized carbon storage and climate mitigation potential. The extent to which CDR activities can be controlled to follow a certain pathway is therefore inherently limited. Furthermore, this should be considered within the multidimensional framework of ecosystem integrity, which may provide better alignment with safeguards and lower risk profiles for the existing carbon stocks and additional potential carbon storage capacity from CDR.[39] In Figure 4, we assess which biophysical and biogeochemical factors are considered in the reviewed studies.

Various techniques are used to estimate CDR potential, including bookkeeping methods,[49] empirical models, machine learning models,[45,47,73] dynamic global vegetation models (DGVMs),[57] integrated assessment models (IAMs),[49] and hybrid approaches with DGVMs and IAMs.[59] Estimates of the maximum or trajectory of carbon storage potential vary widely. Various biophysical factors are considered and with varying degrees of detail, both in space (in terms of ecosystem types, land use, and climate drivers) and time (either static CDR potential maps or trajectories over time that may or may not factor in changing driving factors). Classification of ecosystem types varies from a few biomes[47,56,59,63] to hundreds of ecoregions.[54,66] Coarse-scale resolution estimates benefit from clear and simple assumptions, which can be more straightforward to align with mitigation scenarios and overarching global climate goals, such as those from IAMs. However, they do not reflect the inherent complexity and heterogeneity of real-world ecosystems. Finer-scale information on land cover, ecosystem, or vegetation type ensures that the carbon storage potential for different regions is categorized appropriately, generating more realistic technical CDR estimates to support targeted national and sub-national goals.

Consideration of variability in environmental conditions and disturbances may be equally important, although it is still lacking in many current estimates (Figure 4). For example, factors such

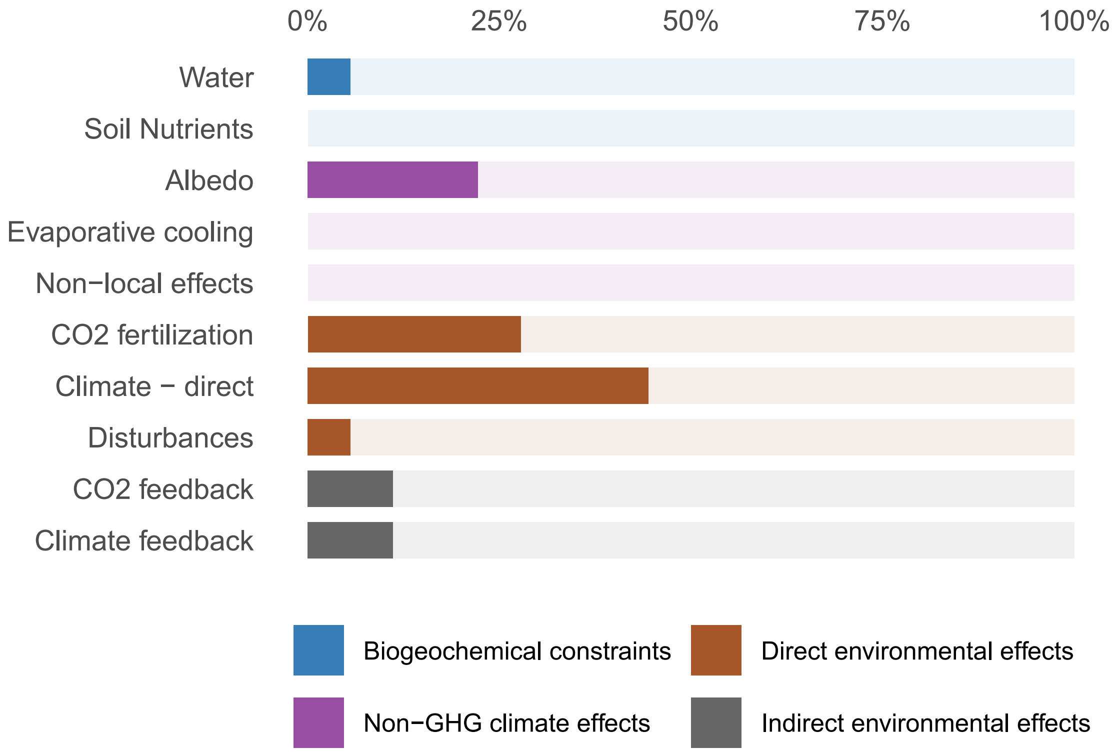

Figure 4. Share of reviewed papers that consider key biophysical and biogeochemical factors in conventional CDR estimates
Water: local water availability constraints, not including precipitation. Soil nutrients: soil fertility and nutrients including nitrogen, phosphorus, and potassium. Albedo: surface albedo changes due to land cover. Evaporative cooling: local cooling due to evapotranspiration. Non-local effects: atmospheric circulation changes and subsequent effects in regions beyond the site of CDR activity. CO_2 fertilization: effects of atmospheric CO_2 concentration. Climate - direct: climate constraints such as temperature and precipitation. CO_2 feedback: effect of CDR on land carbon-concentration feedback. Climate feedback: effect of CDR on land carbon-climate feedback (Table S2).

as soil nutrient availability and rainfall vary widely in space and can influence variations in the growth and carbon stocks of forests by more than a factor of ten, even within relatively narrow definitions of forest type.[74–77] From the limited studies available, the inclusion of these additional environmental constraints tends to dampen estimates of carbon storage capacity.[43,73,78] Consideration of disturbance regimes, which are playing an increased role in the carbon dynamics of forests,[79,80] are also lacking, with only one study explicitly accounting for current disturbance patterns and showing that they significantly reduce the biomass carrying capacity of forests worldwide (Figure 4).[73]

Refining CDR estimates to align with local climate, resource availability (e.g., water, soil fertility), and natural disturbance regimes may better synchronize with ecosystem integrity, which assumes that there is capacity for self-organization and regeneration in the context of prevailing local conditions.[39] It is important to note that prioritizing ecosystem integrity may not always maximize CDR potential. For example, naturally fire-prone and fire-adapted landscapes may have lower CDR potentials than if fire were completely suppressed, while plantation forests may store more carbon than an intact, unmanaged ecosystem in the same location. However, higher ecosystem integrity supports greater diversity in composition (e.g., species), structure (varied age and size classes of plants, deadwood), and function (e.g., tightly bound water or nutrient cycling), which can increase resilience and adaptive capacity in the face of changing environmental conditions.[39] Filtering CDR estimates through the ecosystem integrity lens would likely reduce the risk profile of carbon stocks and favor CDR pathways with long-term stability.[39]

Estimates of CDR potential must therefore consider the changes in environmental conditions and disturbance regimes that are likely to occur over the coming decades to ensure that the risk profiles for CDR pathways are minimized on timescales relevant to achieving global climate goals. Future changes in CO_2 concentration, climate, resource availability (e.g., water, soil nutrients),[81,82] and disturbance regimes[79,80] may significantly alter carbon storage capacity over time. Already, there are signs that the land may be transitioning from a CO_2 fertilization-driven carbon cycle to one driven by climate[83] and disturbance regimes.[79] Factors like CO_2 fertilization and nitrogen deposition may increase carbon storage capacity,[84] while factors such as increasing temperatures, wildfires, aridification,[85] and extractive activities, such as timber harvesting,[86] may decrease carbon storage capacity. A few studies accounted for CO_2 concentration on CDR estimates via modeling approaches,[49,56,57,63] while two studies conducted specific sensitivity analyses,[59,63] showing effects that were varied and sensitive to the choice of model and future emissions scenario (Figure 4). Impacts are uncertain and remain dependent on the choice of model[87–89] and future mitigation scenario.[90] Methods relying on bookkeeping, empirical models, and machine learning necessarily depend on historical observational data, which

Table 1. Rio Convention guardrails (benefits and safeguards)

	Definition
Benefits	
Human well-being	
FS	food security
SE	socio-economic (income and livelihoods)
RT	resources and technology
Ecosystem services	
C	carbon sequestration
AW	air and water
S	soil fertility
Resilience	
D	halting degradation
R	resilience
A	adaptation
Biodiversity	
EP	ecosystem protection
ER	ecosystem restoration
B	biodiversity
Safeguards	
Environmental	
CI	climate integrity
EI	ecosystem integrity
FG	forest governance/protection
Social	
FSP	food security and poverty eradication
F	climate finance
SSD	sovereignty and sustainable development
Rights	
HR	human rights
IP	rights of Indigenous peoples
P	stakeholder participation

inherently reflect the environmental conditions at the time and location they were taken. Approaches that use DGVMs and IAMs typically consider future changes in conditions more comprehensively, including CO_2 and climate feedbacks in some cases (Figure 4), but they may not be as rigorously calibrated or validated for the specific purpose of estimating carbon storage potential.

Historically, rising atmospheric CO_2 levels have been the primary driver of the land carbon sink.[91] Experimental evidence has shown that higher CO_2 levels can temporarily boost carbon stocks in younger, secondary forests like those used in reforestation and afforestation, although these benefits are location and scenario specific and influenced by soil fertility, forest type, forest age, and climate.[92] Long-term, elevated CO_2 levels cannot be universally relied upon for enhanced carbon storage in biomass or soils,[92,93] especially under low-emissions scenarios consistent with Paris Agreement goals. If CO_2 levels plateau and decline, then the land would be placed in conditions with no recent historical precedent, cautioning against an overreliance on empirical and machine learning models. Better consideration of these factors, using additional empirical data and Earth system models, could help determine more targeted and effective land-based climate mitigation pathways (e.g., Rohatyn et al.[62]).

Rio Convention guardrails to CDR implementation

Assessment of "nature-based" CDR requires consideration of the benefits and safeguards of each activity. UNEA Resolution 5/5 provides clear text to this effect: "while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits, [the resolution] recognizes that nature-based solutions: (a) Respect social and environmental safeguards, in line with the three "Rio Conventions" including such safeguards for local communities and indigenous peoples."[12] Characterizing these as Rio Convention guardrails, we extracted benefits and safeguards from the three conventions, focusing on operational language and, where relevant, convention objectives. This yielded a list of 77 instances of potential benefits/safeguards (Tables S3 and S4), which we coded into nine safeguard types across three categories: environmental, social, and rights (Table 1). While the benefits listed in the UNEA resolution are already categorized and widely used (e.g., Roe et al.[49]), we noted that safeguards derived from Rio Conventions differed from those typically referenced in the literature in their focus on climate finance, sovereignty, and sustainable development under social safeguards and ecosystem integrity and preventing natural forest conversion under environmental safeguards. The attention paid to human rights and the rights of Indigenous peoples was prominent across all Rio Conventions.

In contrast, papers estimating nature-based CDR focused on food security and poverty reduction for social safeguards and biodiversity for environmental safeguards, with little to no discussion of rights (Figure 5). Several studies extrapolate environmental and social safeguards from one paper,[28] which defined these as (1) no reduction in existing cropland area, (2) reduced timber production supplemented with additional plantations or reforestation, and (3) avoiding afforestation of non-forest biomes. This represents an insufficient understanding of social and environmental safeguards and does not align with the Rio Conventions. Development of safeguards in land sector mitigation studies should be expanded from the current focus on social and environmental safeguards to also include human rights and the rights of Indigenous peoples, sustainable development objectives, and climate finance. Overall, we found a greater focus on the benefits of nature-based CDR than on safeguards, with constraints often represented as minimizing impacts on agricultural and habitable areas.[27,46,47,49,53]

Climate finance, sovereignty, and sustainable development are key elements of all three Rio Conventions, in terms of both objectives and safeguards. Beyond constraining CDR activities for cost effectiveness (i.e., limiting activities to those costing below USD 50 or 100 per tonne CO_2),[49,50,54,59,64] public financing for up-front restoration costs and supporting taxation and regulatory reform was mentioned in only three studies.[50,56,63] Yet, financing nature's contribution to climate, land degradation, and biodiversity targets could require a tripling in investments by 2030.[94] Aligning ecosystem protection with sustainable development goals (SDGs) could drive up to 25% of the expected land sector abatement requirements until 2050

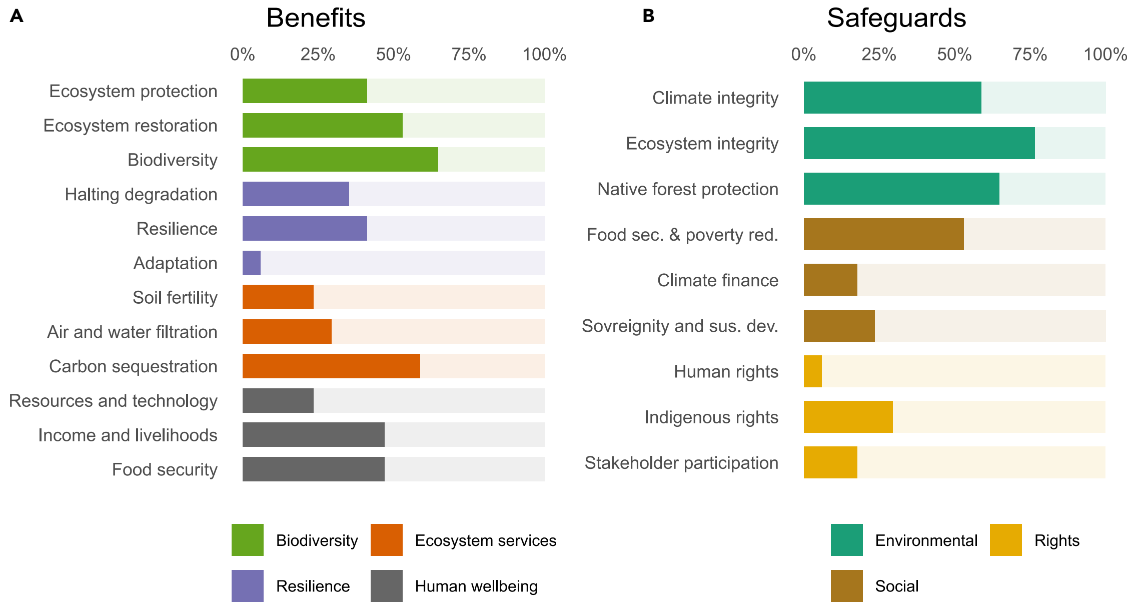

Figure 5. Consideration of benefits and safeguards for conventional CDR in line with Rio Conventions
(A) The share of papers discussing benefits of conventional CDR as defined in the UNEA NBS definition (Table S3).
(B) The share of papers considering safeguards as codified from the Rio Conventions (Table S4).

by reducing emissions from land-use change and livestock, along with dietary changes.[95]

There is significant potential for the restoration of agricultural lands, although avoiding habited lands altogether is applied by some studies as a safeguard for preventing negative impacts on food security and livelihoods.[46,47] Preserving and restoring partial tree cover in agricultural regions (in field borders, gullies, and pasture) could have positive carbon sequestration benefits, potentially with low impacts on production.[66] While there has been considerable interest in increasing soil carbon, the climate mitigation benefits are highly uncertain.[96] There is also great potential in improved but ongoing management of natural forests to increase carbon sequestration (i.e., reduce harvest intensity), but achieving any benefits at scale would require significant decreases in timber consumption. Currently, studies limit the CDR potential from this activity to protect timber production,[49,53] apart from those demonstrating the theoretical potential of ending forest harvest.[46,73]

Several studies acknowledged the need to respect the rights of Indigenous peoples, including respecting collective tenure systems and strengthening land titling.[47,50,56,57,63] The importance of aligning decisions about nature restoration with local priorities to protect well-being and livelihoods was recognised,[46,47,50] as these will work "only when healthy biodiversity is the preferred choice for local people in the long term."[47] However, there is a notable discrepancy between the increasing recognition of human rights across all Rio Conventions and a lack of attention to human rights in papers assessing CDR potentials, with only one paper from our sample referencing human rights.[50]

Discussion of benefits centers around climate mitigation and ecosystem services. A wide range of vital ecosystem services are reported (e.g., biodiversity, water and air filtration, soil health) in addition to carbon sequestration.[27,49,53,57,63,95] Biodiversity was assessed separately from ecosystem services due to its fundamental role in underpinning ecosystem integrity.[39] While many studies emphasized biodiversity, ecosystem integrity was rarely mentioned. Benefits framed as resilience featured in papers that define restoration as halting degradation[46,47,56,57,73] and allowing natural forests to recover from where they had previously been lost as a result of human activity.[47,50,53,56,57,63] Studies that did not frame benefits in terms of biodiversity, resilience, and halting degradation were more likely to include afforestation and the conversion of natural ecosystems or agricultural lands.[45,54,59] Increased resilience of restored ecosystems was associated with adaptive capacity.[49,57]

More recent work has suggested foundational principles and operational criteria for nature-based approaches that include human rights and the rights of Indigenous peoples; retain ecosystem integrity; sustain ecosystem services, including biodiversity; and consider climate integrity.[97] Such work starts to bridge the gap between conventional CDR, particularly that framed as a quantification of nature-based removals, and the objectives of the Rio Conventions. However, discussion of public climate finance and broader reforms to support nature restoration in the context of sustainable development, such as debt relief and tax justice, is lacking.

DISCUSSION

Three key findings emerge from our review that are critical to the effective implementation of conventional CDR to maximize ecosystem integrity and synergies across Rio Conventions: a need for greater attention to impacts on human rights, ensuring restoration efforts contribute to and do not undermine ecosystem integrity, and including global to local climate and biophysical effects in estimates of conventional CDR potential.

A key finding from our review is that analyses of the biodiversity, human well-being, and resilience benefits that can be achieved through nature-based CDR should pay closer attention to alignment with human rights. We find that across CDR estimates, safeguards are often treated superficially, while often, human rights are not mentioned at all. This contrasts with an observable shift to more clearly identifying states' climate mitigation obligations under the main human rights treaties.[98] There is now increasing recognition of the link between human rights and climate change, both within Rio Conventions and due to the connection being made in courts and by human rights bodies.[98] UNEA Resolution 5/5, in particular, emphasizes the rights of Indigenous peoples, who are key to more effective stewardship of natural ecosystems.[99] Research continues to highlight that equitable governance delivering primary control or equal partnership for Indigenous peoples and local communities leads to significantly more positive ecological outcomes.[100–102] Analysis of international human rights legal frameworks suggests that there is a human-rights-based obligation to protect the climate, which extends to prioritizing emissions reductions ahead of forms of CDR that could impinge on human rights to food, water, energy, etc.[103] We suggest that close attention to human rights represents a major gap between projections of CDR potentials and implementation in a framework aligned with Rio Conventions.

The second critical concern for implementation is the widespread use of the term "restoration" to refer to reforestation, with criticism directed at restoration under the guise of extensive tree planting and forest expansion.[58,104] Multiple examples exist where non-forest systems are the principal target of restoration by increasing the number of trees, resulting in high failure rates of large-scale tree-planting programs in non-forest biomes.[105] One review of forest restoration projects in the African Forest Restoration Initiative (AFR100) found 52% of identified restoration sites occurring in savanna or grasslands.[58] The study's authors describe this as a "double jeopardy," where tree planting drives biodiversity loss through the afforestation of native grasslands and the deforestation of primary forests through displacing agriculture.[58] Ecosystem restoration should be identified separately from afforestation or reforestation, which involve distinct forms of forest expansion and tree planting. The lack of an ecological lens in some forest definitions (as land with more than 10% tree cover) is a contributing factor to forest expansion in non-forested biomes,[5,106] as it does not clearly distinguish grassy biomes from forests, categorizing fire-dependent savanna and woodlands as forest.[60] The restoration of existing forests should also be clearly differentiated from tree planting—for example, as forest regeneration.[60] Forest expansion should be evaluated based on site-specific characteristics related to a variety of factors, such as land use, potential for natural regrowth of forest, conservation, and rural livelihood value, rather than just biophysical or forest cover potential to obtain feasible carbon mitigation outcomes.[5–7]

The third important finding relates to the extent to which estimates of future CDR potential account for background climate effects, which have major impacts on the strength and stability of the land carbon cycle, posing risks to the potential and permanence of CDR. Our review shows that many studies do not include this, yet background climate effects should be considered within the multidimensional framework of ecosystem integrity, which may provide better alignment with safeguards and lower risk profiles for existing carbon stocks and additional potential carbon storage capacity from CDR. For example, two-thirds of the CDR from afforestation of global drylands would be needed to offset the warming effects of albedo reduction, suggesting that without targeted efforts that account for albedo and other biophysical effects, A/R may be a poor investment.[62] In general, a more comprehensive view of land-based climate mitigation tends to dampen the overall potential of CDR pathways reliant on reforestation and afforestation. Better consideration of these factors, using additional empirical data and Earth system models, could help determine more targeted and effective land-based climate mitigation pathways.[62]

Estimates of carbon sequestration potential are likely to be upper-bound estimates, not only because they calculate technical potential (as noted by Walker et al.[46]) but also because they do not fully account for changes in natural disturbances (fires, pests, pathogens, storms) or ecophysiological responses of vegetation and soils to changing climate and CO_2 concentration conditions (drought, temperature extremes, declining CO_2 fertilization effects). Care must be taken with historical observations of carbon stocks, as they are generally recorded under fluctuating environmental conditions that can have subtle but significant effects on carbon storage potentials, which data-driven models then project into the future and for different regions where these conditions may be entirely different.[63] The use of DGVMs and hybrid approaches may be useful to help address this shortcoming and integrate concepts of ecosystem integrity, as they explicitly represent key elements such as ecosystem structure, function, and composition.[107] Nevertheless, these approaches remain uncertain, as models disagree on future predictions of the carbon cycle. Ultimately, the contribution of nature-based CDR remains uncertain and is limited by site-specific characteristics and carbon cycle uncertainties, which ought to be factored into assessments of risk. More site-specific targeted efforts can yield much better climate mitigation outcomes while ensuring positive biodiversity, social, and human rights benefits.

OUTLOOK

This review has highlighted the many uncertainties in translating land-based CDR estimates into climate benefits, given the climate mitigation value is not solely based on technical or economic potential. Future research and policy efforts should avoid directly translating CDR potential into climate mitigation targets and pledges, acknowledging the uncertainties and often limited contribution to climate goals from land carbon removals. The four benefits outlined in the UNEA NBS resolution—human well-being, ecosystem services, resilience, and biodiversity—are already used as a framework in many nature-based removal assessments. What becomes clear from viewing CDR through an ecosystem integrity lens is that nature-based approaches to CDR should be implemented for their broader co-benefits and not primarily for carbon sequestration values.

Alignment with safeguards when interpreted in the context of the Rio Conventions are inadequately represented in the literature on nature-based CDR. Attention to human rights and the rights of Indigenous peoples is a critical gap in NBS pathways.

Other safeguards prominent across the three Rio Conventions that do not feature in much of the literature include the need to safeguard sustainable development, provide adequate climate finance, and respect sovereignty. An important point reiterated across several of the studies reviewed is that the climate mitigation benefits of conventional CDR accrue only when this is in addition to, not instead of, emissions reductions.[50,56,57]

Overall, nature-based approaches to CDR would be expected to more comprehensively address feasibility constraints compared to the A/R and BECCS approaches taken in IAM scenarios, but concerns remain, particularly regarding ambiguous definitions around forests, restoration, and reforestation, which in many cases has led to the reforestation of open savannahs and fire-prone biomes with disastrous consequences for biodiversity and human livelihoods. Promisingly, the trend in the literature is moving away from CDR pathways that rely on forest expansion to genuine ecosystem restoration (e.g., Mo et al.[47]) and using assessment methodologies that do not rely on forest cover definitions (e.g., Walker et al.[46]). These studies continue to label reforestation as restoration (and restoration as conservation), but they do show that allowing degraded forest ecosystems to recover their natural carbon carrying capacity offers the largest CDR potential, far exceeding the potential of reforestation, once agricultural and urban areas are excluded from tree planting.[47] Beyond forests, restoration of a diverse range of ecosystems is needed to achieve biodiversity and land degradation goals, which is reflected in many of the sectoral studies reviewed.[46,49,50]

Such trends are yet to be seen in the IAM literature, where land-based removals continue to be primarily delineated as BECCS, A/R, and biochar, thereby hampering assessment of the ecosystem integrity of CDR approaches. The large near-term dependence on conventional CDR motivates further work to address this limitation. Assessing CDR through an ecosystem integrity lens can help to prioritize or align CDR approaches with the objectives of the three Rio Conventions, most importantly in terms of protecting biodiversity, respecting rights, and supporting sustainable development. Future research should thoroughly consider how conventional CDR may impact human rights in order to guide policy implementation. The Rio Conventions guardrails developed here provide a useful legal and political framework for such research.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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