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POSTPRINT

A protein transition can free up land to tap vast energy and negative emission potentials

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Summary

Bioenergy with carbon capture and storage (BECCS) can help stabilize the climate by extracting carbon dioxide from the atmosphere while producing renewable energy. However, biomass availability would limit BECCS potential, and biomass cropland expansion may threaten biodiversity, food security, and water supply. Replacing land-intensive foods can help unlock sustainable biomass production. Here, we estimated BECCS energy and negative emissions using biomass grown on freed-up land when replacing animal-source foods. Biomass production excludes agricultural expansion to protect biodiversity, ensures enough food supply globally to safeguard food security, and constrains irrigation to secure water for people and ecosystems. Negative emissions consider supply chain emissions and the forgone sequestration from natural revegetation. Results show that replacing 50% of animal products by 2050 could release enough land for BECCS to generate 26.4–39.5 EJ_{elec}/year, the scale of coal power today, while removing 5.9–9.4 $GtCO_2e$/year from the atmosphere, almost what coal power emits today.

Keywords

Bioenergy, carbon removal, climate change mitigation, alternative proteins, land use, food security, water security, hydrogen production, CO_2 storage

Introduction

Carbon dioxide removal (CDR) is widely seen as essential to cap global warming at 1.5 °C.[1] Ideally, CDR can help avoid a temperature overshoot by accelerating emission reductions and offsetting residual emissions in hard-to-abate sectors; as a last resort, it can help recover from a temperature overshoot by removing excess emissions from the atmosphere.[2] Among all CDR methods, bioenergy with carbon capture and storage (BECCS) has been the most prominent alternative in climate mitigation pathways.[1] Typical pathways have projected massive BECCS deployment to remove the equivalent of several years of today's GHG emissions.[3, 4] Biomass from residues and wastes can fuel a limited sustainable BECCS potential.[5] Massive BECCS deployment, however, implies massive water and land requirements for additional biomass supply. Agricultural expansion to produce biomass is particularly controversial because it may worsen biodiversity due to the loss of natural land, and food and water security due to competition for land and water resources. The resulting impacts could outweigh the BECCS climate mitigation benefit.[6–8]

A protein transition, the shift in consumption from animal to alternative protein sources, could help reduce agricultural land use, opening up new opportunities for climate mitigation. By replacing land-intensive agricultural products, it can help unlock BECCS potential from dedicated crops. More specifically, reducing demand for animal products can reduce land for feed and pasture, where biomass crops for BECCS could grow.[9] Recent market research shows that alternative proteins (AP), from sources such as plants, microorganisms, and tissue culture, could replace 10–30% of animal products in 2030 and 30–70% in 2050.[10–13] Currently, consumers willing to replace animal products are mainly motivated by health, animal welfare, or environmental reasons.[14, 15] Within the next decade, alternative proteins could reach parity with animal products in taste, texture, and price,[10] which may make it easier for mainstream consumers to replace animal products. Alternative proteins that require less land and emit less greenhouse gases (GHG) than animal products[16–18] offer a "double dividend" to mitigate climate change: reducing GHG emissions and sparing land where natural or engineered climate solutions could sequester carbon.[19–21]

Researchers have estimated the spared land from replacing animal products, and the potential to sequester carbon on the spared land; however, they have usually only considered small replacement levels. For example, global meat consumption in Shared Socioeconomic Pathway (SSP) 1, the SSP with the lowest demand for animal products, is just slightly lower than in SSP2 (with around 20% lower calorie consumption per capita in 2050), the pathway with middle-of-the-road assumptions.[22] Besides, various studies have evaluated the effect of replacing large shares of animal products on the climate mitigation potential of bioenergy and also natural revegetation.[9, 19, 20] They assessed the effects of dietary changes on climate mitigation, considering a specific target for a partial or entire replacement of animal products. Nonetheless, the uncertain prospects of animal product replacement and their potential climate implications call for a more in-depth assessment.

In this study, we estimated the extent of pasture and cropland a protein transition could free up. Given the uncertainty of AP adoption, we analyzed diverse replacement levels of animal products and highlighted results for a likely adoption range. Over the released land, we quantified the potential for biomass production, which BECCS would use as feedstock to produce energy, capturing and storing the resulting carbon dioxide (CO_2). We present energy and negative emission potentials for BECCS when producing three alternative carriers: electricity, hydrogen, and Fischer-Tropsch (FT) diesel. Negative emission estimates account for BECCS supply chain emissions and the forgone sequestration from natural revegetation. BECCS potentials are constrained to avoid burden shift from climate mitigation to other areas. Previous studies on large-scale BECCS deployment have found substantial tradeoffs[23] with food production,[24] biodiversity,[25] and water use.[26, 27] In contrast, our assessment ensures enough food supply globally for every level of animal product replacement by maintaining at least baseline calorie and protein supply. It also avoids agricultural expansion to protect biodiversity and constrains irrigation to secure water for other human activities and environmental flow requirements (EFR). Lastly, we assessed the local CO_2 storage capacity, which may constrain BECCS potential in some regions.[28] Unlike most BECCS assessments, focusing on the potential for biomass production,[28] we present spatially explicit estimates of both biomass production and geological CO_2 storage in highly prospective sites, i.e., sedimentary basins with high prospects of favorable geology for CO_2 storage.

Our findings reveal how a protein transition could provide countries with vast negative emission energy resources: baseload electricity to strengthen their electricity mix, or flexible hydrogen to decarbonize hard-to-abate sectors domestically or spur economic growth through exports. They also indicate that countries could store most of the CO_2 in highly prospective storage sites within their borders. Our results represent technical BECCS potentials. Future research could incorporate various techno-economic and socio-political factors that may hinder adoption. Likewise, emerging research on novel alternative proteins can further clarify uncertainties of adoption and impacts.

Results

Methods summary

In our primary scenario, *Replace*, we evaluated how a protein transition can help free up animal agriculture area (pastureland and feed cropland). Bioenergy crops replace the freed-up areas, avoiding agricultural expansion, to produce the biomass for BECCS. As the mix of different types of alternative proteins in the future is uncertain, *Replace* follows a simple, conservative approach to estimate the released land from a protein transition. It targets pastures and three types of feed crops (forages, maize, and barley), covering over 90% of the projected animal agriculture area in 2050. We assumed that other feed crops we excluded, such as soybeans, oil crops, and pulses, would more than compensate for the displaced animal products if reassigned for direct human consumption – as Hayek et al.[19] and Sun et al.[20] showed.

To contrast *Replace,* we present a second scenario: *Expand*. It exclusively evaluates bioenergy crops expanding over natural land, excluding areas with the highest conservation value (see Scenarios in experimental procedures). Despite the exclusions, *Expand* would not represent a sensible solution because it would further harm biodiversity and Earth system processes.[23, 29, 8] We include it only to compare BECCS performance through bioenergy crops replacing released animal agriculture areas (in *Replace*) against the commonly assumed case of bioenergy crops expanding over natural areas (represented in *Expand*).

Both scenarios secure water for other anthropogenic uses and protect the integrity of freshwater ecosystems. To obtain bioenergy crop yields, we forced the LPJmL model to the SSP2-2.6 scenario, under four General Circulation Models (GCMs), defining irrigation based on the same EFR scheme as in Stenzel et al.[30] (details in experimental procedures). In short, we cap grid cells daily available water for irrigation of bioenergy crops. We prioritize securing water for ecosystems (EFRs, calculated from a historic period) and future water requirements for households, industry, and livestock (HIL). Then, irrigated crops, including bioenergy crops, can use only the water that may remain after securing EFRs and HIL. If no water for irrigation remains, crops are assumed to be rainfed only.

We define negative emissions with the same scope as in a recent study on BECCS potential,[5] considering BECCS supply chain emissions and the forgone sequestration from natural revegetation (i.e., leaving the released land alone). We did not consider additional emission reductions from the broader energy and food systems (e.g., potential emission reductions from replacing fossil fuels or animal products). For BECCS operation, we considered fertilizer emissions and other supply chain emissions (including CH_4). For natural revegetation (the forgone C sequestration), we considered initial C stocks and C accumulation in plants (aboveground and belowground, like Hanssen et al.)[5] and soil organic carbon (SOC) changes at depths up to 200 cm.

We performed a source-sink assessment between bioenergy crops and highly prospective basins for CO_2 storage. Minimizing distances among bioenergy crops, power plants, and storage sites would help reduce costs, mitigate supply chain risks, and maximize negative emissions.[31] Thus, beyond evaluating regional storage potentials, we estimated the optimal basin allocation for each bioenergy crop in every grid cell to minimize the overall distance between underground storage sites and bioenergy crops. Such an allocation was constrained by basins' storage capacity. Their assessment, based on a simple but uniform method at a global scale, considered more conservative storage assumptions than previously proposed methods.[32–34] See experimental procedures for details.

BECCS potential by alternative protein adoption level

We found that replacing 50% of animal products by 2050 could release enough agricultural area for BECCS to generate 26.4–39.5 EJ_{elec}/year, the scale of coal power today (35 EJ_{elec}/year)[35], with negative emissions of 5.9–9.4 $GtCO_2e$/year, almost the current global emissions from coal power (10 $GtCO_2e$/year).[36] Alternatively, BECCS could produce 251–376 Mt H_2, around half the projected global hydrogen demand in 2050 (500–800 Mt H_2),[37] with negative emissions of 5.5–8.7 $GtCO_2e$/year (Figure 1). The lower-range values represent BECCS potential when bioenergy crops replace the same share of animal agricultural area in every grid cell, and the upper-range values when maximizing carbon sequestration within countries (only Europe as a whole). In other words, when animal products are not fully replaced, the maximized values are the result of the optimal location of bioenergy crops and animal agriculture areas to achieve maximum negative emissions, while still supplying the pasture and feed-crop production required for animal agriculture within each country. Both range limits secure enough food supply globally. An AP market share of 30% (i.e., replacing 30% of animal products) could free up enough area to generate 15.8–29.1 EJ_{elec}/year with negative emissions of 3.5–7.2 $GtCO_2e$/year, or produce 150–277 MtH_2/year (equivalent to 18.0–33.3 EJ/year) with negative emissions of 3.3–6.7 $GtCO_2e$/year. For an AP market share of 70%, BECCS could produce 36.9–46.5 EJ_{elec}/year with negative emissions of 8.3–10.7 $GtCO_2e$/year, or produce 351–442 MtH_2/year (equivalent to 42.1–53.0 EJ/year) with negative emissions of 7.7–9.9 $GtCO_2e$/year (Figure 1). For country results, see Figures S1–9. Considering that today's global electricity production E is around 100 EJ/year,[38] a given AP market share could lead to a BECCS electricity potential in 2050 equivalent to around $\frac{AP}{2} \cdot E$ (Figure 1c, lower range values for BECCS electricity).

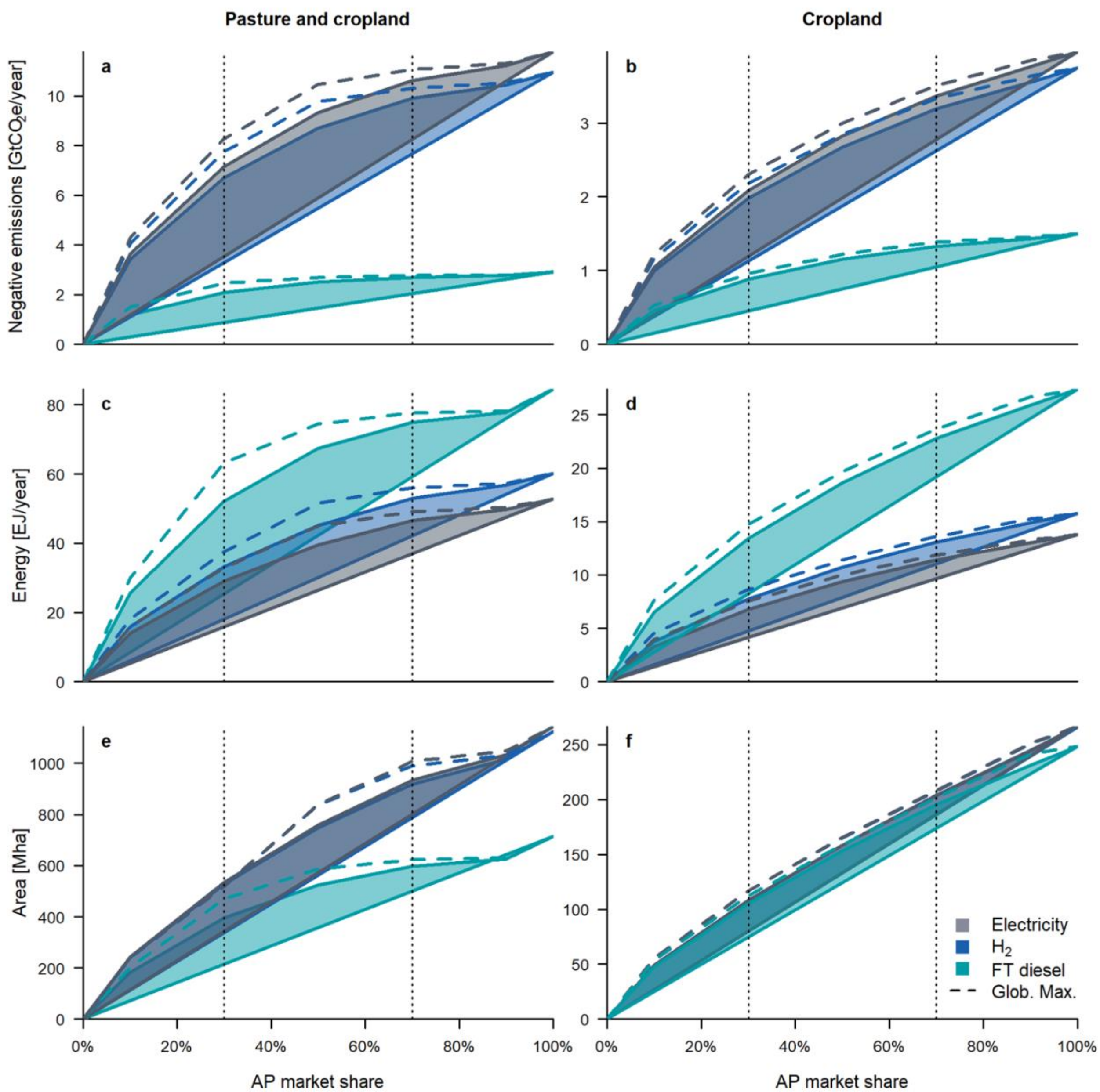

Figure 1. Global potentials under different levels of alternative protein (AP) adoption. *(a, b) Negative emissions, (c, d) produced energy, and (e, f) area used. Vertical lines illustrate the plausible range of AP adoption, between 30 and 70%. The "leafs" (colored areas between the solid lines) show the potential between two cases for bioenergy to replace animal agriculture land: (1) even replacement in all areas (solid straight lines), and (2) replacement that maximizes negative emissions within each country, considering only Europe as a whole (solid curved line). The dashed lines show the replacement that maximizes negative emissions globally. Only negative emissions are optimized; the other graphs show the resulting ranges for energy generated and area used, and all cases secure sufficient food supply. See also Figures S1–9.*

Potentials at full replacement

Entirely replacing animal products with alternative proteins (*Replace* scenario) would release over 3,000 Mha of agricultural land by 2050 (we estimated 3,098 Mha and previous research[19] 3,323 Mha), around 3/5 of today's global agricultural (i.e., cropland and pastureland) area. Our analysis focuses on the nine forest and grassland biomes listed in Table S3, which exclude biomes such as the Deserts and Xeric Shrublands, and Montane Grasslands and Shrublands, hence not considering the total animal agricultural land. The considered areas add up to 1,947 Mha, of which 1,672 Mha are pastures and 275 Mha feed crops. Over these focus areas, we estimated BECCS's carbon storage potential relative to natural revegetation's. BECCS to electricity and to hydrogen achieved negative emissions when using biomass grown on 1,144 Mha (Figure 2a) and 1,125 Mha (including >95% of the evaluated feed crop areas), and BECCS to FT-diesel on only 720 Mha (Figure 1e). BECCS could achieve negative emissions when using biomass crops grown at most latitudes and across forest and grassland biomes (Figure 2). To be more specific, producing biomass in those areas (and using it for BECCS) between 2030 and 2100 (60 years on average, considering linear adoption during the first 20 years) could remove about 700 $GtCO_2e$ (720 producing electricity or 670 hydrogen, Figure 3a) more than natural revegetation – equivalent to over 20 times the global energy-related CO_2 emissions in 2020.

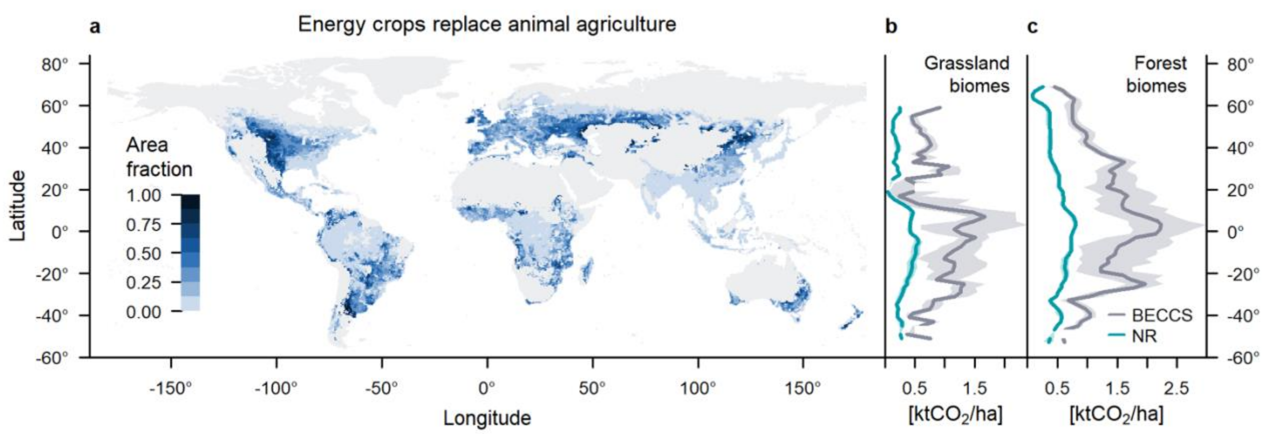

Figure 2. Negative emissions of BECCS replacing animal agriculture. (a) Animal agriculture areas where BECCS electricity could achieve negative emissions. (b,c) Net carbon removal potential through BECCS and carbon accumulation through natural revegetation by 2100 on released animal agriculture areas. Natural revegetation includes aboveground and belowground plant carbon, plus the difference in SOC (SOC in natural areas minus SOC in bioenergy crops). BECCS potential shows net CO_2 sequestration after subtracting supply chain emissions for electricity production. Shaded areas represent a 95% confidence interval using four climate models to estimate bioenergy yields and seven global maps to estimate natural revegetation stocks. The evaluation period is 2030-2100, with 20 years of ramp-up time (Figure 5a).

Source-sink potentials

We project sizeable cumulative negative emission potentials of 158, 125, and 97 $GtCO_2e$ for the large GHG emitters – the US, Europe, and China – between 2030 and 2100 for an electricity pathway (Table S1, Figure S10). Most regions could store all the CO_2 source potential (originally C in bioenergy crops) in highly prospective sedimentary basins (sinks) within their territories, including Brazil, the US, Europe, China, and Russia, which together represent around half of the global negative emission potential for the electricity and hydrogen routes (Table S1, Figures S16–18). We found that a quarter of the carbon in bioenergy crops would spatially overlap with its optimal sink, and 61% would be within 300 km (considered a reasonably economical distance by the IPCC[39]) – with a global average source-sink distance of 249 km (Figure 3e). Countries with insufficient storage capacity may benefit from biomass exports, international storage of CO_2, or CO_2 utilization alternatives.[40] The US, Europe, and China stand out for their considerable sequestration potential with short source-sink distances, having 148, 77, and 80 $GtCO_2$ of the source carbon within 300 km from its optimal sink (Figure 3f–h). Figure S16 and Table S1 show source-sink results for other countries.

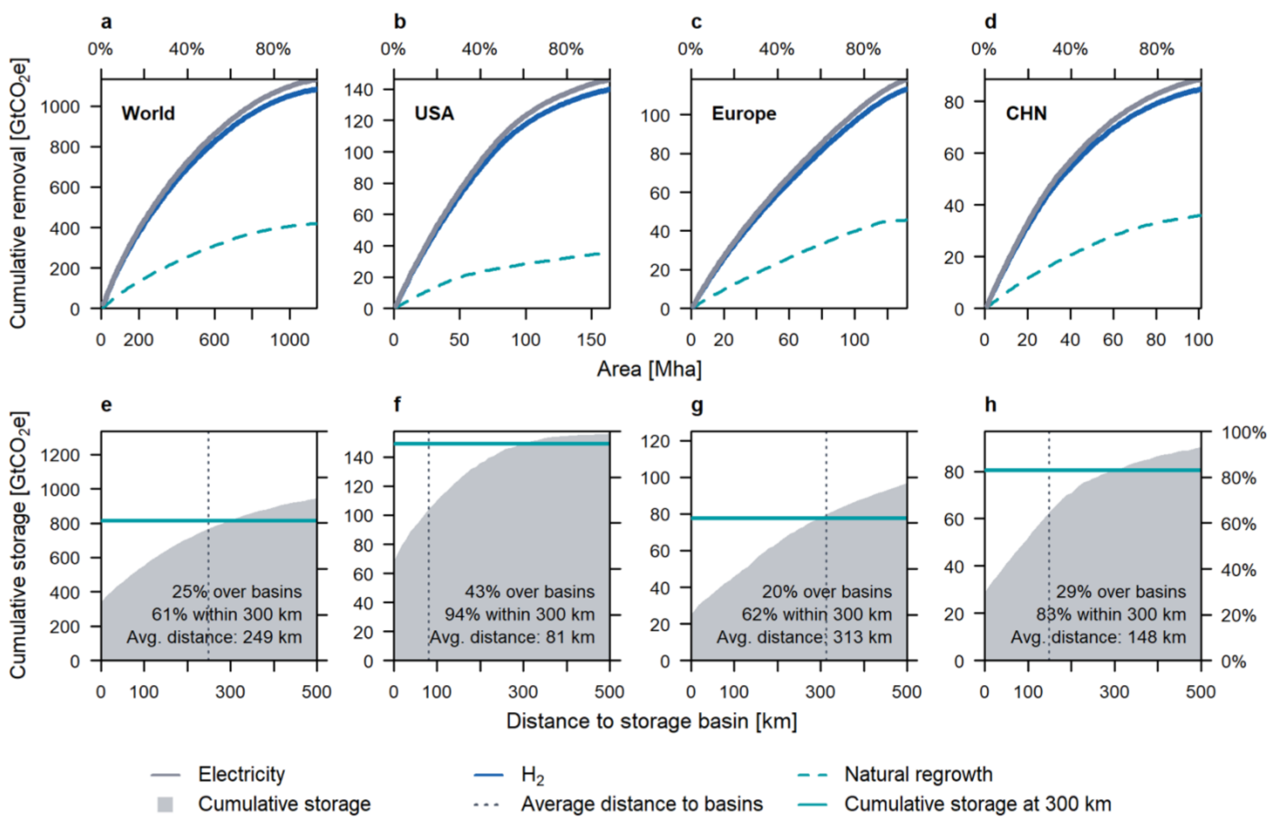

Figure 3. Cumulative removal and storage. *(a–d) Net carbon removal through BECCS and carbon accumulation through natural revegetation by 2100 and (e–h) source-sink distance between bioenergy crops and* CO_2 *storage sites. Negative emissions are the difference between the net carbon removal from BECCS and the forgone carbon stock through natural revegetation. Subplots e–h represent electricity production through BECCS, as it results in higher*

carbon sequestration than hydrogen and FT diesel production. BECCS potential is the average of four climate models, and natural revegetation is the average of estimations based on seven potential natural vegetation maps. The evaluation period is 2030-2100, with 20 years of ramp-up time (Figure 5a). See also Figure S16 and Table S1.

Replace vs Expand

Considering biomass production for BECCS in all areas where negative emissions were possible in *Expand*, BECCS could have a global energy potential of up to 106 EJ_{elec}/year (Figure 4a). However, based on Heck et al.'s[23] definition of risk zones, BECCS global potential in our *Expand* scenario would have uncertain to high risks. Although BECCS potential under *Replace* is around half the energy and negative emissions of *Expand*, it could be much safer and still substantial (Figure 4b). It would entail 53 EJ_{elec}/year, equivalent to about 90% of today's global electricity from coal and gas;[35] and achieve 12.1 $GtCO_2$/year of negative emissions, also about 90% today's global emissions from coal and gas electricity.[36] High-income and upper-middle-income countries, which may be more capable of deploying BECCS,[41] possess around three-quarters of the negative emission potential (Figures S11–13) if countries fully utilize their biomass production for BECCS.

Among the three types of land transitions possible in *Replace* and *Expand*, bioenergy crops replacing feed crops achieves the highest negative emissions per energy produced through BECCS (Figure 4c). Nevertheless, replacing pasture and natural areas can also achieve substantial negative emissions per energy produced. This means that bioenergy crop yields generate substantial carbon removal amounts, which more than compensate for the initial carbon lost due to land use change and additional forgone C storage from natural revegetation over the 60-year evaluation period. Overall, biomass production in grassland biomes results in higher negative emissions per unit of energy produced through BECCS than using biomass produced in forests biomes (Figure 4c).

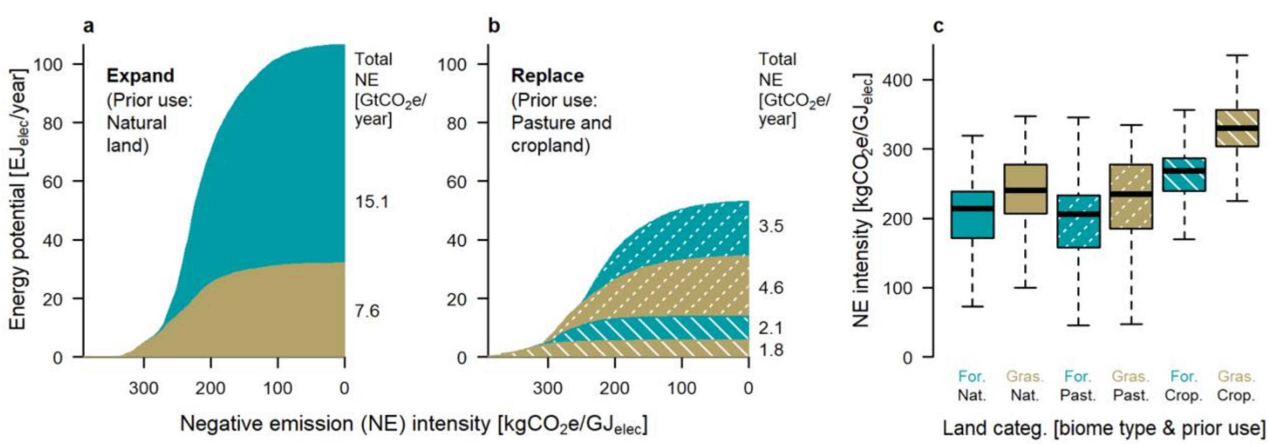

Figure 4. Cumulative energy and negative emission (NE) potential by emission intensity for two scenarios. *Scenarios include bioenergy crops that (a) "Expand" over natural areas and (b) "Replace" animal agriculture. (c) The boxplots with the distribution of negative emission (NE) intensity illustrate the six land categories – a combination of biome type (Gras. - Grassland or For. - Forest) and prior land use (Nat. - Natural vegetation, Past. - Pasture, or Crop. - Cropland). The boxplots do not show outliers. Negative emissions represent net carbon removal through BECCS electricity minus the forgone carbon stock through natural revegetation. The evaluation period is 2030-2100, with 20 years of ramp-up time (Figure 5a).*

Fully using the biomass potential on all the pasture, cropland, and natural areas considered (Figure 5a) could have substantial energy potentials through BECCS for the three energy carrier routes (Figure 5b). Negative emissions could also be substantial for the electricity and hydrogen routes but limited for the FT diesel route (Figure 5c), mainly due to the difference in CO_2 capture rates (90% for electricity and hydrogen versus 52% for FT diesel). Although the FT diesel route has a high energy potential (Figure 5b) from its superior biomass-to-energy conversion efficiency, its climate mitigation potential would be even more limited if emissions during the use phase were considered. Unlike electricity and hydrogen, FT diesel results in additional emissions during use.

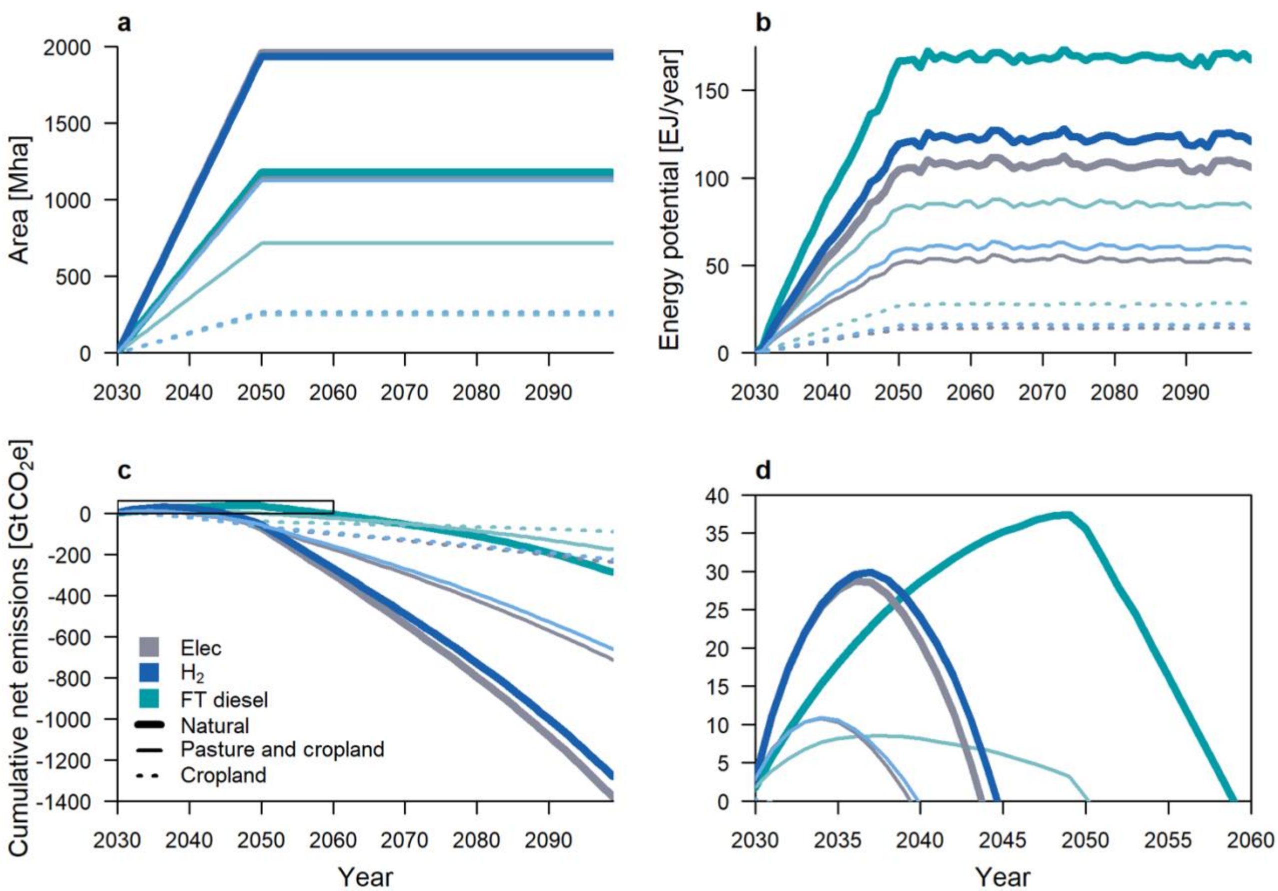

Figure 5. Temporal development of BECCS potentials. *(a) Bioenergy crop area, (b) BECCS energy potential, (c) BECCS cumulative net emissions, and (d) a close-up of the cumulative net emissions during the first decades. All subplots show BECCS maximum negative emission potential via electricity, hydrogen, and FT diesel production over three land categories: natural areas (from Expand), all released pasture and feed cropland areas (from Replace), and only feed cropland areas (from Replace). Negative emissions represent net carbon removal through BECCS electricity minus the forgone carbon stock through natural revegetation. The evaluation period is 2030-2100, with 20 years of ramp-up time (Figure 5a).*

All three BECCS routes can globally achieve negative emissions in the long term. However, in some cases, they may entail large initial excess emissions and long breakeven times to start generating net negative emissions (Figure 5c,d). C loss in plants and soils drives initial excess emissions when transitioning from the initial land use to bioenergy crops. Using all released feed crop areas for producing BECCS feedstock would lead to cumulative negative emissions of 239 and 226 $GtCO_2$ for electricity and hydrogen by 2100, with very low (0.18 $GtCO_2$) initial excess emissions and less than two years to start generating negative emissions. Expanding biomass production over natural areas, in contrast, could lead to massive negative emissions (1380 and 1280 $GtCO_2$ for Elec and H_2), but with initial excess emissions (around 30 $GtCO_2$) that compare to today's global fossil CO_2 emissions (35 $GtCO_2$ in 2021)[42] and almost 15 years to start generating negative emissions. Biomass production on released pastures and feed crops together could lead to cumulative negative emissions of 720 $GtCO_2$ and 670 $GtCO_2$ for Elec and H_2, respectively. Initial excess emissions could reach around 10 $GtCO_2$, and it would take almost 10 years to generate negative emissions. But initial excess emissions and breakeven time of pasture and cropland combined would significantly decrease with less conservative assumptions for initial biomass and SOC losses on pastures (see Discussion).

Upfront emissions and breakeven time

For a more in-depth assessment of upfront emissions among all land-transition types, we defined the *overshoot ratio*. It is an indicator representing BECCS peak cumulative excess emissions, divided by the average yearly negative emissions of the whole evaluation period (i.e., cumulative negative emissions in 2100, divided by the average evaluation period of 60 years). The overshoot ratio (dimensionless, from $GtCO_2/GtCO_2$) and breakeven time (in years) can help illustrate BECCS timeliness to mitigate climate change. Figure 6 results represent the electricity production route (very similar to hydrogen's) for the three types of land transition (from pasture, cropland, or natural land to bioenergy crops for BECCS) and two types of bioenergy crops (grassy, parametrized as miscanthus or switchgrass, and woody as eucalyptus, willows, or poplars). Results in Figures 1–4 assumed the adoption of the crop type with the highest negative emissions in each location. We found that grassy crops overwhelmingly outperformed woody crops, contributing to >97% of the global negative emissions across climate models, scenarios, and energy carrier routes. Furthermore, grassy crops for BECCS have superior timeliness compared to woody crops; that is, they result in lower breakeven times and overshoot ratios than woody crops for all land-transition types (Figure 6). Among land types, bioenergy crops replacing feed cropland achieves the best timeliness, and replacing natural land the worst. Implementing grassy bioenergy crops (the best type in most cases), the interquartile ranges for overshoot and breakeven time differ by around an order of magnitude: overshoot ratios of 0.03–0.13 for cropland versus 0.32–10.5 for natural land, and breakeven time of 2–3 years for cropland versus 7–30 years for natural land (Figure 6). Initial carbon in plants, SOC changes, and time to the first harvest of bioenergy crops are critical drivers of breakeven time and overshoot ratio. In all cases, we conservatively assumed that initial plant C gets burned, releasing emissions to the atmosphere,[43–45] such that the higher the initial plant C, the higher the initial emissions. For bioenergy crops replacing feed cropland, initial plant C and SOC are the lowest, and SOC increases upon establishing woody (i.e., plantations) or grassy bioenergy crops.[46, 47] For bioenergy crops replacing natural land, on the other hand, emissions from sizeable initial plant stock are much higher, and SOC decreases upon establishing bioenergy crops. For the third case, bioenergy crops replacing pasture and cropland (around 3/4 pasture), breakeven time and overshoot ratio are highly uncertain. Conservatively, we assumed high initial plant stocks and large SOC losses when transitioning from pastures to bioenergy crops; however, intensively grazed areas[48] may result in SOC gains when transitioning to bioenergy crops. Figures S14–16 provide an overview of all cases' SOC, plant carbon, and carbon sequestration balances.

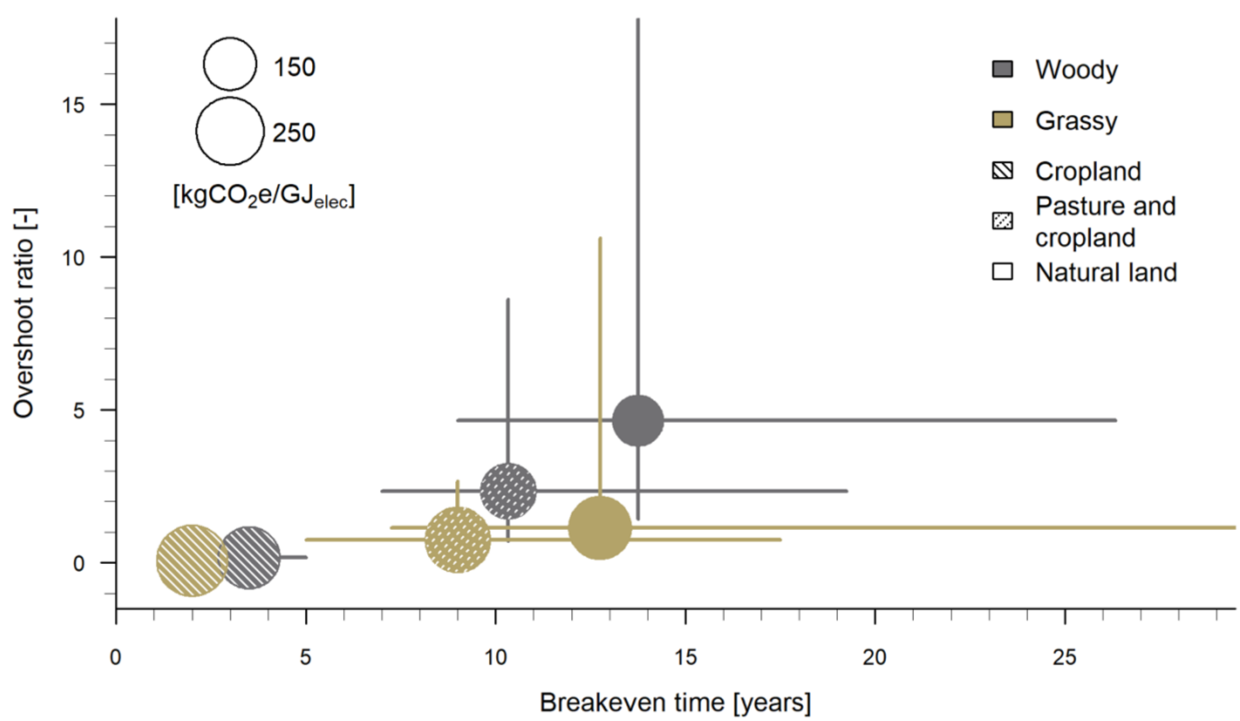

Figure 6. Overshoot ratio and breakeven time for electricity production through BECCS. *Woody and grassy bioenergy crops replace three land categories (natural land, cropland, and pasture and cropland). The overshoot ratio shows peak cumulative excess emissions, divided by the average yearly negative emissions of the whole evaluation period. Breakeven time is the year when BECCS would start achieving net negative emissions. The lines show the interquartile ranges, and the circles are concentric to the medians of overshoot and breakeven time. The circle size is proportional to the median negative emission intensity. The evaluation period is 2030-2100, with 20 years of ramp-up time (Figure 5a).*

Discussion

Harnessing the co-benefits of a protein transition

Replacing animal products can help countries strengthen multiple sectors beyond food. As animal products have predominantly domestic land-use impacts, countries could aim at freeing up agricultural land by influencing demand. Using available multiregional input-output data from the year 2010 (see experimental procedures), we found that 85% of the land use sustaining animal products is domestic (considering only Europe as a whole) (Figure S23). Therefore, if countries incentivize alternative proteins that use less land than animal products, they could tap into BECCS potential by using bioenergy crops to be cultivated over the spared pasture and cropland areas. Such a strategy could have sweeping implications for diverse sectors: in energy, it could boost security of supply with baseload electricity (like advanced coal technology) or decarbonize hard-to-abate sectors with flexible hydrogen;[49, 50] in health, it can improve nutrition by reducing animal product consumption;[51] in commerce, it may give countries a competitive edge in the global hydrogen market;[37] in environment, it can help remove large amounts of CO_2 from the atmosphere without further loss of natural land.

Releasing and using released land

Besides animal product substitution, several other factors can help release agricultural land. Likewise, multiple natural and engineered solutions could compete with bioenergy for the released land. Precision agriculture, increasing crop yields, and reducing food losses, among others, can also free up agricultural land.[52] We focused on alternative proteins because their potential has been less explored, despite the promising outlook that recent market studies foresee.[10–13] As our results suggest, even modest adoption levels of alternative proteins could free up large agricultural areas (Figure 1e,f). Given the unknown replacement prospects for specific products, we assumed even substitution of all animal products, and we aimed to overcompensate for the calories displaced. Future studies could target reductions of the most land-intensive products, e.g. beef,[16] paired with a less conservative replacement, like Humpenöder et al.[53] did with microbial protein replacing beef. Additionally, other emerging alternative proteins like cultured meat and mycoprotein could be suitable beef replacements and are estimated to have lower land needs than most meat alternatives.[18, 17] Released areas could help mitigate climate change, as we explored, but they may also provide multiple other benefits. Land-use options, such as natural succession, reforestation, and biochar, could help mitigate climate change with co-benefits for biodiversity and ecosystem services.[54, 55] While natural solutions could be cheaper and more sustainable, engineered negative-emissions technologies (NETs) like BECCS and direct air carbon capture and storage (DACCS) have much superior permanence of storage (even by several orders of magnitude),[56] higher transparency and accountability, and a greater potential if technology development is decidedly supported.[55]

BECCS in the energy and climate mitigation context

Unlike other engineered NETs, BECCS can produce energy, which may facilitate adoption. BECCS electricity and hydrogen routes seem particularly suitable to support the phase-out of thermal power from fossil fuels. Directly, BECCS could provide baseload electricity to eliminate the need for new coal power plants;[50, 49] indirectly, BECCS could produce hydrogen to replace fossil fuels in existing thermal plants. For example, carbon-negative hydrogen or hydrogen-produced ammonia could replace gas and coal in the many thermal plants of advanced economies that would still be running by 2030 (79% of coal and gas-fired plants).[57] While electricity and hydrogen from BECCS could have substantial negative emission potentials, FT diesel from BECCS could also prove valuable, mainly if it displaces fossil fuels (e.g., in the transport sector). Likewise, biochar could become attractive in some areas: it may also produce energy to displace fossil fuels and generate co-benefits like increased crop yield through biochar additions.[58] If negative emissions rather than electricity drive BECCS adoption, DACCS could become its main competitor, given their similar profile as engineered NETs. Despite DACCS high costs (largely from energy use), it may still turn out to be more affordable than BECCS electricity[59], depending on the energy system, biomass price, and the negative emissions needed.[60] For hydrogen production, BECCS could be cost-competitive in 2030 (at $50–100/tDM) compared to the fossil-fuels and renewables routes.[57] If large areas of highly productive agricultural land become available, e.g., under the 30–70% market shares of alternative proteins that we evaluated, biomass cost would likely decrease, but its precise effect on BECCS competitiveness remains unclear.

Besides dedicated crops, biomass residues offer some additional sustainable potential to sequester carbon through BECCS (or biochar),[5, 58, 61, 62] which we did not consider. We also did not consider the biomass production potential of second-generation lignocellulosic crops (our focus in this study) on abandoned agricultural land due to various factors (like increased crop yields) or when replacing current first-generation bioenergy crops like corn, sorghum, and sugarcane.

Our results show that replacing animal products can help unlock vast energy and negative emission potentials via BECCS while avoiding agricultural expansion and securing water supply for people and ecosystems. Nevertheless, BECCS is no silver bullet against climate change, let alone other environmental challenges. First, BECCS and other NETs should complement rather than replace immediate carbon emission reductions. Relying on future NETs deployment is risky, costly, and unfair to future generations, particularly to vulnerable populations that contributed the least to climate change and will suffer the most from its consequences.[63, 64] Second, BECCS can help mitigate climate change, but biodiversity loss and land-use change may remain beyond safe planetary limits even without further agricultural expansion.[29] Although the transitions that we considered in *Replace* may improve biodiversity and ecosystem services,[52] benefits are limited compared to transitions to more diverse natural ecosystems.[65, 66]

A mitigation boost but not a replacement for nature

Bioenergy can help mitigate climate change in the following decades, but it is no substitute for natural ecosystems to stabilize the Earth system in the long run. If existing agricultural areas are freed up due to the replacement of animal products, as we analyzed, the spared land could gradually return to its natural state or take another interim use to boost climate mitigation. In other words, the adoption of BECCS or other land-based carbon dioxide removal methods does not exclude natural succession altogether. During some decades this century, BECCS could achieve net negative emissions and permanently store in the geosphere billions of tonnes of CO_2. Afterward, natural succession could more slowly store in the biosphere and pedosphere any excess CO_2 (to limit global warming at 1.5°C or even below) that may remain in the atmosphere. The effect of delaying natural succession is beyond our scope. However, further expansion for bioenergy crops at the expense of natural ecosystems would result in dangerous upfront emissions as our results showed, and further exacerbate biodiversity loss.[8] Even some agricultural areas, like some rangelands (rangelands were evaluated within pastures in this study and represent around 30% of the negative emission potential in *Replace*), may be close to their natural state and would be convenient to protect. These may already store considerable carbon stocks in plants and soils, and fully rewilding them may be feasible in the short term.[67]

BECCS challenges and uncertainties

Over the long term, BECCS would likely sequester more carbon than natural revegetation over vast agricultural areas. However, uncertainties remain around timeliness to mitigate climate change, nutrient requirements, water for CCS, CO_2 storage, and more. A fundamental uncertainty is timeliness when bioenergy crops replace pastures, mainly due to unknown SOC changes and initial plant C stocks. For bioenergy crops replacing pastures, we assumed large SOC losses and high emissions from burning substantial initial plant stocks without capturing the resulting emissions; if the replaced pastures were intensively managed, however, breakeven time and overshoot ratio may resemble more the transition from feed crops to bioenergy crops (Figure 6). Besides, various measures may reduce breakeven time and initial emissions for all types of land transitions. To reduce SOC losses, biochar could be added to the soil;[68] and to reduce emissions from the burning of the initial biomass, part of it (e.g., 80%)[5] could be used as feedstock for BECCS, capturing the resulting CO_2. Emissions from SOC changes and the burning of the initial biomass do not have a substantial effect on the total cumulative negative emissions, but they are crucial to improving BECCS timeliness when using bioenergy crops grown over replaced pastures and natural areas.

Another uncertainty that we did not assess is nutrient emissions, which already pose a high risk to the stability of the Earth system, primarily due to fertilizer application in agriculture.[69] Fortunately, if miscanthus dominates bioenergy crops, nutrient requirements may be low,[70] particularly phosphorus and nitrogen. Our results showed that grassy crops (parametrized as miscanthus or switchgrass, without distinguishing one from the other) could deliver >97% of total negative emissions. Based on recent data,[71] we estimated that miscanthus would outperform switchgrass virtually everywhere, contributing around 97% of the total negative emissions for all the assessed energy carriers and climate models.

We also did not assess water use for the energy production plant, but it may not be critical because biomass production is the dominant water-consumption stage along the supply chain of a BECCS system with dedicated crops. For BECCS electricity, past research estimated that biomass production (the focus of our water assessment) accounts for 98% of the water consumption.[72] Finally, BECCS faces diverse challenges, from techno-economic to socio-political, for scaling up CCS technologies and CO_2 storage.[41] To remove carbon at scale when most needed, BECCS and other engineered NETs require strong support today; CCS technologies, for instance, require time and investment to build the infrastructure needed for achieving economies of scale.[6, 55] Geological storage of CO_2 is especially challenging, as realistic storage capacities remain highly uncertain; at this point, further delaying the planning process may also delay CCS deployment, including BECCS's.[73]

Future research could provide a more nuanced assessment of emissions, crop yields, and land use requirements beyond our scope. A broader scope could analyze the potential additional emission reductions from displacing diverse energy sources and how our results may change under a wide range of potential future crop yields. Likewise, new research could assess more in detail the effects of the adoption of both conventional and emerging alternative proteins. Our approach for replacing animal products is likely conservative for land use because it is based on conventional alternatives like pulses, which will likely use more land than emerging alternatives like cultured meat or mycoprotein[74], although uncertainties remain, particularly for cultured meat.[75] Moreover, we overcompensated for the displaced animal products. In terms of emissions, conventional alternatives likely offer a "double dividend";[20] however, the emissions of emerging alternatives are more uncertain. For example, some replacement alternatives, such as cultured meat, involve energy-intensive processes.[74] Therefore, fulfilling their energy requirements through low-emission sources can help maximize overall emission reductions. Part of such energy requirements can even be fulfilled with negative emission energy through a symbiosis: by replacing land-intensive animal products, bioenergy crops on freed-up areas can feed BECCS to produce negative emission energy, which can be used to produce energy-intensive alternative proteins.

Spurring a protein transition to unlock BECCS dual value

We have shown that replacing animal products can help harness substantial energy and negative emission potentials. The estimated energy potentials can help strengthen energy security; negative emissions can help mitigate climate change; and both can provide economic gains for countries. But such potentials cannot be taken for granted. On the one hand, future replacement levels of animal products, the adoption of specific alternative protein products, and the resource requirements of some alternatives (e.g., land use for cultured meat) remain uncertain. As of today, replacement with traditional plant-based alternatives, as we assumed, offer the most certain land-sparing benefit. On the other hand, even if the replacement releases substantial land and water, which can be used for biomass production, diverse barriers may hinder BECCS adoption. The scale of the estimated energy potentials and the climate mitigation benefit from the resulting negative emissions illustrate 1) the importance of adopting resource-efficient alternatives to animal products, and 2) the enhanced dual role BECCS could assume by leveraging freed-up resources if it is promptly and responsibly incentivized.

Experimental procedures

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Oscar Rueda (o.rueda@cml.leidenuniv.nl).

Materials availability

This study did not generate new unique materials.

Data and code availability

All data shown in the manuscript figures and all original code have been deposited at Zenodo under the DOI 10.5281/zenodo.10278171 and are publicly available as of the date of publication. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

Scenarios

Land-use models

This study presents BECCS energy and negative emission potential in this century. The global estimates assume a linear ramp-up period from zero in 2030 to full bioenergy crops deployment in the considered areas in 2050, keeping full deployment until 2100. The available areas follow two scenarios, both aligned with the "middle of the road" narrative of the Shared Socioeconomic Pathway SSP2, Representative Concentration Pathway RCP2.6. Concretely, the scenarios use land-use data from the Inter-Sectoral Impact Model Intercomparison Project ISIMIP2b , created by the Integrated Assessment Model REMIND-MAgPIE.[76] The land-use data is processed by the Dynamic Global Vegetation Model LPJmL, together with climate input from four General Circulation Models (GCMs): HadGEM2-ES, MIROC5, GFDL-ESM2M, IPSL-CM5A-LR. LPJmL simulates the global terrestrial carbon cycle coupled to the water cycle, and the response of carbon and vegetation growth (e.g., the yields for biomass production).

We created a primary and a secondary scenario. In the main scenario, *Replace*, we estimated BECCS energy and negative emissions when bioenergy crops replace agricultural land, which alternative proteins may help release. In the second scenario, *Expand,* bioenergy crops expand over natural land, excluding areas with the highest conservation value. The *Expand* scenario helps put *Replace* results into perspective, but it may not represent a viable option[23, 29, 8] even after the exclusions.

Replace scenario

In *Replace,* bioenergy crops replace animal agriculture land. We constrained the land available for bioenergy crops to ensure enough food supply globally by maintaining at least baseline calorie and protein supply for every level of animal product replacement. We targeted for replacement pastureland and three types of crops for animal feed – forages, maize, and barley. Since a fraction of maize and barley production is used for food, we targeted for replacement only the feed fraction in each country.[77] The three feed crops we targeted would make up over three-quarters of the total feed supply (by weight[19]); together with pastureland, they would cover over 90% of the total animal agriculture area in 2050. Targeting fewer crops helps tackle the biggest opportunity areas and involves less uncertainty than targeting many crops; moreover, it helps us get conservative estimates. Other feed crops that we excluded, particularly soybeans, oil crops, and pulses, can be reassigned for direct human consumption to compensate for the displaced animal products. As Hayek et al.[19] and Sun et al.[20] showed, reassigning a fraction of them from feed to food would deliver sufficient calorie and protein supply to replace animal products. Hence, repurposing those crops altogether for direct human consumption, as we assumed, would more than compensate for the displaced animal products.

First, we estimated the total area of pastures, forage, maize, and barley that bioenergy crops could replace in 2050, and then linearly interpolated a ramp-up period from no bioenergy in 2030 to the total area we considered for replacement in 2050. Since barley and forages are defined in ISIMIP2b data within groups of crops (*temperate cereals* and *others*), we calculated their location based on recent spatial data for those specific crops.[78] Our estimated area for barley and forages is conservative because we only considered areas where the current distribution of those crops overlaps with their crop group (*temperate cereals*) in the land-use patterns from ISIMIP2b. To estimate the area of barley crops in the future, we considered a demand increase of 30% by 2050[19] and a moderate yield growth of 0.53% per year (average for SSP2);[79] as a result, the area for barley could grow a maximum of 11% (compared to today) in each cell, but only if the *temperate cereals* area was large enough to support the expansion. Based on the same yield growth per year, a maximum area increase of 13% (in locations where the area for the *others* group supported the expansion) would suffice to fulfill a demand for forages that grows by 47% in 2050.[19] Pastures and maize were already defined as individual categories in ISIMIP2b, and maize already excluded maize for energy. In our *Replace* scenario, dedicated lignocellulosic crops for bioenergy would replace different fractions of the targeted pasture and feed crop areas. To ensure that bioenergy crops replace existing agricultural land rather than new expansion between 2030 and 2050, we considered only the minimum area before the beginning of BECCS deployment (in 2030) and in the year of full deployment (in 2050).

Our estimated pasture and crop for feed areas are conservative. Although the original source of our land-use scenarios, REMIND-MAgPIE, assumes higher future livestock demand than other IAMs,[80] its global pasture area is among the lowest.[81] The contrast implies higher land productivity possibly due to more intensively managed pastures, higher reliance on feed crops, or both. Therefore, to define also conservative areas for the two feed crops that could also serve as food crops (maize and barley), we assumed only modest increments in the feed/food ratios between today and 2050. Previous research[19] estimated that the global feed fractions of maize and barley would grow 12.3% and 4.8% by 2050 under middle-of-the-road assumptions. In our case, we took for each country (Europe as a whole) the actual maize feed fraction *feed* / (*feed* + *food*) from FAOSTAT[77] (year 2019) as the starting point. Then, only in regions with feed fractions below the estimated global average in 2050 would the feed fraction increase a maximum of 12.3%, in line with Hayek et al.[19]; in the regions with feed fractions already above the estimated global average in 2050, the feed fraction would not grow. We followed the same approach with barley but considering an additional category, "processing," whose main end product is beer[82]. This way, barley feed fraction was *feed* / (*feed* + *food* + *processing*) from FAOSTAT categories[77] (year 2019); and barley's maximum increase was only

4.8%, also in line with Hayek et al.[19] Since the spatial data of maize and barley does not discern feed from food crops, we allocated the same feed fraction to all grid cells within a country.

Expand scenario

In *Expand*, bioenergy crops expand over primary and secondary natural vegetation, that is, excluding urban and agricultural areas (all pasture and crop areas). Besides, we excluded steep slopes (> 30%)[83] where agriculture may be unfeasible and areas of high conservation value: protected areas[84] (IUCN PA categories I-IV), wetlands and water bodies (GLWD-3),[85] Key Biodiversity Areas,[86] Last of the Wild areas,[87] and locations of rare plant species (above median Margalef rarity index[88]). We added polygon areas using ArcGIS software; converted polygons to raster format with a resolution of 0.5 arcmin; and estimated the area fraction for raster format with a resolution of 30 arcmin (0.5°) for use in LPJmL. Urban and agricultural areas were added at the end because our future land use scenarios have a coarser resolution than other datasets. When integrating them, we assumed that conservation-related exclusion areas do not overlap with urban and agricultural areas. Despite the multiple exclusions, the estimated available areas for biomass production, particularly on forest biomes, would further decrease because a fraction of the area in forest biomes would be needed for various forest management activities.

BECCS energy carrier routes

Electricity production considers parameters based on diverse technologies and summarized in a recent review;[5] hydrogen production uses biomass gasification and water-gas-shift technology;[89] and production of Fischer–Tropsch diesel requires that the feedstock is gasified and the resulting synthesis gas catalytically converted to hydrocarbons.[90] (See BECCS parameters in Table S2.)

Negative emissions

Negative emissions result from the difference between BECCS net carbon sequestration and the forgone sequestration from natural revegetation, as proposed by Hanssen et al.[5] Put another way, Equation 1 shows that – for bioenergy crop *i* (herbaceous or woody), energy carrier *j* (electricity, hydrogen, or FT diesel), and location *x* (0.5° spatial resolution) – negative emissions (NE in kgCO_2e) equal BECCS net sequestered carbon (Net_{BE}) minus the difference in carbon stocks at the end of the evaluation period (2100). For all locations, the evaluation period was 60 years (average, considering a ramp-up phase from 0 in 2030 to full area utilization in 2050 and keeping full utilization until 2100).

$$NE_{i,j,x} = Net_{BE,i,j,x} - LUC_{i,x} \quad (1)$$

$$Net_{BE,i,j,x} = Seq_{CCS,i,j,x} - Em_{Fert,i,x} - Em_{SC,i,j,x} \quad (2)$$

$$LUC_{i,x} = \Delta CV_{i,x} + \Delta SOC_{i,x} \tag{3}$$

Net_{BE} is the balance of the total sequestrated carbon (Seq_{CCS}), minus fertilizer N_2O emissions (Em_{Fert}) and other supply chain emissions (including CH_4) from energy production (Em_{SC}). Supply chain emissions have a cradle-to-factory-gate scope for electricity and well-to-tank for hydrogen and FT diesel. LUC quantifies the additional carbon that could have been stored in natural vegetation (ΔCV) and soil (ΔSOC) stocks. ΔCV is the sum of above- and belowground plant carbon in natural vegetation minus belowground plant carbon in bioenergy crops (aboveground stock is excluded because it gets harvested); and ΔSOC is natural vegetation SOC minus bioenergy crops SOC (at depths up to 200 cm) in 2100 (the end of the evaluation period). Equations 4–6 describe the components of the BECCS emissions balance (Net_{BE}).

$$Seq_{CCS,i,j,x} = Y_{i,x} \times A_x \times f_{loss} \times (\eta_{i,j} - \pi_{i,j}) \times \left(\frac{f_{loss} \times cc \times r \times \kappa}{\eta_{i,j} - \pi_{i,j}} - em_{CCS,j} \right) \tag{4}$$

$$Em_{Fert,i,x} = em_{Fert,i} \times Y_{i,x} \times A_x \tag{5}$$

$$Em_{SC,i,j,x} = em_{SC,i,j} \times Y_{i,x} \times A_x \times f_{loss} \times (\eta_{i,j} - \pi_{i,j}) \tag{6}$$

Y is the total bioenergy crop yield over the evaluation period (in tDM/ha; DM is dry matter), A the area (in ha), f_{loss} the biomass loss correction factor (dimensionless), η the conversion efficiency from biomass to final carrier (in GJ/tDM), π the penalty in conversion efficiency due to CCS (in GJ/tDM), cc the carbon content of the feedstock (in kgC/tDM), r the ratio of the molecular weight of CO_2 to C (44/12), and κ the carbon capture efficiency of CCS (tCO_2 captured per tCO_2 emitted) during the production of the energy carrier. em_{CCS} are the additional supply chain emissions from CCS (in $kgCO_2e$/GJ), and em_{Fert} fertilizer emissions per biomass produced (in kgCO2e/tDM). Finally, Equation 7 shows the calculation of total energy (E, in GJ).

$$E_{i,j,x} = Y_{i,x} \times A_x \times f_{loss} \times (\eta_{i,j} - \pi_{i,j}) \tag{7}$$

Table S2 presents the data used for most variables in Equations 1–7. At the core of our assessment, we compare carbon sequestration through BECCS and natural revegetation by integrating two types of spatial data: bioenergy crop yields from the extensively validated dynamic vegetation model LPJmL[23] and carbon accumulation in natural vegetation from state-of-the-art datasets on natural revegetation and potential biomass stocks.[91, 92]. The LPJmL model allows us to perform complex calculations, such as estimating bioenergy crop yields under stringent protection of environmental water flows[30]. And the natural vegetation datasets help us leverage the latest research findings on natural revegetation after disturbance (e.g., from agriculture, the main focus of this study).

Bioenergy crop yields and sustainable water use

To obtain the bioenergy crop yields, we forced LPJmL by the SSP2-2.6 scenario under the same four GCMs (HadGEM2-ES, MIROC5, GFDL-ESM2M, IPSL-CM5A-LR) that we used to define our two land scenarios, *Replace* and *Expand*. For both scenarios, we prioritize securing water supply for households, industry, and livestock and protecting the integrity of freshwater ecosystems. Only the excess water can be used to irrigate crops (including bioenergy crops). Concretely, calculations of bioenergy crop yields follow the environmental flow requirement (EFR) scheme by Stenzel et al.[30]

LPJmL computes at daily time steps terrestrial water cycling coupled to the carbon balance and growth of agricultural and natural vegetation.[93] It dynamically represents land surface processes such as discharge routing, crop growth, water use efficiency, and yield responses to diverse stresses. In managed areas, plants can use either only rainfed water or rainfed and additional water from local storage or main discharge of the grid cell and neighboring cells. Irrigation considers three irrigation techniques with different supply efficiencies: surface, sprinkler, and drip.[94]

We cap grid cells daily available water for irrigation through the Environmental Flow Requirements (EFRs) scheme, which aimed at preserving the long-term freshwater availability.[30] Based on the variable monthly flow estimation method,[95] EFRs allocate different shares of the flow to ecosystems, 60%, 45%, and 30%, during low-, medium-, and high-flow months. EFRs are 30-year averages, based on historical land use[96] and climate for the period 1970–1999. First, we prioritize securing water for households, industry, and livestock (HIL). If EFRs are transgressed in a river basin since the first step, only rainfed bioenergy crops are assumed to be cultivated there. If, after securing EFRs and HIL demand, some water remains but is not enough to fully irrigate all crops, irrigation water is distributed among all crops (energy and non-energy crops) according to the respective crop cultivation area. As Stenzel et al.[30] reported, global yields could decrease by around 3.5% under our EFR scheme. Yield drops could be compensated by diverse water and soil management measures,[30] which we did not consider in this study.

LPJmL is constantly calibrated against in situ measurements, satellite observations, and agricultural yield statistics.[93, 25, 97, 98] Fader et al.[98] calibrated the model to match national yield statistics for 12 crop functional types and a group of other annual and perennial crops.[98] For our purpose, the model considers two types of second-generation bioenergy crops: herbaceous crops, parametrized as miscanthus or switchgrass; and woody crops, as eucalyptus for the tropics and willows or poplars for temperate regions. Herbaceous crops (also called grassy crops) are harvested yearly or as soon as the above-ground carbon storage reaches 400 g/m; woody crops, every eight years, with replantation after a maximum of 40 years. Bioenergy crop yields have been compared against field data by [25] and [97]. While new data[71, 99] on bioenergy crops are currently being used to recalibrate model yields, we used it in this study to perform a simple bias correction that makes yields more conservative (factor of 0.73 for grassy and 0.89 for woody crops, applied uniformly to each grid cell). For all cases, we excluded areas with low yields (yearly yields below 1.25 tDM/ha).

Natural regrowth and land-use change emissions

To understand the BECCS-added climate mitigation value, we estimated land-use change (LUC) emissions as the forgone carbon accumulation from natural revegetation (i.e., natural regrowth) in our two scenarios. We defined a low-parameter natural regrowth model that leverages state-of-the-art datasets on current carbon stocks,[100] accumulation rates,[91] and potential carbon stocks in natural vegetation[92] and soil.[101]

Equations 8 and 9 (based on [91]) describe plant carbon accumulation in the nine biomes we considered. Table S3 specifies which formula is used for each biome.

$$f(age)_{b,l,x} = \left(a_b + c_{b,l,x} \times ar_b\right) \times age_x + (b_b + c_{b,l,x} \times br_b) \quad (8)$$

$$f(age)_{b,l,x} = \left(a_b + c_{b,l,x} \times ar_b\right) \times \ln(age_x) + (b_b + c_{b,l,x} \times br_b) \quad (9)$$

Where $f(age)$ is the plant carbon in natural vegetation (in tC/ha) for biome b, land use l (natural, pasture, or cropland), and location x (0.5° spatial resolution). Parameters a, ar, b, and br are the slope, slope standard error, intercept, and intercept standard error for each biome (Table S3). *age* (in years) of natural vegetation stands is taken from the Global Forest Age Database.[102] We introduced a grid cell-specific calibration factor c to consider the variability within biomes and adjust regrowth curves using available robust results for the 30 first years of natural revegetation.[91] This way, carbon accumulation estimates for each location would be more accurate. Since disturbance intensity affects carbon accumulation rate, we estimated c for three different current land use types: cropland, pastureland, and natural.

Ultimately, regrowth equations (8–9) only estimate carbon stock changes; our calculation (Equation (10)) of total carbon stocks in natural vegetation (P, in tC/ha) also incorporates available data on initial carbon stocks (P_{t_0}).

$$P_{t,b,l,x} = P_{t_0} + \left[f(age_t)_{b,l,x} - f(age_{t_0})_{b,l,x}\right] \quad (10)$$

The resulting total carbon stock P in 2100 is the forgone plant carbon sequestration from natural revegetation. Initial carbon stocks P_{t_0} are based on recent global maps of above- and belowground biomass carbon density.[100] They represent the carbon stock of the foregone natural vegetation at the beginning of the

BECCS evaluation period (2030). For natural land, which would remain natural, the initial stock was the full above- and belowground biomass in 2010 plus regrowth between 2010 and 2030 (this conservatively overestimates the forgone carbon sequestration from natural revegetation because some stocks may decrease between 2010 and 2030 due to natural and human causes, such as wildfires and forest management activities); for cropland, which becomes natural land upon abandonment, the initial stock was only the belowground biomass because aboveground biomass gets harvested; and for pastureland, which also becomes natural, we assumed that the whole belowground and half of the aboveground biomass would remain after abandonment. For both pasture and cropland, we assumed a moderate growth (0.53% per year)[79] of the stocks between the time represented in the data and the beginning of the evaluation period (e.g., between 2010 and abandonment in 2030). Natural regrowth over agricultural land is conservative because, although we assumed that the age of abandoned agricultural land was 0 in 2030 (which implies a rapid initial regrowth of natural vegetation), the abandoned areas will start with a considerable carbon stock. In most cases, such an initial stock would decay, resulting in additional emissions (likely except for some native grasses), but we conservatively kept it during the evaluation period. While carbon stock during the first years is conservative due to the substantial initial stock and fast initial accumulation rates, final stocks could be more accurate because we limited biomass accumulation to a maximum value, taken from seven global datasets on potential biomass stocks.[92] Adding such a constraint makes our estimates more robust, as results rely less on individual datasets (e.g., one dataset for regrowth and one for initial stocks).

To discern among our three target land types, we matched land use maps ([103] for pasture and [104] for cropland and natural land) with the spatial data of current stocks and natural regrowth. And we filled in the gaps that remained in some datasets with the inverse distance weighting interpolation method, considering only data points matching the same biome and land use type.

One drawback of the method to calculate carbon accumulation from natural revegetation is that it does not consider the effect of climate change. Climate change can affect carbon accumulation in both ways: on the one hand, the atmospheric CO_2 fertilization effect could accelerate carbon uptake and also increase the potential carbon in natural vegetation; on the other hand, increased wildfires could outweigh the fertilization effect, overall possibly reducing carbon accumulation in natural vegetation (e.g., in tropical forests).[105] Since BECCS has a much higher sequestration potential than natural revegetation in most cases (Figure 2b,c), variations in the natural revegetation stock (i.e., in the forgone sequestration) are unlikely to have a meaningful impact on BECCS net potential. In any case, variations in the climate and crop yield responses would have a greater impact on BECCS net potential (Figure 2b,c).

Soil organic carbon (SOC) losses from agricultural land use are large but uncertain, particularly in the land transitions we considered, from current agricultural land to bioenergy systems. For this reason, our assessment of SOC changes is simple and conservative. As a first step, we estimated the initial SOC stock for each land type based on the most comprehensive dataset of soil organic carbon.[101, 106] Although we estimate total stocks, what matters to us is SOC changes due to bioenergy crops and the natural revegetation reference case. Initial natural land stocks in 2030 take the "no land use" (NoLU) SOC values; but for agricultural areas (Equation (11)), we estimated SOC losses L based on empirical data where it was possible to compare pastures and cropland with undisturbed sites.[101] Hence, SOC_0 is the resulting stock (in tC/ha) at depth d (in cm) after land-use losses. Next, we estimated SOC stocks (Equation (12)) in year t (the year after the transition) based on expected losses L (dimensionless) from transitions (T) to bioenergy crop i (herbaceous or woody). t_{loss} is the time when SOC losses are highest. For natural revegetation over former agricultural land (Equation (13)), we assumed a constant SOC increase (acc, in tC/ha/year), by biome, based on results from literature reviews on soil carbon accumulation during natural succession (after agricultural use). For continued natural revegetation (i.e., when the original land use is natural already), we assumed no further increase in SOC during the evaluation period. This implies, on the one hand, that we neglect likely further SOC accumulations in some areas; on the other hand, by using "no land use" as SOC_0 for natural areas, we are slightly overestimating SOC losses because natural areas could also have lost some carbon in the past due to previous land uses (and, again, what matters to us is SOC changes, not absolute stocks).

$$SOC_{0,d,l,x} = SOC_{NoLU,d,x} \times \left(1 - L_{T,d,l}\right) \tag{11}$$

$$f(t)_{d,l,i,x} = \begin{cases} SOC_{0,d,l,x} \times \left(1 - \dfrac{t}{t_{loss}} \times L_{T,d,l,i}\right), & t < t_{loss} \\ SOC_{0,d,l,x} \times (1 - L_{T,d,l,i}), & t \geq t_{loss} \end{cases} \tag{12}$$

$$f(t)_{b,d,l,x} = SOC_{0,d,l,x} + t \times acc_{b,d} \tag{13}$$

Table S4 shows the SOC loss parameters for each land transition. To estimate total SOC losses at depths up to 200 cm, we considered a best fit exponential curve, derived from extensive observations and represented in the SOC loss profile in Figure S24.[101] Rectangular areas represent total SOC losses for that depth range. Implementing such a SOC loss profile helped make our estimations of SOC changes more robust because it enabled us to consider extensive data at multiple depths.

BECCS potential by alternative protein adoption level

In *Replace*, we first evaluated BECCS total energy and negative emission potentials by replacing all targeted animal agriculture areas, pasture and three feed crops, with bioenergy crops. More realistically, we also present results for different replacement levels of animal products, from 0 to 100% in 10% intervals. The replacement level is achieved in 2050, considering a linear growth for bioenergy areas and a linear reduction for animal agriculture areas, beginning from 0 in 2030. For replacement levels below 100%, there are numerous ways to select which specific areas to replace. We present three cases: proportional replacement in all areas, global maximization of carbon removal, and regional maximization of carbon removal. Proportional replacement is straightforward, as bioenergy crops replace the same fraction of the animal agriculture area in each cell everywhere. For example, for an AP market share of 30%, we replace 30% of each cell's total animal agriculture area. Global maximization aims to achieve the most negative emissions (Equation (14.1)) via BECCS globally while securing the supply of the remaining animal products in the market (Equation (14.2)). Regional maximization uses the same optimization model but solved by country (only Europe as a whole).

$$\max \sum_{x_a=1}^{m_a} c_{a,x_a} z_{a,x_a} \tag{14.1}$$

$$\text{s.t.} \; -\sum_{x_a=1}^{m_a} p_{a,x_a} z_{a,x_a} \geq (1 - AP) \times P_{Tot,a} - \sum_{y_a=1}^{n_a} p_{a,y_a} - \sum_{x_a=1}^{m_a} p_{a,x_a}, z_a \text{ binary} \tag{14.2}$$

The objective function (Equation (14.1)), solved for animal agriculture product a (pasture, forage, maize for feed, and barley for feed), describes the sum of BECCS net negative emissions c (in tCO_2e) over cells with location x, where the binary decision variable z results in 1. And the constraint (Equation (14.2)) describes the maximum amount of animal agriculture production that can be displaced while still fulfilling the remaining demand for animal products. The negative sign of the first term indicates that positive z values (+1) in the objective function imply the displacement (-1) of animal agriculture production. p (in t) is the production of the animal agriculture product a in a cell, AP (fraction) the market share of alternative proteins (i.e., the animal products displaced), and P_{Tot} (in t) the total yearly production of a in all locations. For pastures, we used land productivity instead of the animal product output itself. This is a conservative constraint because animal density can disproportionally change (e.g., with the supply of concentrate feed). x (with values 1–m) identifies locations where animal agriculture production (for a) overlaps with cells with net negative emission potential, and y (with values 1–n) locations where animal agriculture production does not overlap with negative emissions. Data for animal agriculture production originates from the same model parameters used to create our scenarios (e.g., under SSP2-2.6 with the same GCMs).

We solved the optimizations in R, using the *Rglpk_solve_LP* function,[107] for AP market shares from 0.1 to 0.9 with 0.1 intervals. For the global case, we performed the optimization by animal agriculture product and then added the estimated maximum negative emissions of all cases. For the regional optimization, we repeated the same process for every region and then added the results to obtain the global negative-emissions potentials. We only optimized for negative emissions; to estimate the energy potentials and areas, we multiplied every cell's estimated area and energy by the resulting z values from the optimizations. For all AP adoption levels, negative emissions c are based on the spatial bioenergy yields calculated in the *Replace* scenario, which constrains irrigation (it secures other anthropogenic water uses and environmental flows), assuming complete replacement of animal products. For partial replacement, however, yields may reduce in some areas (possibly at low replacement levels, in areas with limited water for irrigation) if water use upstream increases and it reduces irrigation downstream. All in all, potentials are likely conservative due to the conservative pasture areas estimated, limited growth of feed fractions (for feed crops that can be used for food), and overcompensation of displaced animal products.

Multiregional input-output analysis

To measure countries' control over the fate of their animal agriculture land, we estimated the fraction *domestic* / *total* land impacts from countries' consumption of animal products. We traced land-use impacts through a multiregional input-output (MRIO) analysis using EXIOBASE.[108] EXIOBASE data links final consumption to environmental impacts, considering trade. It provided us data on the regional land use impacts (*pasture* and *cropland)* resulting from nations' final consumption of all animal product categories. The data was available for the year 2010 for 44 countries and 5 Rest of World (RoW) regions. The aggregated land use impacts of countries (Europe as a whole), for which country-level data were available (i.e., the regions in Figure S23, excluding RoW), represent 57% of the global land use of animal products. The resulting domestic fractions of land use may represent a reasonable approximation of the future if current trade trends continue, as our scenario *Replace* assumes.

Geological CO_2 storage and source-sink match

Among different alternatives for CO_2 storage, sedimentary basins have by far the largest capacity.[109] Onshore basins are particularly attractive because they are widespread, usually closer to emission sources, and would be more cost-effective to access than offshore sites.[110] However, the actual potential of geological CO_2 storage in basins remains uncertain.[73] Even ambitious initiatives to evaluate storage capacity in regions like the US, Europe, and Australia[32–34] consider only static storage capacities, ignoring expected limiting injection rates.[73] Furthermore, even static assessments are incomplete and inconsistent, making it impossible to compare estimates among regions fairly.[111] Less uncertain is the prospectivity of CO_2 storage, as it correlates with prospectivity of hydrocarbon potential.[73, 112]

Given the high uncertainty on the amount of CO_2 that each site can store, we implemented a simple but uniform quantification method at a global level;[111] and to leverage the correlation between the prospectivities of hydrocarbons and CO_2, we painstakingly matched global maps of sedimentary basins[113] and highly prospective hydrocarbon provinces.[112] We used the method proposed by Kearns et al.[111] to estimate storage capacity. Kearns et al. follow a similar approach as others to estimate approximate storage capacities with limited data. The IEA[114] and a recent study[109] adopted a volumetric assessment approach, as studies typically do, but using the area covered by sedimentary basins as the only input. They then made assumptions on the basins' thickness, porosity, and other factors to estimate the net storage capacity. If adopted over extensive areas, such an approach can generally match more detailed regional assessments.[111] Kearns et al. estimated that the areal extent of sedimentary basins alone (the only input used by [114] and [109]) accounts for 40-50% of the variation in estimated storage. By further incorporating basin thickness,[115] as Kearns et al. also did, we estimated formation volume, which was estimated to explain 83-89% of the variation in the storage capacity estimates. So, we followed Kearns et al.'s method, assuming that sedimentary formation volume is proportional to storage capacity. We took the lowest proposed coefficient, 0.037 $GtCO_2$ per 1000 km^3,[111] to account for likely limiting injection rates. Our selected coefficient leads to capacity estimates about 7 and 14 times lower than volumetric estimates from the USGS and the US DOE.[111, 116, 117] Despite the uncertainty, the order of the estimates seems reasonable, as past research indicated that dynamic estimates might be a factor of ten lower than static estimates.[118]

We considered onshore basins and practically accessible offshore basins – within 200 mi of the shore, excluding the poles, and at maximum depths of 300 m (based on [119]) – as Kearns et al. proposed. Moreover, we considered only highly prospective basins; as a result, our global layout of CO_2 storage sites is in agreement with past research.[112, 120] We defined highly prospective basins based on [113] and [112], excluding impractical offshore areas, and integrating sedimentary thickness data[115] to estimate the volume.

Unlike crops and storage sites, power plants could have a more flexible but uncertain location. Hence, to measure regions' source-sink match potential, we present an optimization model that minimizes transport distance between bioenergy crops (source) and highly prospective storage sites (sinks). Specifically, we optimally allocated sequestrated carbon (Seq_{CCS}, from Equation (4)) among highly prospective onshore basins and highly prospective, practically accessible offshore basins, considering their storage capacity. We presented the case for the maximum BECCS potential over animal agriculture land (*Replace* scenario, substituting 100% of pasture and cropland) for electricity production, which results in the highest sequestration. Seq_{CCS} is based on the average crop yield under four climate models of the best bioenergy crop (herbaceous or woody, whichever results in the highest net negative emissions). We solved the optimization for every country (only Europe as a whole), assuming no flows across regions. For sedimentary basins extending across more than one region, we split total capacity proportional to the basins' area in each region. Splitting the basins helped avoid double counting and assign every region its "fair" share of capacity. In practice, the capacity of basins across borders would, of course, remain unconstrained by the artificial limits that we introduced. We implemented the optimization for every region using the *lp* function (from the *lpSolve* package)[121] in R and aggregated the results at the end to provide results for the whole world.

$$\min \sum_i \sum_j d_{i,j} x_{i,j} \tag{15.1}$$

$$\text{s.t.} \quad \sum_i x_{i,j} = s_i \qquad \text{for all } i \tag{15.2}$$

$$\sum_j x_{i,j} \leq c_j \qquad \text{for all } j \tag{15.3}$$

$$x_{i,j} \geq 0 \qquad \text{for all } i, j \tag{15.4}$$

In the minimization model (Equations (15.1)–(15.4)), d represents the minimum distance (in km) between bioenergy crop location i and sedimentary basin j. x is the CO_2 flow (in $MtCO_2$), s the source of the sequestered CO_2 in each crop location, and c the basin capacity. Whenever source carbon exceeded the total storage capacity of a region, we allocated only the storage capacity amount by proportionally reducing the CO_2 source in all locations. Table S1 summarizes countries' estimated carbon source and storage potentials. Our source-sink match is only a preliminary assessment because we did not specify the location of the CCS plant where the carbon would be sequestered. We also did not consider competition for CO_2 storage with other sources (e.g., industry or fossil fuel energy). Therefore, if BECCS potential is fully utilized, transport distances would increase. On the contrary, if CCS potential is not fully utilized and there is low storage competition, source-sink distances may decrease, especially if bioenergy crop locations closer to basins are prioritized.

Supplemental information

Document S1: Supplemental figures and supplemental tables

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Author contributions

Conceptualization, O.R. and L.S.; Methodology, O.R.; Formal Analysis, O.R.; Resources, F.S.; Writing – Original Draft, O.R.; Writing – Review & Editing, O.R., L.S., J.M., A.T., and, F.S.; Visualization, O.R.

Declaration of interests

The authors declare no competing interests.

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