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Perspective

Toward quantification of the feasible potential of land-based carbon dioxide removal

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SUMMARY

Global climate-change overshoot scenarios, where warming exceeds Paris Agreement limits before being brought back down, are highly dependent on land-based carbon dioxide removal (CDR). In the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), such scenarios are supported by optimistic global assessments of the technical and economic potential for land-based CDR. However, a further type of potential—the "feasible" potential, which includes socio-cultural, environmental, and institutional factors—is noted in the AR6 but not quantified. Here, we set out research frameworks to work toward quantification of this feasible potential. We first argue that quantifying the feasible potential will substantially reduce current assessed CDR potential. Second, we demonstrate how transdisciplinary methods are improving understanding of feasibility constraints on land-based CDR. Third, we explore frameworks for synthesizing these advances during the next IPCC assessment process. We conclude that the research community should carefully consider the use of techno-economic CDR assessments in evidence for policymakers.

INTRODUCTION

Human activity is placing enormous strain on the land system.[1] Increased demand for agricultural commodities has led to the rapid and widespread expansion of agricultural lands[2] as well as intensification in food and fiber production.[3] This, in turn, has had substantial impacts across multiple planetary boundaries, including for biosphere integrity, biogeochemical flows, and freshwater use.[4] Such widespread impacts raise urgent questions about the sustainability of current food production systems and their resilience to climate change.[5] Furthermore, agriculture, forestry, and other land use (AFOLU) contribute about 23% of annual anthropogenic greenhouse gas (GHG) emissions in carbon dioxide equivalents (CO_2 eq.).[6] As a result, reducing emissions from land use is an urgent climate change mitigation priority.[7]

The land system is a major target not only for reducing greenhouse gas emissions but also for offsetting emissions from the energy, industrial, and transportation sectors through land-based carbon dioxide removal (CDR).[8] Land-based CDR encompasses a wide range of techniques to sequester carbon in vegetation (e.g., through tree planting), soil (e.g., through conservation agriculture), and geological sinks (e.g., through bioenergy with carbon capture and storage).[9] Land-based CDR features prominently in both modeled scenarios of climate change mitigation and countries' own declared plans for decarbonization expressed in their Nationally Determined Contributions (NDCs) under the Paris Agreement.[10]

The Intergovernmental Panel on Climate Change (IPCC) AR6 assessed land-based CDR potential in two main ways: the technical potential, defined as "the biophysical potential or amount possible with current technologies" and the economic potential, defined as the technical potential "constrained by costs, usually by a given carbon price" (p774).[7] Of these, the global technical potential, primarily quantified using "sectoral" or single-CDR assessments, is given in the AR6 as 28.4 $GtCO_2$ eq. y^{-1} in 2050, while the economic potential, primarily quantified using integrated assessment models (IAMs), is given as 7.9 $GtCO_2$ eq. y^{-1}.[7] To put these numbers into perspective, global anthropogenic GHG emissions in 2021 were 55.5 GtCO2 eq.[11] The difference between technical and economic CDR potentials is principally attributed by the AR6 to IAMs capturing competition for land between different CDR practices, which cannot be captured in sectoral (individual) CDR assessments.[7]

The possibility of such planetary-scale CDR underpins the viability of many modeled scenarios of global decarbonization in line with the Paris Agreement and in particular of overshoot scenarios.[12,13] In overshoot scenarios, temperatures temporarily exceed a given threshold before GHG removals enable the world to reach net-negative emissions and hence bring temperatures back below the target.[14] In the AR6 Scenarios Database,[15]

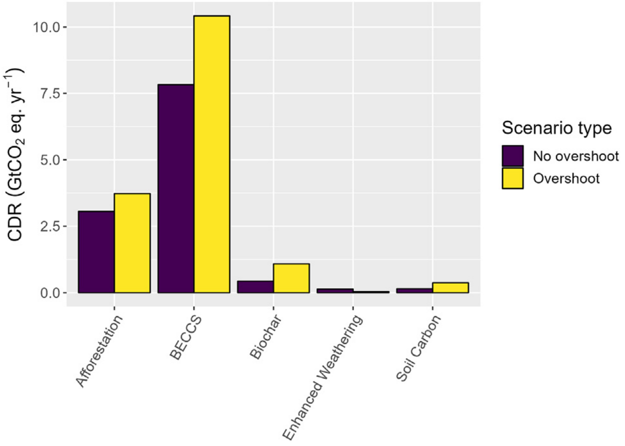

Figure 1. Mean land-based CDRs in 2100 for 1.5°C-compliant scenarios
While >90% of all scenarios involve some level of land-based CDR, overshoot scenarios are particularly dependent upon it. Data from AR6 Scenarios Database.[15]

scenarios with greater than a two-thirds probability of restricting global warming to 1.5°C had mean GHG removals from land-based CDR of 13.8 Gt CO_2 eq. y^{-1} in 2100 (probabilities based on the MAGICC climate emulator[16]). Of these, overshoot scenarios have mean removals of 15.4 Gt CO_2 eq. y^{-1} compared with 11.4 Gt CO_2 eq. y^{-1} in scenarios without overshoot (Figure 1). Furthermore, overshoot scenarios comprise 436 of 648 scenarios with at least a two-thirds probability of restricting global warming to 1.5°C in 2100.[15] Just 29 of 436 such overshoot scenarios do not involve land-based CDR. Together, this implicitly gives great confidence to the deliverability of land-based CDR at the scales required.

However, serious concerns have been raised about the feasibility of such planetary-scale CDR. Informed by optimistic techno-economic projections, CDR now features in 121 out of 167 NDCs under the Paris Agreement;[10] in developed countries' NDCs, the residual emissions offset by CDR are assumed to be at least 17.9% of present-day levels.[17] Consequently, the global land gap report calculated that delivering governments' pledges for all land-based CDR techniques would require 1.2 billion hectares of land.[18] This area is of the same order of magnitude as the current global cropland area (1.56 billion hectares).[6] Land-use change on this scale may overlook the fact that we now inhabit a "used" planet: there is little land that can be used for CDR without complex trade-offs.[19]

The case of soybean expansion provides a useful heuristic for the possible implications of the rates of land-use change implied by countries' NDCs. Globally, the planted area of soybeans increased by 105.7 Mha (+443.8%) from 1961 to 2021, an area representing about 7% of present-day global cropland area.[20] This degree of change was driven by profound shifts in global economic forces, notably the accession of China to the World Trade Organization and its subsequent increase in demand for meat.[21,22] Soybean expansion has been identified as a central driver in Amazon deforestation.[23] However, Turner et al.[24] calculated that global decarbonization scenarios consistent with warming of 2°C or lower in 2100 had a median rate of bioenergy crop expansion for bioenergy with carbon capture and storage (BECCS) of 8.8 Mha y^{-1} (8.4% y^{-1}). This is more than three times greater than the historical rate of expansion of soybeans, and so is unprecedented in human history.[24] Such rapid rates of change have clear implications for planetary boundaries[25,26] and for the UN Sustainable Development Goals.[27] In short, the feasibility of achieving the land-based CDR targets set out in countries' NDCs is uncertain, and their consequences for human wellbeing and the environment are potentially severe.

Further evidence of the likely importance of feasibility constraints on CDR potential comes from existing large-scale land-use schemes for climate change mitigation. For example, the USA Renewable Fuel Standard (RFS) has been the largest program to date of subsidies for biofuels.[28] However, rather than reduce emissions, the RFS led to land-use changes within the USA that caused corn ethanol produced by the scheme to have emissions that were 24% higher than conventional petrol.[28] Furthermore, the RFS has been heavily criticized for driving displaced or "indirect" land-use change, particularly in the Amazon,[29] although the extent of this is disputed.[30] Similarly, the California forestry offset program has struggled to deliver robust carbon removals,[31] being challenged by over-crediting[32] and unbudgeted losses due to fires.[33] These early attempts at real-world delivery of land-based climate change mitigation do not disprove the possibility of future large-scale CDR. However, they do illustrate potential for substantial challenges to the feasibility of delivering land-based CDR even at relatively small scales, long before the unprecedented rates of delivery envisaged in overshoot scenarios and NDCs are attempted.

The IPCC AR6 defines the feasible potential of CDR as the economic potential "constrained by environmental, socio-cultural, and/or institutional barriers" (p774).[7] Comprehensive quantitative assessment of feasibility constraints remains limited. Feasibility has instead primarily been explored through expert elicitation[34,35] or analysis of one aspect of CDR projections such as the implied rate of land-use change in CDR projections.[36] As a result, in the AR6, the feasible CDR potential is not quantified. To our knowledge, the only existing attempt to quantify land-based CDR feasibility globally was that of Roe et al.,[37] who used secondary data to construct a national-scale feasibility index. Data presented in Roe et al.'s study suggest countries with technical potential greater than 0.1 CO_2 eq. y^{-1} have lower environmental, social, and political feasibility than countries with technical potential less than 0.1 CO_2 eq. y^{-1}. Notably, these aspects of CDR assessment are often overlooked by IAMs.[38]

However, in spite of growing evidence that techno-economic CDR assessments neglect crucial processes that will constrain real-world delivery, such highly optimistic and uncertain assessments continue to inform large commitments to CDR in government policies.[10,17,18] In response, integrated assessment modeling has begun to explore decarbonization scenarios with lower residual emissions and therefore reduced CDR.[13,39] This is a positive and necessary step, but, as long as the assessed potential for CDR includes the multi-Gigaton scales envisaged in the AR6, governments will be able to claim compliance with the Paris Agreement on that basis while also taking limited action to reduce present-day emissions.[40,41] The climate change research community is currently beginning work on the Seventh IPCC Assessment Report (AR7), a process that will last until around 2030 and form the basis of the next major synthesis of evidence presented to global policymakers. Therefore, there is both cause and opportunity for a rethink in how the potential for land-based CDR is quantified and presented to policymakers.

In this perspective, we review understanding of feasibility constraints on land-based CDR. We argue that feasibility has been substantially neglected as a concern in CDR assessments and that feasibility will likely very considerably constrain real-world implementation of assessed techno-economic CDR potentials. This, in turn, will likely mean that many scenarios of global decarbonization, and government policies based upon them, cannot be delivered. However, we also show how improvements in quantifying the feasible CDR potential are being made through better representation of constraints, highlighting the important role of alternate model paradigms to IAMs. We suggest research frameworks to achieve a robust quantification of CDR feasibility and argue that such quantification must be a central goal for the research community in the IPCC AR7.

DEFINING FEASIBILITY CONSTRAINTS ON LAND-BASED CDR

We provide our perspective on the central feasibility constraints on land-based CDR potential, following the IPCC categorization of environmental, socio-cultural, and institutional barriers (hereafter referred to in aggregate as feasibility constraints). Of these categories of constraint, environmental barriers are the best studied and quantified (e.g., Calvin et al.[42] and Nolan et al.[43]). Therefore, our discussion focuses primarily on socio-cultural and institutional barriers, as well as interactions between different constraints. Importantly, we focus on how such constraints affect the underlying plausibility of delivery. We acknowledge there are many additional constraints, including environmental impacts[42] and normative considerations,[44] on the *desirability* of CDR: discussion of these concerns should continue to accompany any scenarios presented to policymakers.

Socio-cultural barriers

Human behavior

Human behavior is one of the main factors affecting land-based CDR feasibility. The land system is composed of a huge number and diversity of actors, each embedded within varied social, institutional, and governance contexts that constrain their agency.[45,46] If land-based CDR is to achieve its mitigation potential, many of these actors need to change their established activities at great speed and scale across large geographic extents.[47]

Land-use models and policies often assume that land managers act as economic optimizers with full knowledge of the options available to them.[48,49] This makes transformative change in land management appear feasible over short timescales and gives rise to projected rates of land-use change for CDR that are unprecedented in human history.[24] Such projections neglect a range of behavioral time-lags including adoption rates and contested decision making at the science-policy interface.[47,50,51] For example, studies of land-system actors emphasize the complexity of behaviors arising from contextual and individual characteristics, which preclude consistent responses across large areas.[52–54] Similarly, numerous case studies demonstrate that farmer decision making remains strongly dependent on social networks, which are often of limited geographical or typological extent.[55–57] These networks also interact with governance systems to produce uneven distributions of change.[58,59] Meanwhile, a range of motivations associated with financial, social, and environmental factors make responses differ even within small populations of land managers.[60–62] As a result, actual land-use change is highly suboptimal, with spread of superior management options typically occurring over decades.[51,63,64]

Structural factors

Land-system change is inherently bound up with questions of poverty, inequality, and sustainable development.[65,66] The global land system is composed of more than 600 million farms, 90% of which are family farms, and 70% of which are less than 1 ha in size.[67] At the same time, smallholder farmers have been under pressure from large-scale land acquisitions by national governments and international corporations: between 2000 and 2019, 25.2 million hectares of land were acquired in the Global South.[68] Overall, the diversity of actors in the land system creates conflict over land rights and tenure, with power disparities embodied in differing and contested modes of ownership.[69] For example, there are contested claims over more than half of Brazilian lands with registered ownership.[70]

The impact of structural factors on CDR feasibility is well illustrated by the experience of agroforestry. Agroforestry has potential to be a win-win management option that increases farmers' incomes while simultaneously enhancing resilience to climate change and improving ecosystem health.[71] Globally, more than US$10 billion has been invested by government and non-state actors in promoting agroforestry.[72] However, uptake of agroforestry among smallholder farmers has been limited.[73] Insecure land tenure can prevent farmers from investing in agroforestry, which requires time for trees to grow.[74,75] Further barriers include difficulties in knowledge diffusion[76] and farmers' capacity to cover upfront costs.[77,78] Fundamentally, resistance to agroforestry adoption is consistent with an inherent conservatism born of necessity among farmers close to the poverty line,[79] for whom unknown innovations in practice represent an inherent risk to the food security of their dependents.[80]

Structural barriers to CDR uptake are not limited to the most precarious subsistence farmers. The industrialization of agriculture, while bringing benefits of innovation and increased yields, can create structural barriers to adaptation by imposing economic constraints on farmer decision making.[81,82] For example, contract farming can lead to incentive structures that mean farmers knowingly over-apply fertilizers—a key source of farm emissions—because of fears of jeopardizing contracts with suppliers.[83,84] Furthermore, studies in the US Midwest have shown how profit imperatives can drive farmers to adopt fertilizer practices that protect short-term yields but that run counter to CDR objectives and may even drive up costs of production over the longer term.[85] In Brazil, even the larger commercial soybean farmers can become bound into contracts with seed producers that force them to prioritize existing loan repayments and to commit exclusive trade arrangements with the fertilizer and seed companies on which they depend.[86] These commitments can tie producers to particular production practices, limiting their ability to adopt novel practices such as CDR.

Overall, these examples from contrasting farming contexts indicate how techno-economic assessments of CDR potential

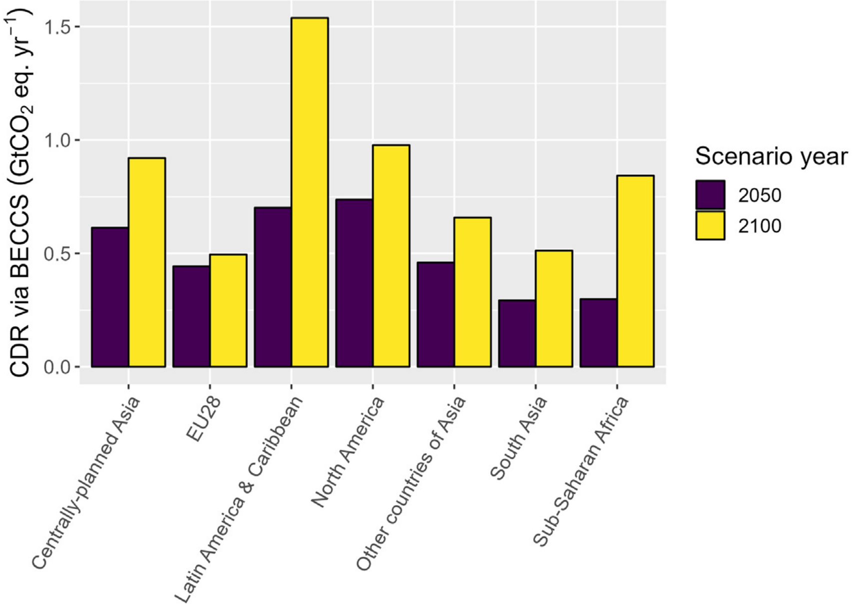

Figure 2. CDR through bioenergy with BECCS in selected regions from AR6 scenarios reaching <1.5°C in 2100

BECCS expansion is extensive in all regions, notably in Latin America and the Caribbean, a region where governance of agricultural expansion has proved challenging. Expansion was also rapid in sub-Saharan Africa between 2050 and 2100 (+0.55 $GtCO_2$ eq. y^{-1}), pointing to the dependence of scenarios on tackling structural challenges in the region. We have used the 10-region global classification adopted in the AR6 Scenarios Database (R10). Centrally planned Asia is "primarily China"; EU28 is the 28 nations of the European Union (including the United Kingdom); South Asia is "primarily India." Data from AR6 Scenarios Database.[15]

that do not consider structural factors may substantially overestimate rates of uptake.[35]

Institutional barriers

Monitoring, reporting, and verifying

Land-based CDR occurs over vast areas, making reliable calculation of resulting carbon fluxes challenging and highly uncertain.[87] Furthermore, the complexity of the carbon calculations creates a space where technical discourses may mask actors' motivation to delay decarbonization with overclaimed offsets.[40,88] This challenge has led to carbon crediting programs exaggerating the scale of removals.[32,33] Novick et al.[89] outline a vision for the science required to inform robust land-based CDR in the US: an extensive network of flux towers covering forests, croplands, wetlands, and coastal ecosystems complemented with widespread field sampling of soils, state-of-the-art Earth observation data, and models. While such a scientific infrastructure may be deliverable in developed-world contexts, it is questionable whether such an approach is feasible globally. Hence, the difficulty of quantifying carbon removals from land-based CDR, and associated over-crediting, is likely to remain.

A further difficulty with quantifying real-world sequestration lies in national government's incentive not to consider emissions and environmental impacts internationally: an incentive embedded in global climate negotiations since the Kyoto protocol.[90] The potential for biofuel policies to drive indirect or displaced deforestation is well established,[29,30] yet governments have been reluctant to include such considerations in environmental policies. For example, the European Union's recent Green New Deal may achieve its aims by offshoring much environmental damage associated with food production.[91]

Institutional capacity and decision making

Assuming that rates of carbon sequestration can be accurately captured, there remains a question of whether institutional actors can implement those methods appropriately. Institutional capacity for CDR has received most attention with reference to countries attempting to control rapid deforestation.[92] For example, strong lobbying from agribusiness led to changes in forest conservation policy in Brazil in 2012, forgiving previous illegal deforestation by smaller private landowners.[93] This amnesty has since been shown to have prevented restoration of 14.6 million hectares of illegally created agricultural land, an area estimated to be able to store 2.4 gigatonnes of carbon in natural vegetation.[94] Dramatic shifts in government policy of the kind that beset attempts to control deforestation during the presidency of Jair Bolsonaro exacerbate the challenge, as they can involve the deliberate dismantling of institutional capacities.[95,96] Given such challenges in the Amazon basin, it is notable that, in scenarios where global temperatures are <1.5°C in 2100, BECCS expands most rapidly in Latin America and the Caribbean (1.54 $GtCO_2$ eq. y^{-1} in 2100; Figure 2). Hence, there is potentially a mismatch between economic drivers of CDR uptake and governance capacity to support effective delivery.

Institutional implications for land-based CDR are not restricted to developing countries. Implementation has also been inadequate in rich countries with strong institutional capabilities.[97] One reason is that institutions in those countries are closely associated with the fossil fuel industry, which has supported their development.[98,99] However, even genuine attempts to expand land-based CDR involve trade-offs against other priorities such as food production and landscape protection, enshrined in the same strong institutional frameworks.[100] This means that CDR strategies are most likely to be successful when they align with normative principles already embedded in governance systems.[27]

Institutional capacities do not only relate to public policy. The private sector will need to play a critical role if nature-based objectives, such as climate change mitigation, are to be achieved. Current private-sector decarbonization pathways are inconsistent with the Paris climate goals,[101] and marketization of carbon can easily favor cost-effectiveness over CDR effectiveness, raising the risk of private finance actively if inadvertently undermining climate goals.[102] Guaranteeing positive contributions requires novel alignments of institutional actors with complementary resources, knowledge bases, and capacities, operating within detailed regulatory frameworks.[103] Models that do not consider such complications are unlikely to accurately project CDR feasibility.

Environmental barriers

Delivering planetary-scale CDR without accompanying (and self-defeating) deforestation requires large agricultural yield increases, while simultaneously decreasing GHG emissions from agriculture. Existing Paris Agreement-compliant scenarios of global bioenergy and forest area expansion for CDR assume cereal yield increases of >50% from 2020 to 2100.[104] The environmental and societal sustainability of such yield increases is questionable. Approximately 70% of ground- or surface-water withdrawals by humans are already used for irrigation,[105] land-use change and intensification of land use are dominant direct drivers of biodiversity loss,[106,107] and approximately 2Gt CO_2 eq. y^{-1} of emissions result from N_2O due to fertilizer use.[6] For these reasons, the joint Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and IPCC workshop report on biodiversity and climate change recommended CDR from BECCS should be limited to 1–2.5 $GtCO_2$ y^{-1} in 2050.[108] Keeping to the upper limit of this constraint (2.5 $GtCO_2$ y^{-1}) would remove half (217 out of 436) of overshoot scenarios in the AR6 database. In 2100, just three overshoot scenarios stay within this threshold.

Furthermore, land degradation in arable lands poses a substantial challenge to the sustainability of present-day yields before any future yield increases are considered. As much as 70% of agricultural soils in the EU are managed unsustainably[109]; similarly, Prăvălie et al.[110] estimate ~62% of global arable lands are threatened by a land degradation process, while ~7% are affected by two or more degradation processes. Substantial efforts will need to be made to maintain present-day yields, with future yield gains at least requiring "sustainably intensive" implementation.[111]

Concurrently, observations and modeling studies are increasingly identifying impacts of weather extremes that accompany climate change as causes of reduced yield increases or even losses.[112,113] Transformative agricultural innovations such as achieving large increases in photosynthetic efficiency or taking better advantage of root-microbial interactions,[114–116] could *in principle* help to contribute to sustainable yield increases, even under climate change, but so far these methods are still in the experimental phases. Therefore, assumptions about "technological" yield increases in modeling studies, which do not consider negative environmental side effects or resilience to extreme weather impacts, remain speculative at best.

Interactions between barriers

As a coupled socio-environmental system, land-system processes operate across the socio-cultural, institutional, and environmental constraints described above. Resulting human-Earth system interactions are a vital consideration for CDR feasibility. For example, the geo-political conflict in Ukraine highlights how shocks can cascade through the globalized food production system and illustrates how limited farmers' agency can be to increase (or even maintain) yields in response to system shocks and subsequently elevated commodity prices.[117,118] An important way in which human-Earth system interactions may affect CDR feasibility is impermanence: the potential for environmental changes, policy change, or technical failure to cause previously sequestered carbon stocks to be re-released.[119]

For example, fire poses an obvious risk to sequestered carbon stocks in soil and vegetation that is likely to be exacerbated under climate change.[120] Fire has already caused significant disruption to the California forestry offset market, having destroyed much of the reserve pool set aside to hedge against future risk.[33] However, as a coupled human-natural system,[121,122] fire risk to sequestered carbon stocks also comes from interactions with socio-economic processes. For example, anthropogenic pasture management fires frequently escape into logged forest edges in the Brazilian Amazon.[123] There are no easy management solutions to such problems: simply removing fire from a landscape is frequently counter-productive.[124] In developing-world contexts, government bans on farmers' fire use have frequently led to chaotic fire regimes driven by uncontrolled, clandestine fire use and arson as a protest.[125] Conversely, in developed-world contexts, intensive suppression of fires has led to the "fire paradox": over-suppression leading to fuel buildups that ultimately lead to increased fire.[126]

Fire is far from the only process that poses a risk to terrestrial carbon stocks.[127] Drought-induced tree mortality has already led to significant reductions in the carbon sink across 43% of Canada's boreal forests,[128] with emerging evidence of a wider trend in elevated mortality due to extreme weather.[129] Changing species interactions under climate change may also increase tree mortality due to biotic disturbances.[130] Drought, insect, or storm-induced stress and mortality form a complex web of interactions, including with fire,[127] which makes these challenging to project over time. Future disturbance risks to enlarged terrestrial carbon stocks under a warming climate are not currently considered in techno-economic CDR assessments.[120,131]

QUANTIFYING THE FEASIBLE POTENTIAL OF LAND-BASED CDR

Thus far, we have explored current knowledge and uncertainties regarding the feasible potential for land-based CDR. Half of the overshoot scenarios in the AR6 database exceed the IPCC-IPBES assessment of 2050 BECCS capacity consistent with achieving the Aichi biodiversity targets. This is before socio-cultural and institutional constraints are considered. As such, there is good reason to believe that techno-economic assessments of land-based CDR need to be revised downward before countries commit to such levels in net-zero policies and, indeed, before real-world delivery is attempted.

This situation begs a fundamental question: what then, is a feasible target for annual removals? While the knowledge gaps identified above represent a substantial and time-critical challenge to the research community, nevertheless, real progress is being made toward quantifying such a feasible potential. Therefore, we now first highlight promising approaches, pointing to the importance of methods beyond currently dominant optimization-based modeling. Second, we present and explore possible research frameworks toward a robust quantification of the feasible potential for land-based CDR. We conclude by arguing this must be made an urgent research priority during the IPCC AR7 process.

Promising approaches

Socio-cultural constraints

Improved modeling of human behavior can take several forms. For example, optimization-based approaches (i.e., IAMs) can be combined with externally defined constraints on rates of land-use change (e.g., Grant et al.[34]) and/or incorporate spatial dependencies to approximate influence between land managers. Alternatively, explicit process representation can be built in. For example, variations in land manager motivations and willingness to adopt new approaches is also a common element of agent-based models (ABMs).[49,132] Applications of ABMs at local to landscape scales are widespread; however, application of such models at global extents remains a major challenge.[133] The Competition for Resources between Agent Functional Types (CRAFTY) ABM is one example of how this challenge is being addressed (see Box 1). Alongside scaling up, representing structural factors such as land tenure remains a challenge. One approach to this was demonstrated by Humpenöder et al.,[35] who used expert elicitation to define plausible land-system changes under poverty reduction and business-as-usual scenarios as an external constraint on an optimization-based model. Furthermore, process-based representation of indebtedness constraining farmers' agency was recently incorporated in a large-scale ABM.[134]

Institutional constraints

While challenging, it is possible to represent key aspects of institutional capacity and decision making in land-system models.[135] One example is provided by an extension of the CRAFTY modeling framework that includes institutional agents as well as land-management agents.[136] Institutional agents in this model have independent objectives, potential actions, and abilities to monitor and learn from their attempts to control modeled land-use change. They also act across different but overlapping spatial extents, from global to local scales within the model. These institutional agents can therefore be used to represent actors in distinct policy areas, sectors, or countries, attempting to achieve conflicting objectives on the basis of imperfect knowledge and limited capacities for intervention. Findings include strongly non-linear responses to the subsidization of favored land uses and even counter-productive effects resulting from conflict between the interventions of different agents.[136] The complexities of such interactions highlight a fundamental remaining challenge in representing influence networks operating at differing spatial scales: that model outputs very quickly become chaotic.[137] One possible solution to this is, rather than simulate all model processes, to use empirically defined responses obtained through meta-analysis of local-scale studies.[138]

Environmental constraints

Environmental constraints to CDR uptake are among the best quantified, primarily in the form of stylized scenarios in dynamic global vegetation models (DGVMs). Taking the example of BECCS, Heck et al.[25] demonstrate that large-scale adoption leads to increased transgression of planetary boundaries for water, biodiversity, biogeochemical flows, and land-system change. Similarly, Ai et al.[143] highlight the critical role of water scarcity for irrigation as a constraint on BECCS. Further, Henry et al.[26] show how global food security and bioenergy targets are very challenging to achieve within the planetary boundary for land-system change. More broadly, Krause et al.[87] found that IAMs' assumed rates of biophysical carbon sequestration from CDR mostly could not be reproduced by DGVMs. Therefore, such environmental constraints could be calculated for the portfolio of land-based CDR options, with an associated uncertainty envelope from an ensemble of biophysical models. Such constraints could be used to provide environmental limits on CDR adoption in both optimization-based and simulation-based land-use models.

Multi-system constraints

Understanding interactions between constraints (for example, re-release of sequestered carbon due to policy change) is likely to require integration of models of different aspects of the land system.[144] Indeed, incorporating interactions between human systems and biophysical systems has been a long-term ambition within Earth-system modeling.[145] For example, Hibbard et al.[146] highlight the potential to address questions ranging from water to biogeochemical cycles through coupling of IAMs and Earth-system models (ESMs). However, model coupling and integration can be challenging semantically, conceptually, and technically, requiring consistency and alignment of representational frameworks, quantities, and scales.[144,147] Consequently, progress in coupling IAMs and ESMs has remained somewhat limited, not least due to the difficulty of reconciling differing spatial and temporal resolutions and structures.[148] In addition to such technical issues, significant underlying challenges include defining appropriate representations of human decision making[149,150] and capturing two-way interactions between socio-economic and environmental change.[151]

Alternative approaches to IAMs can bring substantial advantages for understanding the feasible potential of land-based CDR in light of the barriers discussed above (Boxes 1 and 2).

Box 1. CRAFTY case study

The value added by process representation of human decision making in land-use models was recently demonstrated by Brown et al.[48] (Figure 3). Taking Europe as a case study, they compared outputs from a constrained-optimizing integrated assessment platform (IAP), similar to that used to inform techno-economic CDR assessments, with outputs from the CRAFTY modeling framework. CRAFTY[139] is an ABM that explicitly represents land managers' decisions, including the role of modulating processes such as the diffusion of knowledge or practice through spatially and temporally constrained social networks.

This study found that the IAP produced large differences in land-use patterns between time slices, without incorporating assumptions about the feasibility of rates of change in the real world. CRAFTY, in contrast, gave much lower rates of land-use adoption by simulated agents, which better matched observed rates of change and so captured path dependencies in levels of knowledge and capacities that the IAP did not. As such, the study demonstrates how improved model representations of human behavior can be used to simulate feasible rates of land-use change for CDR. Other studies have gone beyond comparison to combine optimizing and agent-based approaches, a method that has the potential to establish a range of potential feasibility for CDR options (e.g., Bartkowski et al.[140]).

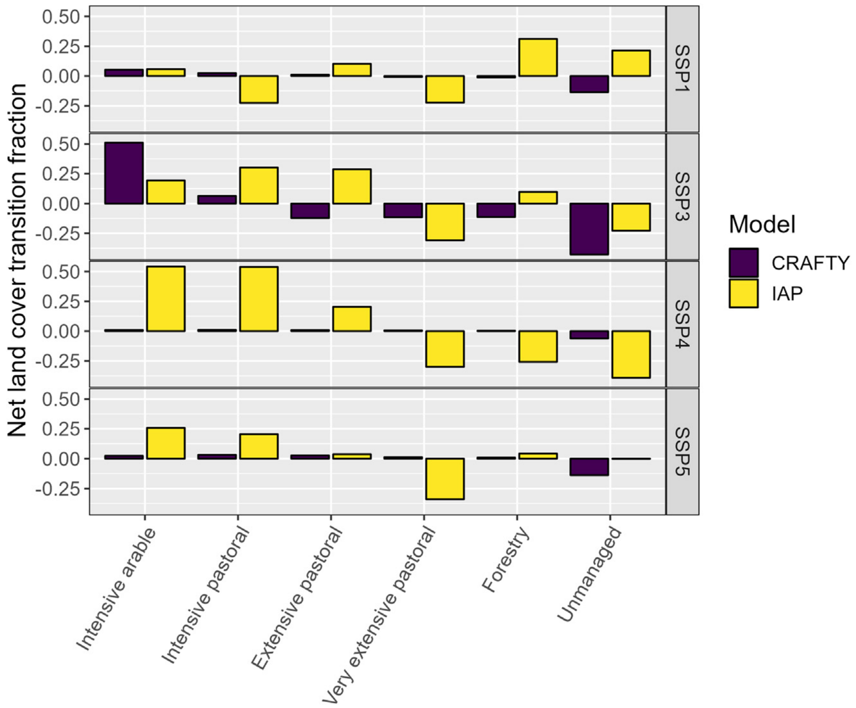

Figure 3. Rates of net land-use change in the European Union, projected by the optimization-based Integrated Assessment Platform and the CRAFTY ABM

The Integrated Assessment Platform (IAP) has large land-use changes across the shared socio-economic pathways (SSPs). By contrast, CRAFTY has relatively static land-use patterns under SSPs 1, 4, and 5, demonstrating the difficulty of land-system optimization for CDR delivery. Conversely, under the challenging socio-economic conditions of SSP3, CRAFTY captures the potential for an environmentally harmful large-scale transition away from forestry and unmanaged land uses and toward intensive arable systems.[141] The SSP narratives are defined by O'Neill et al.[142] as follows: SSP1, "Sustainability: taking the green road"; SSP3, "Regional rivalry: a rocky road "; SSP4, "Inequality: a road divided "; and SSP5, "Fossil-fuelled development: taking the highway." Data from Brown et al.[48]

Notably, spatial, simulation-based approaches can be constructed to run at the same spatiotemporal resolution of ESMs. Integrating the Wildfire Human Agency Model (WHAM!) with the JULES-INFERNO DGVM is an early example of a model ensemble that allows novel exploration of socio-environmental processes at the global scale (Box 2).[152] As well as reducing technical difficulty, this alignment of model structure should enable running models in a "'tight" or fully coupled ensemble and thereby create capacity for feedbacks to emerge from the interactions of model processes.[150]

Ways forward

Toward integrated land-system modeling

Capturing the diversity of processes that affect CDR feasibility is an enormous challenge. For example, evaluating the potential impact of climate, geo-political, or technological shocks on CDR potential requires not only understanding of their direct impacts on agricultural production but also how such shocks will cascade through the food system, including government responses to the possibility of resulting food insecurity and farmers' ability and willingness to alter land-management practices.[157] Likewise, the cross-scale dynamics of globalized agricultural commodities trade, local versus national land governance, and the importance of large-scale private actors pose serious challenges to modeling the land system.[135]

Several projects are now underway to develop model capacity capable of engaging with such questions,[158] of which the land-system modular model (LandSyMM)[159] is a prominent example. LandSyMM integrates the advanced DGVM LPJ-GUESS with the Parsimonious Land Use Model (PLUM) global agricultural trade and land-use model.[159,160] PLUM represents the relationship of food demand in each country with income and food prices using the modified, implicit, directly additive demand system (MADAIDS) model,[161,162] which allows representation of dynamic changes in consumption and dietary patterns. LPJ-GUESS simulates crop yields at a given location, in response to climate change, across different irrigation and fertilizer

Box 2. WHAM! case study

Fire regimes are an example of a human-Earth system interaction of crucial importance to land-based CDR in which the human side of the interaction is currently inadequately represented in simulation models. For example, the first Fire Model Intercomparison Project (FIREMIP) found existing approaches to representing anthropogenic impacts on fire were the largest single limitation in the fire modules of DGVMs.[153,154] This representation is typically limited to universal functions to account for anthropogenic fire ignitions as a simple function of population density. Human roles in managing fire spread, fire suppression and management, and fuel fragmentation are not considered.[155,156]

By contrast, WHAM! takes an agent-based approach to represent the diversity of anthropogenic fire uses (for example, for hunting or to clear crop residues)[125] as well as wider fire management activities (such as fire suppression; Figure 4).[152] This is important because the different purposes of human fire use can result in markedly different burned area from a single ignition (i.e., very small for crop residue burning to very large for hunting activities).[125] WHAM! also represents the impact of fire policy and its relationship to fire management and suppression. As the model can be run at the same spatiotemporal resolution as DGVMs, coupling is readily achievable.[155] Furthermore, initial results from coupling of WHAM! with the INFERNO DGVM demonstrate improved capacity to reproduce remotely sensed burned area data.[152]

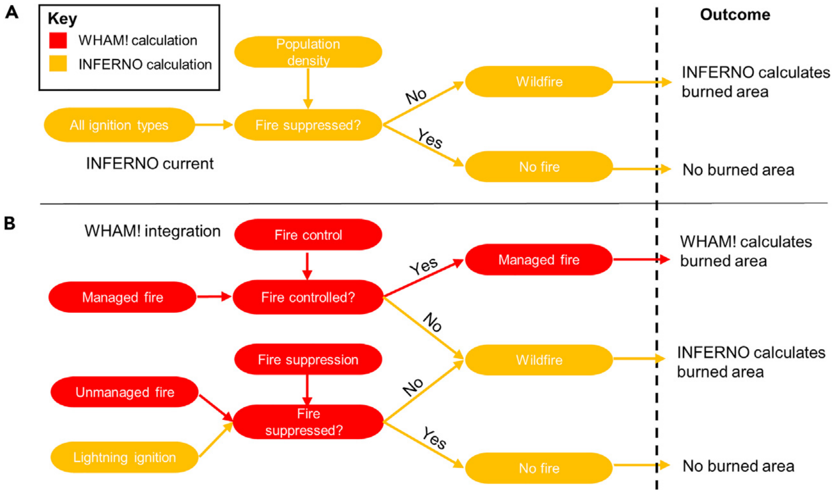

Figure 4. Representation of burned area

Area burned by (A) the INFERNO DGVM alone and (B) with WHAM! integrated. WHAM!, a novel global ABM, enables INFERNO, a fire-enabled dynamic global vegetation model, to represent human impacts on global fire regimes with more detailed mechanistic representation than previously. In so doing, WHAM! improves INFERNO's capacity to reproduce observed global fire regimes.[152]

application rates. These yield potentials allow land-use decisions to be based on spatially specific yields from a process-based vegetation model in the simulation of adaptation and mitigation options.[163]

These developments have allowed assessment of land-system dynamics in a more nuanced way than previously possible. PLUM operates on a 0.5° spatial resolution for land use and country scale for food demand and trade (rather than aggregated world regions, as is typical in IAMs), which facilitates exploration of global system responses to changes in individual countries policies.[164] It also enables spatially explicit exploration of climate change mitigation and adaptation practices, constrained by both future responses of ecosystem productivity to climate change and atmospheric carbon dioxide levels, and socio-economic constraints arising from the costs of adaptation measures in agriculture.[160] However, endogenous representations of institutions via CRAFTY has thus far only been achieved at the national-scale.[165]

While comprehensive, process-based, global, and coupled socio-ecological land-system modeling remains in development, substantial advances are also being made at intermediate spatial scales (see Johnson et al.[158] for a review). For example, the NetZero plus project in the United Kingdom[166] is developing a policy support tool for UK tree planting that combines detailed soil and vegetation carbon fluxes with impacts on food production, water quality and flood risk, and biodiversity. Outputs of CDR potential from such national-scale models could therefore be compared with down-scaled global CDR projections for an initial quantification of the feasibility gap in a given country or region.

Combining insights from diverse methods

Given the urgency of defining the feasible potential of CDR, and the scale of the research and technical challenges involved, the integration of insights from multiple disciplines is likely to be needed to advance understanding. Coordination between research groups from across disciplines is likely to maximise progress, limit duplication of work, and enable inter-methodological comparison and thereby uncertainty quantification. Such coordination could take many forms (Table 1).

At a minimum, external constraints giving maximum rates and extents of land-use change should be incorporated into IAMs producing scenarios for the IPCC AR7. This is currently the most common form of feasibility assessment; for example, it is being used to test the overall feasibility of mitigation pathways after the Glasgow COP.[167] For land-based CDR, such constraints have so far been derived from expert elicitation and applied to one aspect of the system, whether rate of land-use change[34] or poverty.[35] Brutschin et al.[168] set out a framework for constructing such quantitative feasibility constraints, which could now be expanded to include a set of common indicators across socio-cultural, institutional, and environmental factors.

For socio-cultural constraints, these could be based on historical rates of land-use change (e.g., Turner et al.[24]) or process-based behavioral modeling (e.g., Brown et al.[48]). Structural constraints, such as food and land tenure insecurity, could be quantified using a combination of meta-analysis (e.g., Ruzzante et al.[169]) and/or expert elicitation combined with relevant proxy indicators such as the Human Development Index. Institutional constraints are perhaps the most challenging to capture; expert elicitation could be the best option before improved process-based modeling capabilities are developed.[170] Environmental constraints can readily be derived from the impacts of CDR in DGVM scenarios and should include a reality check of carbon uptake rates.[87,171]

However, it should be noted that expert elicitation has long suggested that modeled land-based CDR projections are based on highly optimistic and very uncertain assumptions,[172] and yet such knowledge has not altered the fundamental magnitude of assessed CDR potential (Figure 1). Therefore, buy-in from across modeling groups to make feasibility considerations central to model function is vital. Furthermore, given vast spatial heterogeneities in the land system, there is no guarantee top-down threshold-based constraints will fully capture the underlying spatial dependencies of the real-world processes. It may be that, rather than broad models of all aspects of climate change mitigation, feasibility assessment will require a variety of more detailed models focused on specific aspects of feasibility.[173] Moreover, without endogenous representations of feasibility constraints (e.g., through land-system simulation models), it will not be possible to understand the interactions and (anti-)synergies between constraints.

Therefore, a more ambitious target would be to have multi-method quantifications for each of the categories of land-system constraint that comprise feasibility. Such an approach could combine regional and global land-system simulation models, optimization methods with external constraints and/or in comparison with more detailed national-scale assessments, stylized

Table 1. Research frameworks to enable quantification of the feasible potential of land-based CDR

Framework	Methods involved	Pros	Cons
External constraints	optimization methods (IAMs) with externally defined constraints on land-use change	most technically simple approach achievable within AR7 timescale	does not capture interactions between constraints full range of feasibility constraints may not be implementable within IAMs uncertain definition of constraints, e.g., with expert elicitation
Multi-method quantification	all relevant methods, including stylized DGVM scenarios and empirical approaches	draws on the full range of currently available methods should allow some consideration of all categories of feasibility consideration	complex to coordinate across research groups risk of inconsistencies across contrasting research methods
Feasibility model intercomparison project	land-system simulation models	endogenous quantification of feasibility constraints and their interactions methodologically consistent	substantial technical challenges to model development unlikely to be deliverable for IPCC AR7

Frameworks are presented from least to most challenging to deliver. “External constraints” represents an important but incremental shift from present approaches, while “multi-method quantification” or a “feasibility model intercomparison project” would entail significant evolution of the *status quo*.

DGVM scenarios, and empirical approaches (e.g., meta-analysis methods or a multi-dimensional feasibility index [(after Roe et al.][37]). This approach would potentially produce outputs with similar framing to the methodological distinction made in the IPCC AR6 between by “sectoral” (single-CDR) assessments and integrated assessments (i.e., IAMs). The principal challenge in this approach would be the likely need to reorganize IPCC Working Group III to incorporate and coordinate inputs from a wider range of methods.

Finally, model intercomparison projects (MIPs) have proved a useful way of quantifying modeling uncertainties regarding climate change impacts and mitigation. However, as modeling capacity required for comprehensive feasibility assessment is still under development, defining a coherent protocol for a “feasibility MIP” may not be a realistic research ambition for the AR7 process. Indicative of the challenges ahead, the first intercomparison of land-use models found that differences in model structures and approaches (e.g., ABM, computable equilibrium) were at least as great as differences between scenarios, pointing to fundamental uncertainties in the drivers of land use and their model representation.[174]

Overall, whichever method is chosen to quantify feasibility, there is a strong possibility that many apparently Paris-compliant scenarios, and overshoot scenarios in particular, will be found unfeasible.[47] This, in turn, will necessarily place an increased importance on present-day emissions cuts, technical approaches such as direct-air carbon capture and storage (DACCS), or more radical geoengineering approaches in both decarbonization scenarios and government policies. Therefore, a failure to quantify feasibility constraints robustly in the next IPCC Assessment Report (IPCC AR7) risks giving unwarranted cover for policymakers further to forestall decarbonization efforts.[88]

Furthermore, we suggest implementation of environmental constraints should *precede* incorporation of additional CDR methods in IAMs, such as enhanced weathering with mining residues.[175] There is already evidence in the IPCC AR6 Scenarios Database that such methods are being used not to reduce climate change impacts but rather to delay decarbonization (Figure 1). Exploration of BECCS's environmental constraints have led to a gradual revaluation of BECCS potential. In the IPCC AR5, BECCS's 2050 economic potential was assessed as 2–10 $GtCO_2$ eq. y^{-1},[176] while, in the IPCC AR6, it was assessed as 1.8 $GtCO_2$ eq. y^{-1}.[7] Incorporating additional speculative CDR techniques before their wider environmental and societal impacts are considered risks repeating this cycle at a time when carbon budgets are already precariously small.

Conclusions

Overshoot scenarios that temporarily exceed the 1.5°C target but then reduce temperatures below this level by 2100 are underpinned by the viability of multi-gigatonne-scale CDR. Pathways that delay present-day decarbonization on the assumption of future CDR contain an inherent risk: if CDR cannot be delivered at the required levels, we will be stuck with increased climate change impacts and no way safely to reduce temperatures. Through our review of current understanding of feasibility constraints on global land-based CDR potential, we have argued that, together, these constraints will prevent real-world delivery of the rates of sequestration required by overshoot scenarios. Therefore, achieving the goals of the Paris Agreement is likely to require steeper present-day emissions cuts and larger implementation of technical CDR methods such as DACCS than is suggested by many decarbonization scenarios.

However, it is perhaps inevitable that, until feasibility constraints on land-based CDR delivery are robustly quantified, more optimistic techno-economic assessments will continue to form the bedrock of evidence presented to policymakers. Given the small remaining carbon budget, the research community must make determining the feasibility of any decarbonization pathways presented to policymakers a top priority. We have set out ambitious, but realistic, transdisciplinary research frameworks to quantify the feasible potential of land-based CDR during the AR7 process. It is imperative we deliver. The alternative is to risk endorsing present-day delays to decarbonization only to later discover global temperature rises cannot be reversed.

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AUTHOR CONTRIBUTIONS

All authors contributed to the writing of the original draft as well as revising and editing. O.P. and C.B. conducted data visualization.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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