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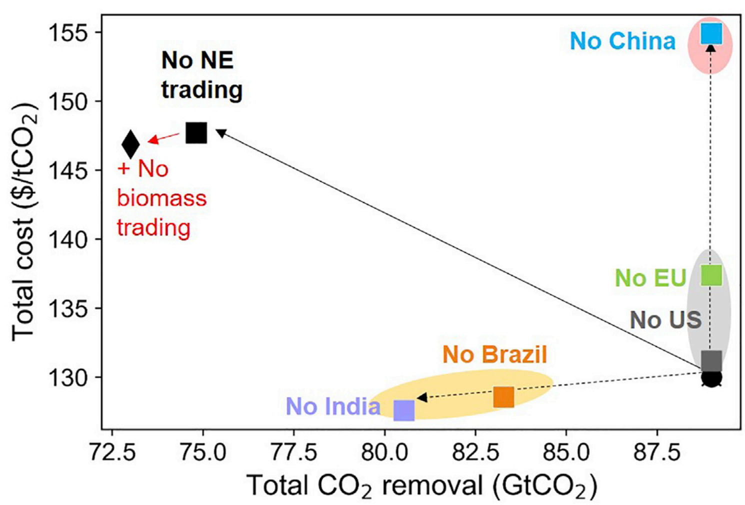
Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal

Graphical Abstract



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In Brief

Removing CO_2 from the atmosphere is needed in addition to deep mitigation of CO_2 emissions. As not all countries possess the geo-biophysical assets to provide sustainable, permanent, and affordable CO_2 removal, a cooperative and collaborative approach to CO_2 removal, based on equitable burden sharing and CO_2 sink trading, is needed to meet global CO_2 removal goals at least cost.

Highlights

- Significant differences in life cycle removal cost via BECCS exist among regions
- BECCS cost curve becomes very steep when sustainable biomass boundaries are pushed
- Not all regions are equally endowed in sustainable biomass and CO_2 storage assets
- Inter-regional trading is required to meet global CO_2 removal targets at least cost

Fajardy & Mac Dowell, 2020, One Earth *3*, 214–225
August 21, 2020
https://doi.org/10.1016/j.oneear.2020.07.014

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Article

Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal

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https://doi.org/10.1016/j.oneear.2020.07.014

SCIENCE FOR SOCIETY Carbon dioxide (CO_2) emissions mitigation and removal are both required to deliver on the "well below" 2°C target by the end of the century. While CO_2 emissions budget allocation and trading of carbon credits have been discussed in the context of CO_2 emissions mitigation, these concepts have yet to be defined for CO_2 removal. As acknowledging bio-geophysical constraints acting to limit the extent to which individual countries can remove CO_2 from the atmosphere, it is crucial to recognize the value of (1) allocating CO_2 removal burdens in an equitable way and (2) inter-regional trading of CO_2 removal assets to guarantee the fulfilment of global climate commitments in an affordable and sustainable manner. With bioenergy with carbon capture and storage as an archetypal CO_2 removal method, and five regions of the world, this study aims at highlighting the importance of active cooperation and collaboration in delivering global CO_2 removal.

SUMMARY

In delivering the Paris climate target, bioenergy with carbon capture and storage (BECCS) is likely to play an important role, both as a climate mitigation and a carbon dioxide removal technology. However, regional drivers of BECCS sustainability and cost remain broadly unknown and the regional attribution of a global CO_2 removal burden remains largely undetermined. This study explores the mechanisms behind cost-optimal BECCS deployment with evolving regional CO_2 removal targets and energy sectors to provide insights into the ways in which different regional players will interact as a function of their bio-geophysical endowments and their ability to trade these assets. An important finding is that inter-regional cooperation—in choosing the right burden-sharing principle to establish regional targets—and collaboration—in trading negative emissions credits and biomass—are central to sustainably and affordably meeting these targets. This multilateralism in biomass and carbon credits trading constitutes important value creation opportunities for key providers of CO_2 removal.

INTRODUCTION

The 1.5°C target set by the Paris agreement in 2015 has rendered atmospheric carbon dioxide removal (CDR) indispensable. According to Integrated Assessment Models (IAMS), 190 to 1,190 $GtCO_2$ of cumulative removal is potentially required before the end of the century, depending on the pace and extent of climate change mitigation efforts.[1,2] Within the portfolio of CDR methods, bioenergy with carbon capture and storage (BECCS) has raised multiple concerns.[3,4,5,6,7–9] Recognizing these caveats, "BECCS done right" could play a key role in climate change mitigation.[3,4] The where, when, and extent of environmentally sustainable, economically viable, and socially acceptable BECCS deployment remains, however, undetermined.

IAMS suggest different levels of regional deployment of BECCS to meet climate targets at the lowest cost. Peters and Geden[10] summarized BECCS optimal deployment across four IAMs, and show that China, the US, the EU, Brazil, and India would provide alone between 33% and 65% of total CDR via BECCS, with on average China providing the highest share, followed by the US, India, the EU, and Brazil. Although this study provides valuable insights into the cost-optimal ways to climate change mitigation, a first caveat is that least cost deployment does not necessarily mean sustainable deployment. Even when focusing on sustainability, studies have shown how BECCS impact on selected indicators (e.g., water use, biodiversity loss) varies as a function of the prioritization of individual sustainability indicators.[11,5] Finally, it is not clear that optimal

deployment of BECCS (economic or otherwise) coincides with what regions can sustainably do (resource wise), nor with what an equitable contribution to the CO_2 removal burden might be.

For a range of bio-geophysical and socio-political reasons, not all regions are equally endowed in their ability to sequester CO_2 and produce biomass sustainably. For example, North America, Latin America, and Russia have been identified as regions with high potential for the production of energy crops on set-aside land.[12,13] While global CO_2 storage capacity is generally not considered as a bottleneck, regional assessments substantially vary in capacity and in reliability. While the US boasts over 8,000 $GtCO_2$ of storage with a 75%–100% confidence, only 50 $GtCO_2$ have been identified in India, with a 56%–75% confidence.[14] Furthermore, key IAMs assumptions, including regional BECCS cost, life cycle greenhouse gas (GHG) emissions, as well as land and CO_2 storage availabilities remain relatively opaque.[15] For instance, 130 $GtCO_2$ of BECCS is deployed in India in some scenarios,[10] which significantly exceeds current assessments of available CO_2 storage capacity in that region.

It is equally problematic to determine how a global CO_2 removal burden might be equitably distributed between a range of actors who are individually at different stages of development. While there is a general agreement that historical responsibility should be considered when determining national contributions to climate change mitigation, there is no unanimous agreement as to whether historical responsibility should be interpreted as proportional (based on present or historical CO_2 or GHG emissions) or conceptual (based on "capacity" by the proxy of gross domestic product or population) burden sharing.[16,17,10,18] A blended approach—for example, weighting both population and emissions in the same equation[18]—provides an alternative, although equitable weighting factors are equally difficult to determine. What is already complex in the context of allocating emissions is even more so with CDR. A determining factor of this allocation will be whether CO_2 removal is done to (1) offset past and residual emissions after maximum emissions mitigation efforts, or (2) to compensate for today's lack of action and increasing emissions.

A prerequisite of these considerations is that climate change is globally tackled in a cooperative environment. Cooperation as a condition for effective climate change mitigation has been extensively discussed.[19,20,21,22] A common cooperative approach is that of "climate clubs,"[20] which are part of the wider category of "public good" or "voluntary" clubs. A climate club can be defined as a group of countries—typically smaller than the UNFCCC—that actively cooperate to reduce damages induced by climate change through international agreements (e.g., an international carbon price), and entice/maintain country membership through a set of club "goods" or members-only incentives (e.g., bilateral emissions trading or know-how exchange).[20] While, in principle, climate clubs involve all approaches to combat climate change, including mitigation, adaptation and removal, most of the literature focuses on climate change mitigation.[20] Studies have quantified the gains and identified the optimal structure of these climate clubs both at the global level[21,22] and the state level (for example, cooperation between US states in Galán-Martín et al.[19]). As far as CO_2 removal is concerned, cooperation between countries is only mentioned in the context of research collaboration for advancing carbon capture and storage (CCS), at the global scale[23] or the European scale.[24] However, there are inherent differences between the economic systems and enabling policies that deliver conventional mitigation and those that deliver carbon removal.[25] Both cooperation and collaboration involve countries working toward a common goal, but collaboration involves the creation of a physical output, through active exchanges between countries. While mitigation can be done more effectively through cooperation alone, owing to the uneven distribution of key resources (e.g., CO_2 storage or biomass), delivering large-scale atmospheric removal of CO_2 is likely to require active collaboration.

While distinct in terms of economies and climates, China, India, the US, Brazil, and the EU, according to IAMs, could be instrumental in deploying BECCS.[10,26] This study uses these five regions to investigate the importance of inter-regional collaboration, and provide insight into the regional drivers of BECCS cost-optimal and sustainable deployment. To understand the economic, sustainability, and geophysical trade-offs between these regions, the first section in the Results and Discussion breaks down BECCS cost in different regions. The following two sections present BECCS cost-optimal deployment for a range of (1) CO_2 removal targets, (2) biomass availability and land use constraints, and (3) biomass supply chain assumptions. The final section of the Results and Discussion then unpacks the regional allocation of a global CO_2 removal target, and explores the impact of inter-regional trading of biomass and negative emissions credits scenarios on BECCS removal potential and cost.

RESULTS AND DISCUSSION

Drivers of BECCS Cost

To explore the main drivers of BECCS cost, we first evaluate different supply chain configurations, and quantify the total cost per ton of CO_2 removed in different regions, using either local or imported biomass (Figure 1).

Overall, factors such as the plant capital cost, feedstock processing, and transport are key drivers of BECCS cost. While importing biomass from high productivity regions can be preferable from a resource minimization perspective,[11] using local biomass consistently appears to be more cost-effective, assuming these broader sustainability aspects are treated as externalities. The cost of removal in each region varies as a function of supply chain configuration. A key parameter affecting these variations is the feedstock yield. In the UK, a high yield range has been noted for energy crops in the literature,[27,28,29] which explains the wider error bar. This shows that improved yield in the UK could bring BECCS cost close to that in other regions.

It is important to note that these costs are obtained for the deployment of a large-scale bioelectricity plant, and could be lower in the context CCS retrofitting and/or other bioenergy conversion pathways, such as fermentation or gasification. In a recent literature review by Fuss et al., [30] the authors highlight the high range of BECCS cost in the literature (between \$17/tCO_2 and \$446/tCO_2) as a function of the technology, region, feedstock, and terminology used (e.g., CO_2 avoided, captured, or removed). They, however, point to significantly lower cost ranges for BECCS pathways involving gasification

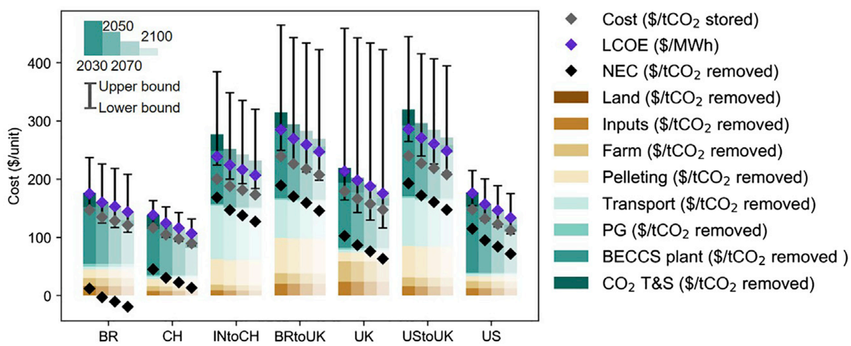

Figure 1. Breakdown of BECCS Cost in Different Regions

The cost can be read per ton of CO_2 removed (bars), per ton of CO_2 stored (gray diamond), per MWh (purple diamond), and in terms of breakeven negative emissions credit (NEC) (black diamond) in Rio de Janeiro, Brazil (BR), Hainan, China (CH), Georgia, US, and the UK, using local or imported (INtoCH, BRtoUK, and UStoUK) biomass. Using imported biomass can substantially increase the cost of removal because of added cost and emissions of biomass transport. Cost variability (upper and lower bounds reflect optimistic and pessimistic supply chain configurations) is mainly driven by feedstock yield. BECCS cost decreases over time primarily because of capital cost reduction, followed by reduced supply chain emissions due to decarbonization of the energy system. In countries with low cost of BECCS and high cost of electricity, the NEC can become negative (e.g., Brazil).

(\$33–83/tCO_2), or fermentation (\$22–195/tCO_2), compared with biomass combustion (\$98–321/tCO_2).

Figure 1 also quantifies the total cost per ton of CO_2 stored, which is distinct to the cost per ton of CO_2 removed, emphasizing the importance of considering BECCS life cycle emissions when evaluating BECCS cost. Importantly, as the energy system becomes decarbonized, the gap between the cost per ton of CO_2 removed and the cost per ton of CO_2 stored decreases. Finally, Figure 1 also represents the levelized cost of electricity of a BECCS plant, and the no negative emission credit (NEC) required for the revenues from electricity generation and CO_2 removal equates the total system cost, referred to as "breakeven NEC" in this study (see Experimental Procedures). In regions with low cost of BECCS and high electricity price (see Figure S5), the NEC becomes negative (e.g., Brazil) in the second half of the century. BECCS cost is thus found to be region specific, with obvious implications for NEC trading.

BECCS Deployment: Where, When, and How Much?

In this section, we use the MONET framework, illustrated in Figure 6, to determine region-specific trajectories for the cost-optimal deployment of BECCS with evolving CO_2 removal targets, subject to biomass and land availabilities, water risk, and CO_2 storage capacity constraints. Figure 2 illustrates cumulative biomass production (coloring) and CO_2 storage (markers) by the end of the century, for a low (Figures 2A and 2B) and high (Figures 2C and 2D) biomass availability, and a low (Figures 2A and 2C) and high (Figures 2B and 2D) CO_2 removal target. Both CO_2 removal target trajectories were calculated based on a share of total CO_2 removal via BECCS in the SSP1/P2 ("low target") and SSP2/P3 ("high target") representative pathways to meet a 1.5°C target.[1,2] This is further detailed in the section on "What Is an Equitable Allocation of the Global CO_2 Removal Burden?"

At low targets, biomass is not a limiting factor and activity tends to be concentrated near CO_2 storage sites owing to the high cost of biomass transport. BECCS is primarily deployed in China and the eastern US, while its deployment is limited in the EU and Brazil, and non-existent in India. For the EU, this can be explained by higher costs and low availability of marginal land. For Brazil and India, it was considered that no or little CO_2 storage was available in Brazil and India, due to lack of quantitative data (see Fajardy[31] for CO_2 storage data and sources), which acts to limit BECCS deployment in these regions. At higher targets, however, most regions become crucial in reaching higher levels of removal. BECCS is largely deployed in the EU, and biomass from regions with no/less CO_2 storage (Brazil, India) is shipped to closest storage sites. This naturally leads to a more expensive system, with a 57% increase in cumulative cost of removal (per tCO_2). Higher targets cannot be met only using energy crops on marginal land. When biomass supply is limited in this way (only 185 Mha of marginal land can be used for BECCS, or 5% of the total area represented by the five regions in this case study), a maximum of 176 GtCO_2 (4.3 GtCO_2/year by 2100) can be removed between 2030 and 2100, compared with the target of 237 GtCO_2 (58% of 408 GtCO_2, the P3 target). The target can only be met in the high biomass availability scenario, when additional land (e.g., cropland, grassland or forests) is made available for biomass production, in addition to crop residues. In this case, with an average cost of electricity of \$103/MWh, and an average BECCS carbon intensity of -0.91 tCO_2/MWh, the global breakeven NEC decreases back to \$38/tCO_2. The expansion of bioenergy production on managed and natural land, here amounting to 230 Mha of land use change in addition to the 185 Mha of marginal land (12% of the total land area of the five regions), could, however, have unintended consequences on the economy or the environment.

BECCS cost-optimal deployment also varies with the configuration of the biomass supply chain (e.g., yield, emission factor of input products and fuel).[3] Figure S1 illustrates how cumulative biomass production, CO_2 storage, and total cost of removal changes as a function of these choices. Total cost of removal is found to decrease by 16%–18% in the optimistic scenario and increase by 26%–27% in the pessimistic scenario, while the global breakeven NEC is found as low as \$12/tCO_2 under a low target, and as high as \$163/tCO_2 under a high target. The structure of the supply chain, however, remains globally unchanged. This confirms that our findings regarding the relative importance of each region in deploying BECCS are robust even when considering the variability in biomass supply chain conditions.

BECCS Cost Curve

As shown in Figure 2B, BECCS average cost of removal can increase significantly when BECCS deployment impinges upon planetary boundaries. BECCS cost curve at the end of the century is represented in Figure 3, in a limited biomass scenario, for

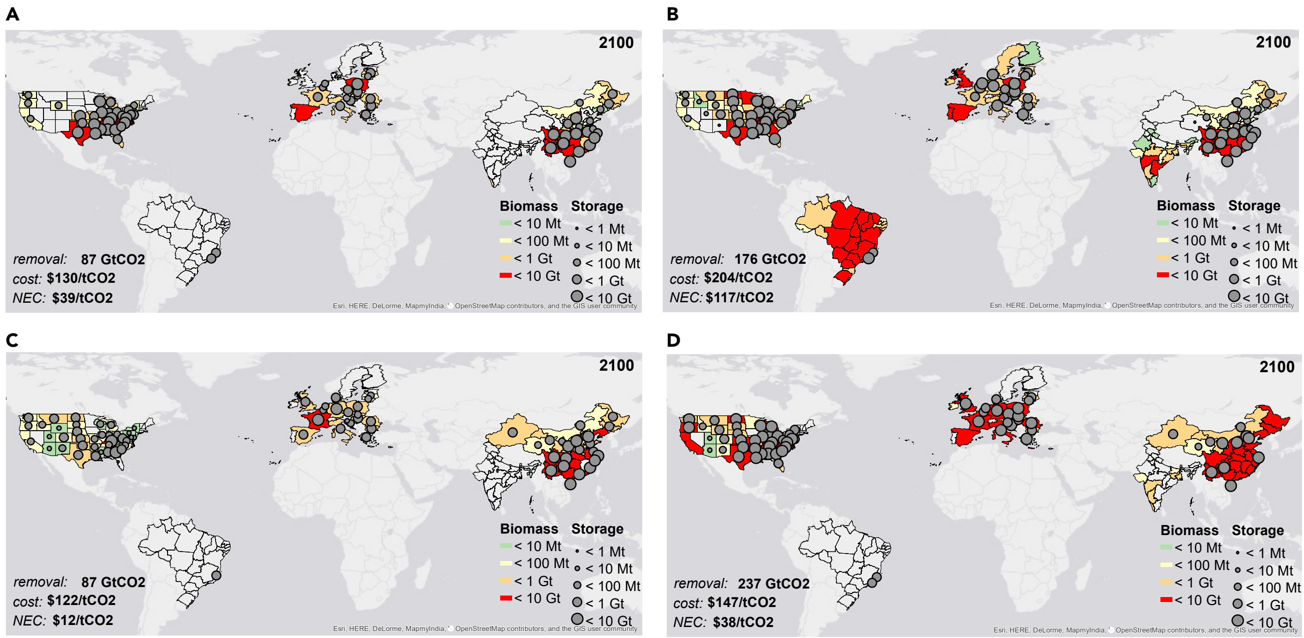

Figure 2. Map of BECCS Cost-Optimal Deployment by 2100

Results are for a low (A and B) and high (C and D) biomass availability scenario, and for a low (A and C) and high (B and D) CO_2 removal target. Cumulative biomass production is represented by the coloring of the cells, while cumulative CO_2 storage by the size of the markers. At low targets, China and the US see most of BECCS deployment. Expanding biomass production on other types of land enables to meet both targets at lower costs, but could have unintended economic-environmental consequences.

low (Figure 3A) and high (Figure 3B) targets. To account for revenues from electricity generation, the equivalent NEC cost curve is represented in Figures 3C and 3D. The color of the dots indicates where the CO_2 is stored, while the colored areas indicate cost ranges and potential of alternative CDR methods.

At low targets, the cost of BECCS plants operating in different countries increases from \$100–110/tCO_2 removed in China, to \$120–140/tCO_2 removed in the US/EU. To meet higher targets, biomass feedstock further from CO_2 storage sites is utilized, thereby increasing feedstock supply chain emissions and cost. While Figure 2 shows that the average cost in this scenario is \$200/tCO_2 removed, Figure 3 shows that increasing CO_2 removal targets leads to the mobilization of BECCS configurations removing increasingly marginal amounts of CO_2, at a removal cost higher than \$350/tCO_2 removed, and up to \$1,100/tCO_2 removed. To put these numbers in context, the cost range and CO_2 removal potential of alternative CDR methods,[30] afforestation and direct air capture, are represented in Figure 3. BECCS cost curve is found to be higher than afforestation and lower than direct air capture. When accounting for revenues from electricity generation, the net cost of BECCS (equivalent to the NEC), is found to be competitive with afforestation in certain regions. This implies that a portfolio of CDR methods will be required, with the composition of this portfolio varying in time and space. It is important to note that the cost and potential values used for afforestation and direct air capture are estimates subject to the same case-to-case, and regional, variability as BECCS. In addition, the portfolio of CDR methods is not limited to these three technologies, but also involves methods, such as enhanced weathering, biochar, and ocean fertilization. Further research exploring the co-deployment of different CDR methods, under the same boundaries and set of assumptions, is required to determine how much and where the deployment of each technology is best suited, if at all, and to quantify and qualify the potential for synergies between different options.

It should be noted that these results are sensitive to (1) the amount of marginal/set-aside land considered in this study, which is relatively uncertain and likely to vary over time, (2) the range of feedstock considered, which was purposely limited to energy crops on marginal land as a base case scenario, to avoid competition with existing bioenergy uses, (3) the BECCS pathway considered, which was limited to large-scale bioelectricity plant, excluding local BECCS opportunities, such as retrofitting CCS on exiting bioethanol[32,33] or pulp and paper plants,[34,35] (4) the burden-sharing assumptions used to downscale the global target to the cumulative target of Brazil, India, China, the EU, and the US, and (5) the fact that regions with potentially large BECCS potentials relative to their CO_2 removal targets (e.g., Africa, Russia, Canada) have not been considered in this study. This conservative and greenfield approach to BECCS deployment, allows for a like-to-like comparison between regions, and can illustrate how pushing biomass availability boundaries may increase the total removal cost via BECCS.

CO_2 Removal: Who Benefits?

What Is an Equitable Allocation of the Global CO_2 Removal Burden?

The Intergovernmental Panel for Climate Change (IPCC) summarized IAMs 1.5°C scenarios into four mitigation pathways: P1,

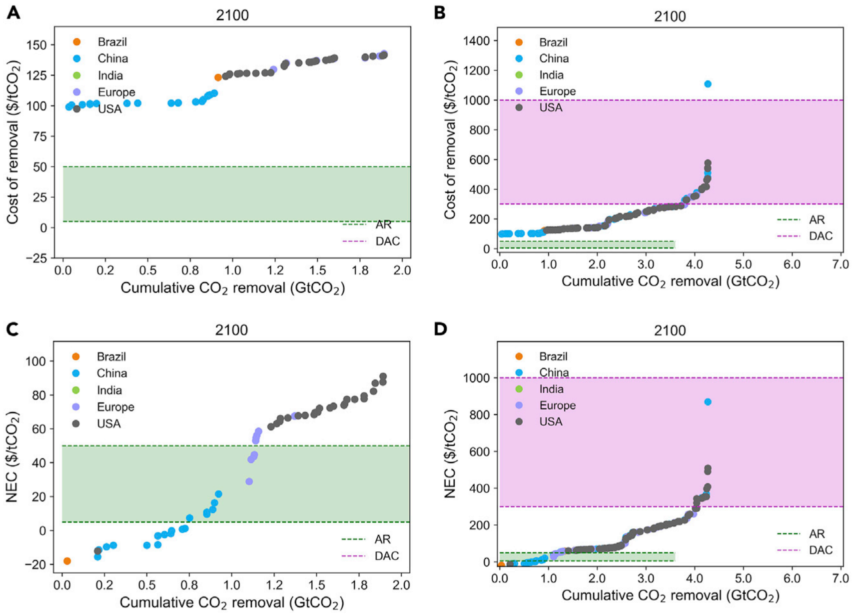

Figure 3. BECCS Cost and Negative Emissions Credit Curves in 2100

Cost (A and B) and NEC (C and D) curves are for low biomass availability at a low target (A and C) and a high target (B and D). When biomass is limiting, BECCS is no longer cost-effective, which indicates opportunities for alternative CDR methods (AR, afforestation; DAC, direct air capture, cost data ranges from Fuss et al.[30]).

a low energy demand scenario where the low CDR need can be met with afforestation and land use management, P2 and P3 middle-of-the-road scenarios with BECCS where CDR requirement is higher and between 150 and 408 cumulative GtCO_2 of removal via BECCS is deployed, and P4, a fossil fuel/energy intensive scenario, which requires the deployment of 1,180 GtCO_2 cumulative removal via BECCS.[1,2] To put P4 in context, over 400 EJ of bioenergy per year is used in 2100, which is potentially well above sustainable bioenergy potentials.[36] In this study we focus on P2 and P3 scenarios. Deciding on an equitable allocation of these global targets at the regional level depends on many factors, including past emissions, population, wealth, rate of emission reduction, etc. In this study, global targets were allocated based on absolute historical GHG emissions. Annual historic GHG emissions from 1850 to 2014 were collected for each country.[37,38] Regional targets were then determined using the following formula:

$$Rtarget(c,time) = Gtarget(time). \times \frac{Cum.GHGemissions(c)}{\sum_{c\ in\ World} Cum.GHGemissions(c)}, \quad c\ in\ \{Brazil, China, EU, India, USA\} \qquad \text{(Equation 1)}$$

To clarify, the regional target at a given year is exogenous, and does not change as a function of how much mitigation/removal is done in previous years. Furthermore, it was assumed that a regional CO_2 removal target is met where the CO_2 is physically stored and monitored. Table 1 summarizes cumulative emissions per region and the computed regional share of global targets. As Modeling and Optimization of Negative Emissions Technologies (MONET) only represents a subset of the world, annual CO_2 removal targets constraints considered in MONET are 58%—the sum of all individual shares based on a historical GHG emissions burden sharing of global targets—of the world annual CO_2 removal targets obtained from P2 and P3 scenarios of the IPCC.

While we use these BECCS deployment scenarios as exogenous indicative CO_2 removal targets for our modeling exercise, we also acknowledge the potential interactions with the amount of CO_2 removal and the decarbonization of the energy system, which in turn affects the biomass value chain sustainability assumptions. Instead, conservative assumptions regarding the evolution of the energy system were made, and are discussed in the Experimental Procedures.

CO_2 Removal Surplus

Naturally, cost-optimal deployment might greatly differ from this regional distribution of the global CO_2 target. In the previous section, a global CO_2 removal target was met in a cost-optimal and collaborative manner, regardless of the countries' individual target. Some regions might be providing more or less CO_2 removal than they ought to, effectively doing CO_2 removal on behalf of other regions, either because of a higher cost, or a lack of resources. In the context of mitigation, certain group of countries—EU Emissions Trading Scheme is one example—are able to trade emissions at a market-adjusted carbon price, effectively having countries abating emissions on behalf of others. In a theoretical CO_2 removal climate club, countries could trade these negative emissions credits, effectively having regions removing CO on behalf of others. Other membership benefits could involve, for example, trading biomass feedstock at preferential border tariffs. Based on these regional removal targets, it is possible to compute the algebraic difference between cost-optimal regional removal—how much removal is done in the cost-optimal deployment—and regional removal targets. In this study, this is referred to as the CO_2 removal surplus when positive or default when negative, and is calculated with the following formula:

$$CO_2RemovalSurplus / Deficit(c,time) = cRCO2_{opt} \times (c,time) - CO2Target(c,time), \qquad \text{(Equation 2)}$$

where $cRCO2_{opt}$ is the optimal amount of CO_2 removal per region, and *CO2Target* is the regional CDR target. When the regional surplus is non-zero sum, the global target is not met.

Figure 4 shows annual levels of CO_2 removal surplus and annual CO_2 removal cost (right axis) under the four biomass availability/target scenarios.

Table 1. Regional Cumulative GHG Emissions and Shares of Global CO_2 Removal Targets in MONET

Regions	Cumulative GHG Emissions 1850–2014 (MtCO2)[a]	CO_2 Removal Target (% Global Target)	Cumulative P2 Target ($GtCO_2$)	Cumulative P3 Target ($GtCO_2$)
Brazil	122	4.3	6	18
China	336	11.9	18	48
EU	462	16.4	24	67
India	157	5.5	8	23
US	571	20.2	30	82
Total MONET regions	1,647	58.3	87	238
Total world	2,826	100	149	407

[a]Historic GHG emissions.[14,39]

At low targets (Figures 4A and 4C), BECCS total cost does not significantly increase over time, which shows that capital cost reductions of BECCS plants and decarbonization of the energy system compensate for the increasing CO_2 removal target. However, the trend shifts at higher targets (Figures 4B and 4D) when biomass and CO_2 storage supply become active constraints. An important conclusion is that countries with well distributed, high capacity, CO_2 storage, as well as cheap biomass supply (China in this study), accumulate significant surplus, thereby providing significant value to other regions.

The System's Value of Individual Countries

The premise that a few countries may be doing CO_2 removal on behalf of others assumes that countries are allowed to trade negative emissions credits. Equally, some scenarios rely on having countries or regions with low CO_2 storage capacity, but with abundant biomass supply (Brazil in this study), send biomass to regions with high CO_2 storage capacity, implicitly assuming biomass trading flows between regions. A lack of "collaboration," by trading neither NEC nor biomass, could incur two risks: (1) unmet CO_2 removal target and (2) higher cost of removal. Different scenarios are explored to illustrate the impact of geopolitical and economic collaboration:

1. "No NEC trading": no NEC trading between regions, i.e., regions have to meet their own CDR target, and cannot rely on other countries' storage sites, or store CO_2 on behalf of others.
2. "No biomass trading": no biomass trading between regions, i.e., regions have to use their own biomass, and cannot import/export biomass.
3. "No region *x*": all regions trade NECs and/or biomass with one another, except with region *x*. This means that all regions except region *x* meet their targets collaboratively, while region *x* has to meet its own CO_2 removal target and/or use its own biomass.
4. "No trading": no biomass nor NECs can be traded among regions.
5. "All": NECs and biomass trading is allowed between all regions.

Figure 5 explores the impact of collaboration on these two dimensions, by representing the total cost of removal as a function of cumulative CO_2 removal across the century, in different trading scenarios, at low (Figure 5A) and high (Figure 5B) targets. Squares represent scenarios where NEC trading is constrained, crosses where biomass trading is constrained, and diamonds where both are constrained.

At low targets (Figure 5A), trading NECs has a first-order impact on CO_2 removal and cost of removal. In a scenario without NEC trading, the global cumulative target is missed by 14 $GtCO_2$, and total cost of removal increases by 14%. Trading biomass, however, has a lesser impact, and constraining biomass trading in addition to NEC trading further decreases cumulative CO_2 removal by one $GtCO_2$.

We can also quantify the individual impact of integrating a particular region in the NEC trading market (colored squares). In doing so, we see that different players bring different values when trading NECs. A first category of players stand out as "Independent providers" (in red), i.e., regions with good storage availability, low cost, and low carbon biomass close to storage sites (e.g., China). Excluding these regions from the collaboration leads to a much higher cost (here 19%) as they can no longer provide surplus for other regions. Another emerging category includes the "independent beneficiaries," i.e., regions with good storage and biomass availability but higher cost, (e.g., the EU and the US). Excluding them from the collaboration leads to a higher cost if excluded as they have to fulfill their own targets, but the target is still met. Finally, the "dependent beneficiaries" are regions that are unable to meet their own targets due to lack of storage (i.e., Brazil and India).

When targets are higher, and biomass becomes a limiting factor (Figure 5B), trading biomass (x) has a much higher impact than trading NECs (squares). When biomass cannot be traded, cumulative CO_2 removal decreases by 65 $GtCO_2$. The value of players in trading biomass also changes (colored crosses). Regions with high biomass availability (i.e., Brazil and India) emerge as critical biomass providers: limiting the trade of Indian, and to a greater extent Brazilian, biomass decreases total removal potential. In this scenario, regions such as China are non-critical biomass providers: limiting the trade of Chinese biomass slightly impacts the cost (1% increase) but does not compromise meeting the target. Finally, regions such as the EU and the US are non-critical biomass beneficiaries: limiting the trade of EU and US biomass does not impact the cost or the ability to meet the target.

The value of different regions in trading negative emissions and/or biomass therefore differs on CO_2 removal targets and which element—biomass or storage—is critical and/or limiting in achieving these targets. Some regions can be alternatively providers and beneficiaries, and in all cases full collaboration leads to the highest chance of meeting global targets at the least cost. While international cooperation is required to agree on regional responsibility to contribute to climate change mitigation and removal, active collaboration between regions is essential to meet global CO_2 removal targets. While Article 6 of the Paris Agreement establishes a framework for the collaboration through carbon offsetting, and emissions trading, no scope is given for the trading of CO_2 sinks, either in the form of biomass or geological storage. Accounting for the trading of sinks in

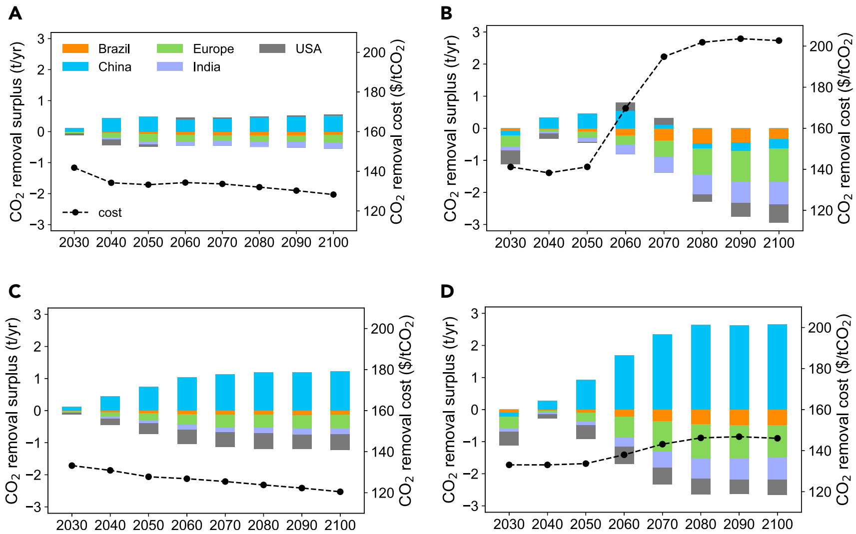

Figure 4. CO_2 Removal Surplus and Cost Over Time

CO_2 removal surplus (left axis) and annual CO_2 removal cost (right axis) are for a low (A and B) and high (C and D) biomass availability, and low (A and C) and high (B and D) CO_2 removal targets scenarios. Regions with high CO_2 storage and high-low cost biomass availability (e.g., China) provides most of the CO_2 removal surplus across the century.

addition of sources opens opportunities for regions with high bioenergy production or CO_2 storage potential.

Does Electricity Generation Matter?

BECCS has the co-benefit of generating electricity in addition to removing CO_2 from the atmosphere. The value of electricity is greatly dependent on the structure of the electricity system, as well as the prevailing policy environment, and therefore robust prediction of electricity prices is challenging. In this thought experiment, we assume regional electricity prices remain constant over the century, and minimize the breakeven NEC, with results presented in Figure S2. It is observed that, when accounting for electricity revenues in BECCS total cost, China remains the main provider of CO_2 removal. However, a structural change in BECCS cost-optimal deployment is that the EU provides more CO_2 removal than the US, owing to higher electricity prices in the EU. Considering the value of electricity generation, higher BECCS cost regions, such as the EU could play a more important role than might have otherwise been assumed.

Sensitivity to CO_2 Storage Availability

These results are highly dependent on assumptions as to how much CO_2 storage is available in each region. In the Supplementary Figures, we explore the impact of having more storage in Brazil, and storage at all in India, on BECCS cost-optimal deployment (Figure S4), and the value brought by each region to the collaboration (Figure S3). When more storage is available in India and Brazil, we find that total cost decreases by 7% at low targets, and 51% at high targets. Brazil is a critical independent provider, with a cost increase of up to 24% when Brazil meets its target alone, and an 8-GtCO_2 decrease in CO_2 removal. This shows the importance of the availability of well distributed storage sites in lowering the cost of BECCS and identifying the critical players in delivering cost-effective CO_2 removal.

Finally, these results are equally dependent on the burden-sharing method used to downscale the global target to the cumulative target of Brazil, India, China, the EU, and the US, which constitutes an entire research question in itself. They nonetheless quantify the value of negative emissions and biomass trading between regions, and highlight the need for the determination of region-specific CO_2 $_2$removal targets, to foster value creation opportunities for regions with high BECCS potential.

Conclusions

This study explores the cost-optimal deployment of BECCS over time between five key regions: Brazil, China, the EU, India, and the US. Owing to the coarse spatial (country or state level) and temporal (an annual time step is used to model BECCS water-energy-carbon balance) resolutions of the modeling framework, this work does not intend to make forecasts as to BECCS future deployment, nor does it attempt to accurately model BECCS dynamic deployment over time. Instead, the modeling framework has been designed to provide insights into the sensitivity of BECCS deployment to international collaboration, with the evolution of global CO_2 removal targets, the decarbonization of the energy system, and potential BECCS cost reductions. Higher spatial and temporal resolution model (e.g., sub-country level with an hourly resolution) would be required to capture the value of BECCS deployment within a given energy system, to meet a given decarbonization target.

Factors such as yield, labor cost, and electricity cost were found to be strong drivers of cost and required CO_2 removal credit to make a BECCS system economically viable. Regional differences between these factors led to significant BECCS cost variations between regions, with end of the century cost of removal as low as \$85/tCO_2 in South China in an optimistic biomass supply chain scenario (e.g., high yield or low carbon footprint of inputs), and as high as \$450/tCO_2 in the UK in a pessimistic biomass supply chain configuration (e.g., low yield or high carbon footprint of inputs), using local biomass. Biomass transport can also lead to a substantial increase in BECCS cost, up to 50% increase in the case of the UK importing biomass from Brazil, in the median scenario. Depending on regional CO_2 storage and biomass availability, these differences suggest a potential cost-optimal BECCS deployment structure where low cost BECCS regions provide CO_2 removal for higher cost BECCS regions.

In determining BECCS cost-optimal value chain over time, the total cost of removal was found to decrease over time at low targets (P2). This suggests that potential BECCS capital cost reductions as well as the decarbonization of the energy system are key to reverse the projected tendency of BECCS cost of removal increasing with the CO_2 removal target. At higher targets, however (P3), sustainable bioenergy supply limits were reached, which led BECCS cost to increase well past the \$100–350/tCO_2 removed range. This represents the limits where

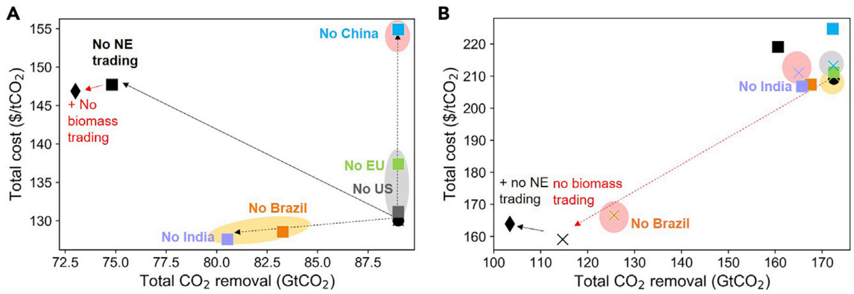

Figure 5. The Impact of Collaboration on Global CO_2 Removal via BECCS

Total cost of removal and cumulative CO_2 removal are presented under full collaboration (circle), negative emissions trading constraints (squares), biomass trading constraints (crosses), or both (diamonds), for specific (colors) or all (black), under a low target (A) and a high target (B) scenario. Note that the figures are not plotted against the same x and y axes. Without/with less collaboration, total cost of removal can increase by up to 14%, and cumulative CO_2 removal by down to 65 $GtCO_2$.

BECCS is no longer cost competitive with alternative, non-land-based, CDR technologies (e.g., direct air capture).

Accounting for revenues from electricity generation was found to improve BECCS regional competitiveness. The negative emission credit required for a BECCS system to have a zero cost balance—or breakeven NEC—was found to be overall lower in the UK than in the US, although BECCS total cost was found lower in the US than in the UK. When minimizing total cost, including revenues from electricity, the structure of the cost-optimal BECCS value changed, with the EU—with higher cost BECCS but also high wholesale electricity price—playing a larger role than the US in delivering negative emissions. These tendencies are naturally very dependent of the regional value of electricity, which is likely to evolve as the structure of regional energy system changes. The value of electricity will also greatly impact the incentives mechanisms required for BECCS systems to be financially viable. In regions with low BECCS cost and high electricity prices, such as Brazil, negative emissions credit required for a BECCS system to breakeven were found negative, which highlight that not all countries will necessarily require a large incentive to deploy the BECCS technology.

The combination of low costs and the proximity of cheap and sustainable biomass supply to $_2$storage sites led China to be the main provider of CO_2 removal in the cost-optimal configuration, followed by the US and the EU. When optimizing the BECCS value chain subject to biomass and negative emissions trading constraints, it was observed that different regions brought different value to CO_2 removal. As a function of regional CO_2 storage and biomass availability, different regions were identified as providers or beneficiaries, while full inter-regional collaboration in biomass and negative emissions trading led to highest chance of meeting global targets at the lowest cost. International trading, certification, and governance frameworks will therefore have to be designed carefully to integrate (1) how to agree on the fulfilling of regional CO_2 removal targets in the case of multi-polar value chains, (2) the tracking of CO_2 emissions along the value chain to determine the net removal achieved, and (3) a negative emissions credit exchange platform/market to encourage that BECCS be deployed in the most cost and resource efficient way.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

The lead contact for all data- and code-related requests is Dr. Niall Mac Dowell.

Materials Availability

This study did not generate new unique materials.

Data and Code Availability

Input datasets and code supporting the current study have been published by Fajardy.[40,31] Resulting datasets are available from the lead contact on request.

The MONET Framework

This study was performed using the MONET framework. A first feature of the model is the calculation of the water, land, carbon, energy, and financial costs of producing, processing, transporting, and converting biomass in a BECCS plant, as well as capturing, transporting, and storing the CO_2 over the lifetime of a BECCS project. Five countries/regions of the world are represented at the state/province level (the US, India, China, Brazil) or the country level (the EU). A second feature of the model is the linear optimization of BECCS deployment from 2030 to 2100 with a decadal time step, subject to global or regional CO_2 removal targets, land, biomass, and CO_2 storage availabilities, and BECCS plant build rate constraints. Degrees of freedom for the optimization program include type of biomass used, location of biomass supply regions, transport route/mode, and location of BECCS plant/CO_2 storage. The description of the carbon, energy, and water models, as well as the accompanying data, is available in previous publications.[40,31]

Scenarios

We refer to the following scenarios throughout the study:

1. Bioenergy availability

To address different levels in bioenergy supply, two bioenergy supply scenarios were considered:

(a) Low impact: bioenergy can only be obtained from bioenergy crops grown on set-aside land.
(b) High impact: bioenergy is obtained from bioenergy crops grown on all land types (with resulting land use change emissions), and agricultural residues (wheat straw).

In both scenarios, the amount of set-aside land corresponds to the lower-bound scenario of a marginal land quantification study led by Cai et al.,[41] of which parcels located in high water stress regions were excluded (see Conclusions).

2. CO_2 removal target

We used two BECCS deployment pathways to 1.5°C from the IPCC,[1,2] allocated to each MONET region based on absolute historical GHG emissions (see section on "What Is an Equitable Allocation of the Global CO_2 Removal Burden?"):

(a) SSP1 (P2) as a "low target"
(b) SSP2 (P3) as a "high target"

3. Supply chain assumptions

For a given value chain configuration—feedstock type, region of production, land used for production, transport route, location of conversion plant—the performance of a BECCS system can vary greatly as a function of the value

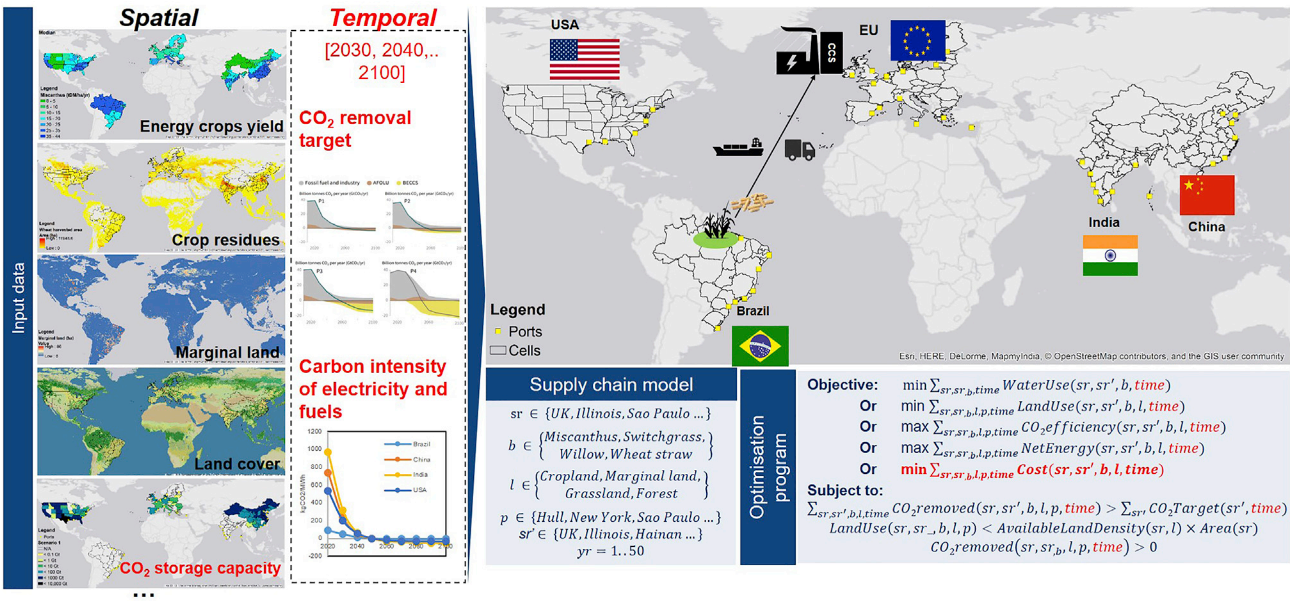

Figure 6. Illustration of the MONET Framework[3,4,11,40]

In red are the new features of the model that were added for the purpose of this study.

of key parameters, such as biomass yield, biomass composition, land use change emissions, carbon intensities of energy sources and chemicals used along the chain.[3,4] To quantify the impact of this variability, we evaluate MONET under three scenarios:

(a) Median: all data points are at average value.
(b) Optimistic: high biomass yield, low carbon intensity of energy sources and chemicals, low biomass moisture, high biomass carbon content, low land use change emissions, etc.
(c) Pessimistic: low biomass yield, high carbon intensity of energy sources and chemicals, high biomass moisture, low biomass carbon content, high land use change emissions, etc.

Owing to a lack of data describing inter-region and region-specific cost variation, as well as the impossibility to predict future costs, we ran one central cost scenario. We, however, consider that it is a reasonable assumption to say that the world cost structure (e.g., low cost developing economies, higher cost in developed economies) is not likely to change, which means that the relative value of each region when it comes to least cost deployment is maintained.

Updates on the Supply Chain Modeling Framework

The following sub-models were modified since the last iteration of the MONET framework:[11]

- Fertilizer input: previously, fertilizer application rates (in kg/ha/year) for each nutrient (N, P_2O_5, and K_2O) and biomass type were exogenous and obtained from the literature. Application was considered annual regardless of the crop harvest cycle, and unrelated to yield. This particularly penalized low-yield regions and crops with longer harvest cycles (e.g., willow). To remedy these caveats, fertilizer input was calculated as a function of yield and the biomass nutrient content (%N, %P, %K) following the methodology in de Wit and Faaij[42] To be conservative, however, no previous natural deposition of nitrogen in the soil was considered, as it was the case in de Wit and Faaij.
- Biomass pelleting: biomass pelleting is costly, both financially and energy wise, and is only interesting if biomass is transported across long distances. In this new version of the model, biomass is not pelleted if converted (sub-region *sr'*) in the same region it is produced (sub-region *sr*). If *sr'* equates *sr*, biomass is only dried, and transported in the form of bales (for wheat straw, switchgrass, and *Miscanthus*), or chips (willow).
- Pellet grinding at the power plant: before combustion, biomass needs to be finely ground. Pellet grinding energy costs from Williams et al. [43] were previously used, and amounted to as much as 394 MJ/ton for wood pellets. Recent work from the same authors showed that using other types of mill could significantly reduce this energy cost, to as low as 117 MJ/ton for wood pellets, and 99 MJ/ton for *Miscanthus* pellets.[44]

Planning and Infrastructure Constraints

We assume perfect foresight in planning BECCS deployment between 2030 and 2100, i.e., all decades are solved simultaneously. Once a BECCS plant is built somewhere, we assume it has to be operated throughout its whole lifetime (no stranded assets). Sufficient CO_2 storage therefore needs to be available for the lifetime operation of these installed plants. We assume a plant lifetime of 30 years. At any given decade, we assume a build rate constraint for new-built BECCS plants of 1 GW/yr. However, no CO_2 transport network and storage infrastructural constraints are considered.

BECCS Cost Model

Akin to the energy, carbon, and water balances performed on different BECCS value chains, a cost balance was added to MONET, accounting for the cost of biomass production (land, chemical inputs, machinery operation, and labor), processing (capital, operation, labor, and energy costs of pellet plants), transport, and conversion in a BECCS plant (capital cost, including reduction over time, operation and maintenance, and labor and fuel costs), as well as CO_2 compression, transport, and storage. The capital cost of the BECCS plant was assumed to decrease over time. Depending on the data availability, input data were added at the state level (US states, Chinese provinces, Indian states, Brazilian states) or the country level (Brazil, China, EU countries, India, the US). When available, cost data added at the state (e.g., fuel and chemicals) were used. For some of the input parameters, when input data were only available for the US, Purchasing Power Factors were used to determine regional costs relative to those in the US. The input data for the cost model, as well further details on assumptions and sources, are available in Fajardy.[40,31]

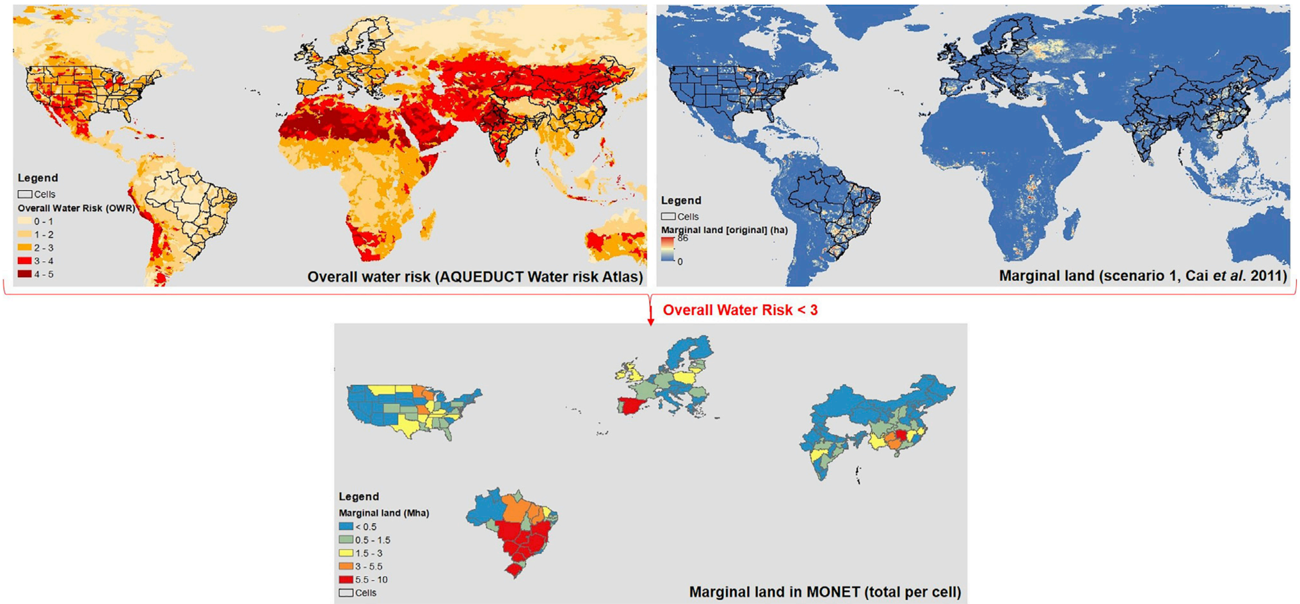

Figure 7. Illustration of the Water Risk and Marginal Land Spatial Analysis

A map of set-aside land (scenario 1 in Cai et al.[41]) was overlaid with an overall water risk index map adapted from the AQUEDUCT Water Risk Atlas,[39] to determine the spatial distribution of set-aside land outside of high water stress regions (OWR >3). The availability of set-aside land was then aggregated by sub-region *sr*.

Key modeling outputs include:

- total levelized cost per ton of CO_2 removed, which accounts for all supply chain CO_2 emissions,
- total levelized cost per ton of CO_2 stored, which does not account for CO_2 leakages along the value chain,
- levelized cost of electricity or LCOE ($/MWh),
- NEC (in $/t$CO_2$) required for the revenues from electricity generation and CO_2 removal to equate total system cost, for a given BECCS project:

$$NEC(sr,sr',b,l,p,p',t,time) = \frac{tCost(sr,sr',b,l,p,p',t,time) - tEG(sr,sr',b,t) \times cost_{elec}(sr')}{tRCO2(sr,sr',b,l,p,p',t,time)}, \quad \text{(Equation 3)}$$

where *tRCO2*, *tCost*, and *tEG* are the total cumulative CO_2 removal, cost and electricity generation, respectively, per ton of biomass, and over the lifetime of a BECCS project, while $cost_{elec}$ is the regional electricity price.

Temporal Evolution of the Energy System

To be consistent with time-evolving CO_2 removal targets, we consider the decarbonization of both the electricity and transport/fuel sectors over time in each 1.5°C representative pathway (P1 to P4). For the decarbonization of the electricity, we computed the carbon intensity of the electricity using the IAMC 1.5°C scenario explorer database,[1] for Asia, Latin America, and the OECD/EU (or ASIA, LAM, and OECD/EU in the database). We computed the decreasing trend of the electricity carbon intensity relative to a 2020 value, and applied it to the model's business as usual electricity carbon intensity in each region (for China and India using ASIA trends, Brazil using LAM trends, and the US and EU using OECD/EU trends). The carbon intensity was considered to be zero when negative. For fuel use at the biomass production (machinery) and transport (truck and shipping) levels, no clear decarbonization pathway can be obtained from the IAMC 1.5°C scenario explorer database. In the International Energy Agency (IEA) "Modern Truck Scenario" (MTS), a combination of fuel switching and energy efficiency measures is projected to decrease road freight final energy demand from 36 EJ in 2015 to 27 EJ in 2050, while well-to-wheel GHG emissions drop from 3.1 GtCO_2 in 2015 to 1.2 GtCO_2 in 2050.[45] This suggests a 52% drop in road freight transport CO_2 intensity per unit of energy by 2050. In adopting a conservative approach, we assumed a freight transport decarbonization trajectory starting from 0% in 2030 and increasing with a 20% increment per decade (20% in 2040, 40% in 2050, etc.) all the way to 100% in 2080. Decarbonization options for freight road transport include (1) natural gas (in compressed [CNG] or liquefied [LNG] form, LNG being more suitable for higher mileage, larger payload vehicles[45]), (2) hydrogen, (3) electric vehicle, and (4) biofuels. In the IEA MTS, most of the decarbonization is achieved through the switch to hybrid (approximately 30% of the heavy vehicle fleet) or fully electrified (approximately 35% of the heavy vehicle fleet) trucks, while biofuels meet 23% of final road transport energy demand in 2050.[45] Transport decarbonization not being the subject of this work, and recognizing that the actual road transport decarbonization will likely be different, we assume for simplicity that road transport decarbonization is achieved through fuel switching to biofuels. In line with the theme of our study, we consider that biofuels are, however, not 100% carbon neutral, and have an associated supply chain emissions factor. Owing to the uncertainty around shipping emissions reduction, we assume that shipping biomass in container ships remains undecarbonized. For biomass drying, finally, we assume that natural gas is used in 2030, and is switched to 100% wood drying as early as 2040. The cost of fuels remains, however, constant over time. We acknowledge that these assumptions might be oversimplifications, but they offer a conservative approach toward decarbonization of transport, as an emission factor of biofuel is considered.

Accounting for the Overall Water Risk

The MONET framework enables the quantification of the blue (fresh), green (from precipitation), and gray (from pollution) amounts of water required throughout the entire BECCS value chain, both at the farm and the power plant levels. However, in the optimization framework, no water availability constraint is considered. To account for potential water risk, the overall water risk (OWR) factor developed by the AQUEDUCT Water Risk Atlas, hosted by the World Resource Institute,[39] was used to avoid bioenergy production in regions with high water stress. The OWR index is a regional measure of both physical (water quantity and quality) and regulatory or reputational risks. The overall risk associated with the quantity of water available is assessed through the evaluation of

baseline water stress, water stress variability (inter annual and seasonal), flood occurrence, drought severity, upstream storage, and groundwater stress, while the quality of water is measured by upstream activity (e.g., Is the water available coming from a waste water stream or a protected land area?). Regulatory risks are assessed through the density of media coverage on water issues in a particular region, the population's access to water, and the percentage of amphibian species classified as threatened, which is proxy to measure the fragility of a freshwater ecosystem. The overall water risk is computed by a weighted average of all of these risks factors, with different weights as the function of the industry (69.7% for physical quantity, 9.1% for physical quality, and 21.2% for regulatory risks across all sectors).[39] This method results in a regional index between 0 and 5 (from low risk to extremely high risk), which is represented in Figure 7. To avoid bioenergy production in regions with high water stress, a geospatial analysis was performed with the ARCGIS software to quantify the amount of set-aside land available outside high water stress regions (OWR > 3, i.e., high to very high water risk). A 30 arc geographic resolution map of set-aside land availability (scenario 1 or "marginal mixed crop and vegetation land, part of abandoned land" in Cai et al.[41]) was intersected with a sub-basin level map of overall water risk.[39] The methodology and the final set-aside land availability per region is available in Fajardy.[40,31]

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.07.014.

ACKNOWLEDGMENTS

The authors thank Imperial College London for the funding of a President's PhD Scholarship, as well as the Greenhouse Gas Removal (GGR) grant, funded by the Natural Environment Research Council (NERC), under grant NE/P019900/1. The authors also thank Solène Chiquier from Imperial College London for curating the CO_2 storage capacity dataset.

AUTHOR CONTRIBUTIONS

M.F. and N.M.D. conceived the study. M.F. carried out the calculations and designed the figures. M.F. and N.M.D. contributed to the writing of the paper.

DECLARATION OF INTERESTS

M.F. is an advisor for the Carbon Removal Center. N.M.D. is a non-executive director of the company Settle for Less.

Received: January 28, 2020
Revised: June 5, 2020
Accepted: July 28, 2020
Published: August 21, 2020

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