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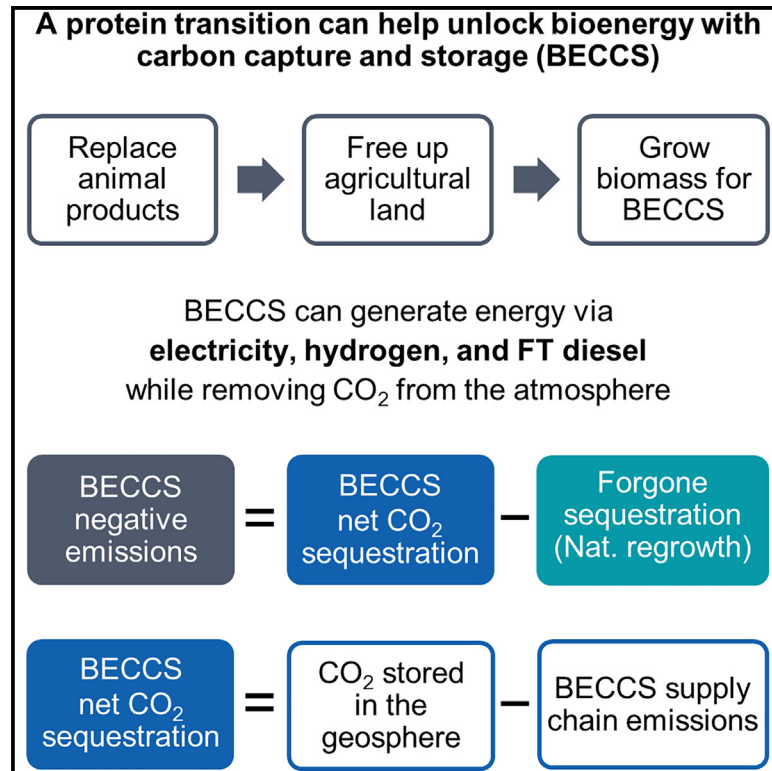
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A protein transition can free up land to tap vast energy and negative emission potentials

Graphical abstract



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In brief

Bioenergy with carbon capture and storage (BECCS) could help stabilize the climate by removing CO₂ from the atmosphere. However, researchers increasingly urge avoiding bioenergy cropland expansion because it may further exacerbate biodiversity loss, food insecurity, and water scarcity. Biomass availability may, therefore, limit BECCS potential. Through a protein transition—replacing animal-source foods—countries can unlock sustainable biomass production by freeing up vast land and water resources. This way, they can tap substantial energy and carbon removal potentials via BECCS.

Highlights

- Replacing animal products can free up vast pasture and cropland areas
- Using freed-up land for biomass production can help unlock a large BECCS potential
- BECCS electricity and H₂ can provide substantial energy and negative emissions
- BECCS FT diesel has a high energy potential but a limited mitigation potential



Article

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

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SCIENCE FOR SOCIETY To limit global warming at 1.5°C, climate mitigation pathways project the need to remove 100–1,000 billion tonnes of carbon dioxide from the atmosphere. Bioenergy with carbon capture and storage (BECCS) has been the most prominent carbon removal method considered. However, massive BECCS deployment would likely require cropland expansion to produce the biomass feedstock needed. Such an expansion may worsen biodiversity due to the loss of natural land and food and water security due to competition for land and water resources.

A transition from consuming animal-source proteins to alternative (e.g., plant-source) proteins could help unlock sustainable biomass production for BECCS. Animal-source foods use resources inefficiently because animals consume more food than they provide, and feeding the animals requires considerable land and water. We show that a protein transition could free up extensive resources for BECCS to achieve substantial energy and carbon removal potentials.

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 the potential of BECCS, 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 5.9–9.3 GtCO₂e/year from the atmosphere, almost what coal power emits today.

INTRODUCTION

Carbon dioxide (CO₂) 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 to 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 greenhouse gas (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 climate mitigation benefit of BECCS.^{6–8}

A protein transition, the shift in consumption from animal to alternative protein (AP) sources, could help reduce agricultural



land use, opening up new opportunities for climate mitigation. By replacing land-intensive agricultural products, it can help unlock the potential of BECCS 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 APs, from sources such as plants, microorganisms, and tissue culture, could replace 10%–30% of animal products by 2030 and 30%–70% by 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, APs could reach parity with animal products in taste, texture, and price,¹⁰ which may make it easier for mainstream consumers to replace animal products. APs that require less land and emit less GHGs 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 the shared socioeconomic pathway (SSP) 1, the SSP with the lowest demand for animal products, is just slightly lower than in SSP2 (with ~20% lower calorie consumption per capita in 2050), the pathway with middle-of-the-road assumptions.²² In addition, 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 complete 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 that 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 CO₂. 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 tradeoffs²³ 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 CO₂ storage capacity, which may constrain BECCS potential in some regions.²⁸ Unlike most BECCS assessments, which focus on the potential for biomass production,²⁸ we present spatially explicit estimates of both biomass production and geological CO₂ storage in highly prospective sites (i.e., sedi-

mentary basins with high prospects of favorable geology for CO₂ storage).

Our findings reveal how a protein transition could provide countries with vast negative emission energy resources: base-load 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 CO₂ in highly prospective storage sites within their borders. Our results represent technical BECCS potentials. Future research could incorporate various technoeconomic and sociopolitical factors that may hinder adoption. Likewise, emerging research on novel APs 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. Because the mix of different types of APs 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*. *Expand* exclusively evaluates bioenergy crops expanding over natural land, excluding areas with the highest conservation value (see the scenarios in the experimental procedures). Despite the exclusions, *Expand* would not represent a sensible solution because it would further harm biodiversity and Earth system processes.^{8,23,29} 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 the experimental procedures). In short, we cap grid cells' daily available water for the 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, then 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 carbon sequestration), we considered initial carbon stocks and carbon accumulation in plants (aboveground and belowground, as in 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 the storage capacity of basins. Their assessment, based on a simple but uniform method at a global scale, considered more conservative storage assumptions than did previously proposed methods^{32–34} (see the experimental procedures for details).

BECCS potential by AP 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 $\text{EJ}_{\text{elec}}/\text{year}$, the scale of coal power today (35 $\text{EJ}_{\text{elec}}/\text{year}$),³⁵ with negative emissions of 5.9–9.3 GtCO_2e (gigatonnes of CO_2 equivalent)/year, almost the current global emissions from coal power (10 $\text{GtCO}_2\text{e}/\text{year}$).³⁶ Alternatively, BECCS could produce 251–376 megatonnes (Mt) of H_2 , approximately half the projected global hydrogen demand in 2050 (500–800 MtH_2),³⁷ with negative emissions of 5.5–8.7 $\text{GtCO}_2\text{e}/\text{year}$ (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 $\text{EJ}_{\text{elec}}/\text{year}$ with negative emissions of 3.5–7.2 $\text{GtCO}_2\text{e}/\text{year}$, or produce 150–277 MtH_2/year (equivalent to 18.0–33.3 EJ/year) with negative emissions of 3.3–6.7 $\text{GtCO}_2\text{e}/\text{year}$. For an AP market share of 70%, BECCS could produce 36.9–46.5 $\text{EJ}_{\text{elec}}/\text{year}$ with negative emissions of 8.2–10.6 $\text{GtCO}_2\text{e}/\text{year}$, or produce 351–442 MtH_2/year (equivalent to 42.1–53.0 EJ/year) with negative emissions of 7.7–9.9 $\text{GtCO}_2\text{e}/\text{year}$ (Figure 1). For country results, see Figures S1–S9. Considering that today's global electricity production E is $\sim 100 \text{ EJ}/\text{year}$,³⁸ a given AP market share could lead to a BECCS electricity potential in 2050 equivalent to $\sim \frac{AP}{2} \cdot E$ (Figure 1C, lower range values for BECCS electricity).

Potentials at full replacement

Entirely replacing animal products with APs (*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), $\sim 3/5$ 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, 1,672 Mha of which are pastures and 275 Mha are feed crops. Over these focus areas, we estimated the carbon storage potential of BECCS relative to natural revegetation's. BECCS to electricity and to hydrogen achieved negative emissions when using biomass grown on 1,143 Mha (Figure 2A) and 1,124 Mha (including $>95\%$ of the evaluated feed crop areas), and BECCS to FT diesel on only 714 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 $\sim 700 \text{ GtCO}_2\text{e}$ (~ 710 producing electricity or ~ 660 hydrogen; Figure 3A) more than natural revegetation, equivalent to over 20 times the global energy-related CO_2 emissions in 2020.

Source-sink potentials

We project sizable cumulative negative emission potentials of 158, 125, and 97 GtCO_2e for the large GHG emitters—the United States, Europe, and China—between 2030 and 2100 for an electricity pathway (Figure S10; Table S1). Most regions could store all of the CO_2 source potential (originally carbon in bioenergy crops) in highly prospective sedimentary basins (sinks) within their territories, including Brazil, the United States, Europe, China, and Russia, which together represent $\sim 50\%$ of the global negative emission potential for electricity and hydrogen routes (Table S1; Figures S16, S17, and S18). We found that 25% 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 Intergovernmental Panel on Climate Change [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 United States, Europe, and China stand out for their considerable sequestration potential with short source-sink distances, having 149, 77, and 81 GtCO_2 of the source carbon within 300 km from its optimal sink (Figures 3F–3H). Figure S16 and Table S1 show source-sink results for other countries.

Replace versus Expand

Considering the 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 $\text{EJ}_{\text{elec}}/\text{year}$ (Figure 4A). However, based on the definition of risk zones by Heck et al.,²³ BECCS global potential in our *Expand* scenario would have uncertain to high risks. Although BECCS potential under *Replace* is $\sim 50\%$ of the energy and negative emissions of *Expand*, it could be much safer and still substantial (Figure 4B). It would entail 53 $\text{EJ}_{\text{elec}}/\text{year}$, equivalent to $\sim 90\%$ of today's global electricity from coal and gas³⁵; and achieve $\sim 12 \text{ GtCO}_2/\text{year}$ of negative emissions, also $\sim 90\%$ of today's global emissions from coal and gas electricity.³⁶ High-income

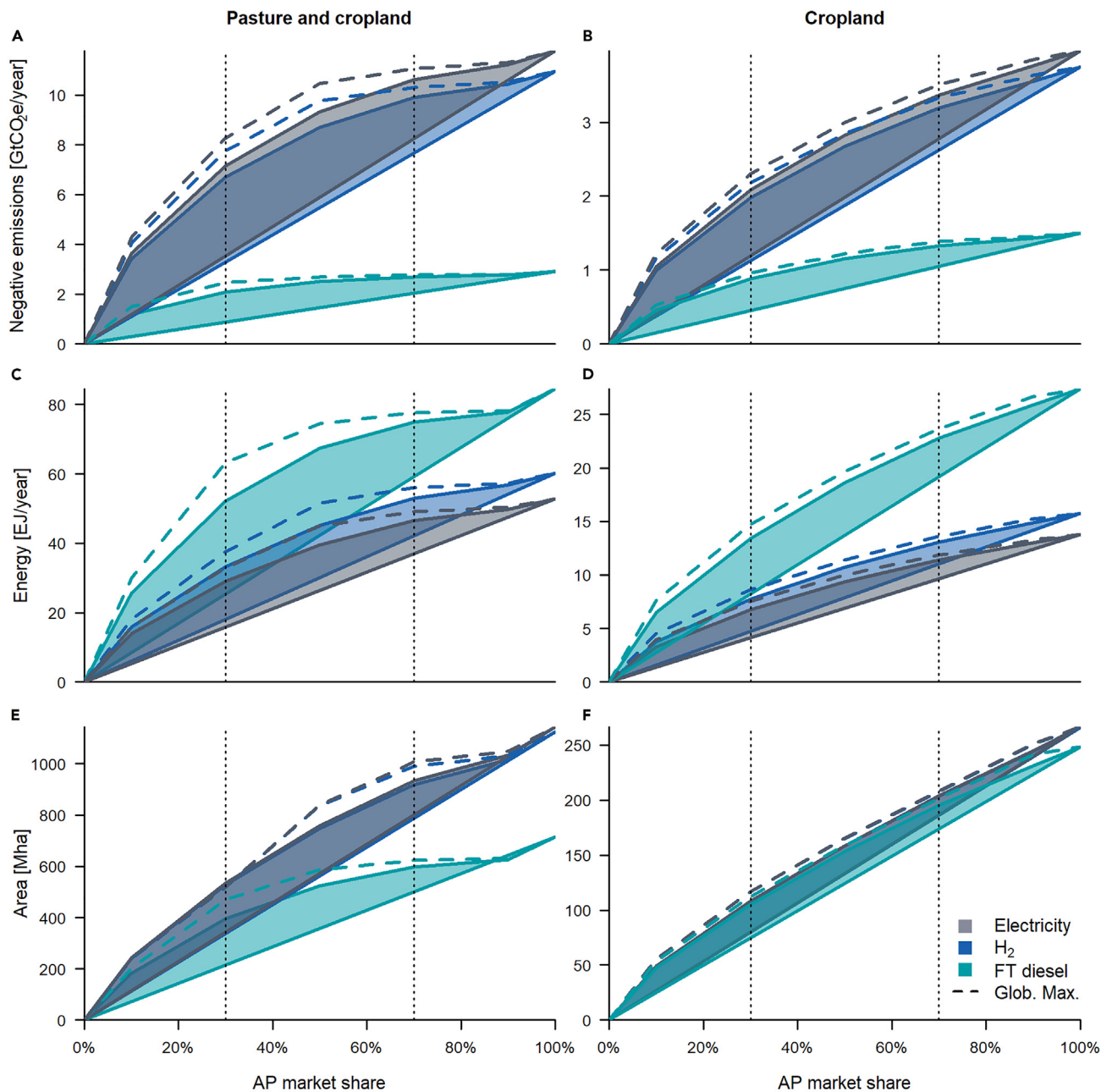


Figure 1. Global potentials under different levels of AP adoption

(A and B) Negative emissions, (C and D) produced energy, and (E and F) area used. Vertical lines illustrate the plausible range of AP adoption, between 30% and 70%. The “leaves” (colored areas between the solid lines) show the potential between 2 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–S9](#).

and upper-middle-income countries, which may be more capable of deploying BECCS,⁴¹ possess ~75% of the negative emission potential ([Figures S11–S13](#)) if countries fully use 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 carbon storage from natural revegetation over the 60-year evaluation period. Overall, biomass production

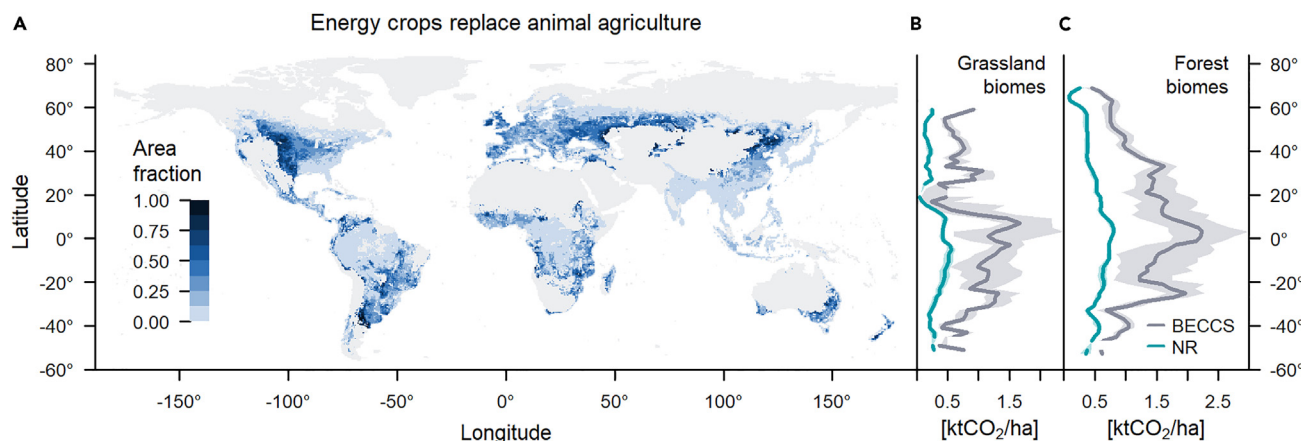


Figure 2. Negative emissions of BECCS replacing animal agriculture

(A) Animal agriculture areas where BECCS electricity could achieve negative emissions.

(B and 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 CO₂ sequestration after subtracting supply chain emissions for electricity production. Shaded areas represent a 95% confidence interval using 4 climate models to estimate bioenergy yields and 7 global maps to estimate natural revegetation stocks. The evaluation period is 2030–2100, with 20 years of ramp-up time (see Figure 5A).

in grassland biomes results in higher negative emissions per unit of energy produced through BECCS than using biomass produced in forests biomes (Figure 4C).

Fully using the biomass potential on all of 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 CO₂ 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.

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 (Figures 5C and 5D). Carbon loss in plants and soils drives initial excess emissions when transitioning from the initial land use to bioenergy crops. Using all of the released feed crop areas for producing BECCS feedstock would lead to cumulative negative emissions of 238 and 225 GtCO₂ for electricity and hydrogen by 2100, with very low (0.19 GtCO₂) initial excess emissions and <2 years to start generating negative emissions. Expanding biomass production over natural areas, in contrast, could lead to massive negative emissions (1,381 and 1,280 GtCO₂ for electricity and hydrogen), but with initial excess emissions (~30 GtCO₂) that compare to today's global fossil CO₂ emissions (35 GtCO₂ 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 ~710 and 660 GtCO₂ for electricity

and hydrogen, respectively. Initial excess emissions could reach ~10 GtCO₂, and it would take almost 10 years to generate negative emissions. However, 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 the peak cumulative excess emissions of BECCS, 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 GtCO₂/GtCO₂) 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, 2, 3, and 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

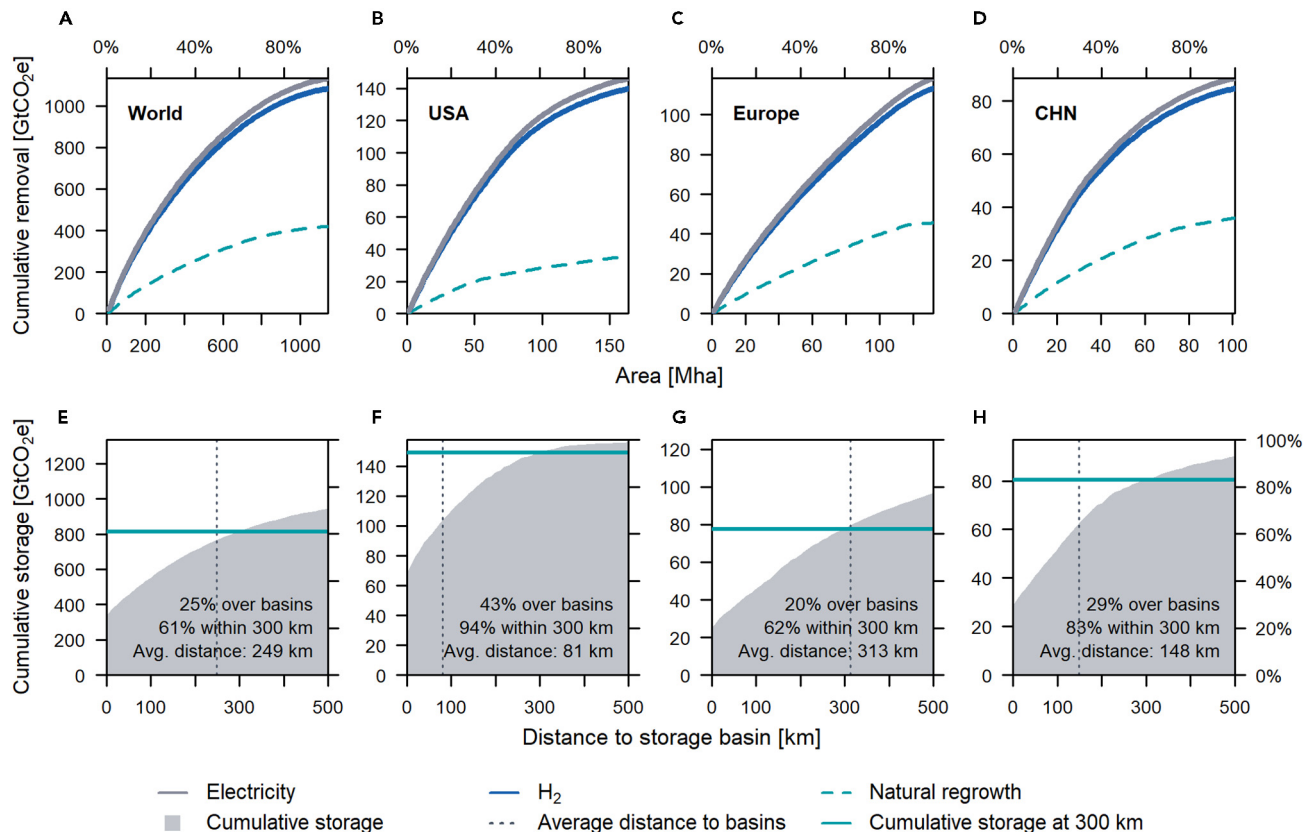


Figure 3. Cumulative removal and storage

(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 CO₂ 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, because it results in higher carbon sequestration than hydrogen and FT diesel production. BECCS potential is the average of 4 climate models, and natural revegetation is the average of estimations based on 7 potential natural vegetation maps. The evaluation period is 2030–2100, with 20 years of ramp-up time (see Figure 5A).

See also Figure S16 and Table S1.

interquartile ranges for overshoot and breakeven time differ by approximately an order of magnitude: overshoot ratios of 0.04–0.13 for cropland versus 0.32–10.6 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 of the cases, we conservatively assumed that initial plant carbon gets burned, releasing emissions to the atmosphere,^{43–45} such that the higher the initial plant carbon, the higher the initial emissions. For bioenergy crops replacing feed cropland, initial plant carbon 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, however, emissions from sizable initial plant stock are much higher, and SOC decreases upon establishing bioenergy crops. For the third case, bioenergy crops replacing pasture and cropland (~75% 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 areas⁴⁸ may result in SOC gains when transitioning to bioenergy crops.

Figures S14–S16 provide an overview of the SOC, plant carbon, and carbon sequestration balances of all of the cases.

DISCUSSION

Harnessing the cobenefits of a protein transition

Replacing animal products can help countries strengthen multiple sectors beyond food. Because animal products have predominantly domestic land-use impacts, countries could aim at freeing up agricultural land by influencing demand. Using available multi-regional input-output data from the year 2010 (see the 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 APs that use less land than animal products, they could tap into the potential of BECCS 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 or decarbonize hard-to-abate sectors with flexible hydrogen^{49,50}; in health, it can improve nutrition by reducing animal product consumption⁵¹; in commerce, it may give countries a competitive edge in the global hydrogen

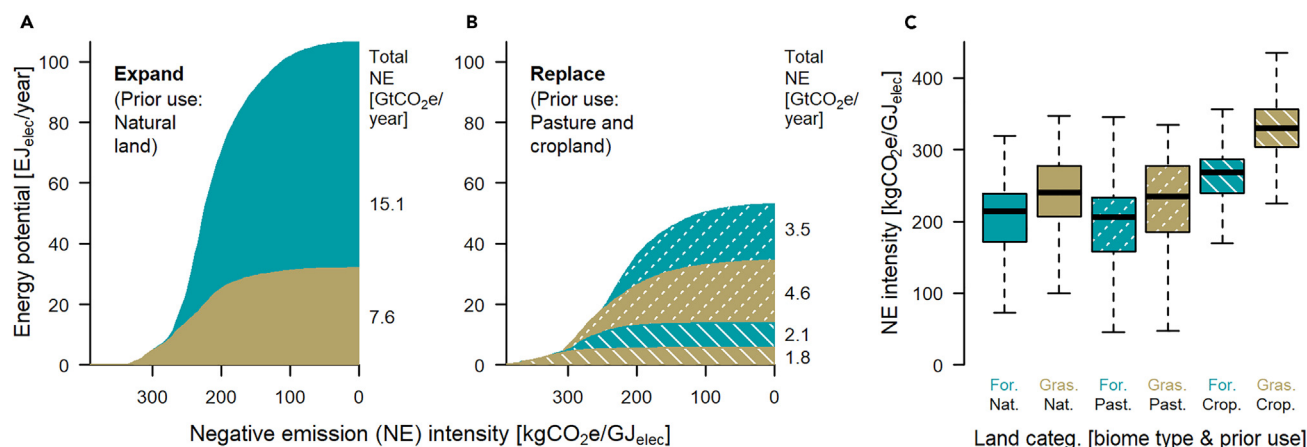


Figure 4. Cumulative energy and negative emission (NE) potential by emission intensity for 2 scenarios

Scenarios include bioenergy crops that (A) *Expand* over natural areas and (B) *Replace* animal agriculture.

(C) The boxplots with the distribution of NE intensity illustrate the 6 land categories—a combination of biome type (Gras., grassland; For., forest) and prior land use (Nat., natural vegetation; Past., pasture; Crop., cropland). The boxplots do not show outliers. NEs 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 (see Figure 5A).

market³⁷; in the environment, it can help remove large amounts of CO₂ 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 APs 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 APs could free up large agricultural areas (Figures 1E and 1F). 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, as Humpeöder et al.⁵³ did with microbial protein replacing beef. In addition, other emerging APs such as cultured meat and mycoprotein could be suitable beef replacements and are estimated to have lower land needs than most meat alternatives.^{17,18} 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 cobenefits 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 phaseout of thermal power from fossil fuels. Directly, BECCS could provide baseload electricity to eliminate the need for new coal power plants^{49,50}; 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 cobenefits such as increased crop yield through biochar additions.⁵⁸ If negative emissions rather than electricity drive BECCS adoption, then 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 APs that we evaluated), then 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 (e.g., increased crop yields) or when replacing current first-generation bioenergy crops such as corn, sorghum, and sugarcane.

Our results show that replacing animal products can help unlock vast energy and negative emission potentials via BECCS

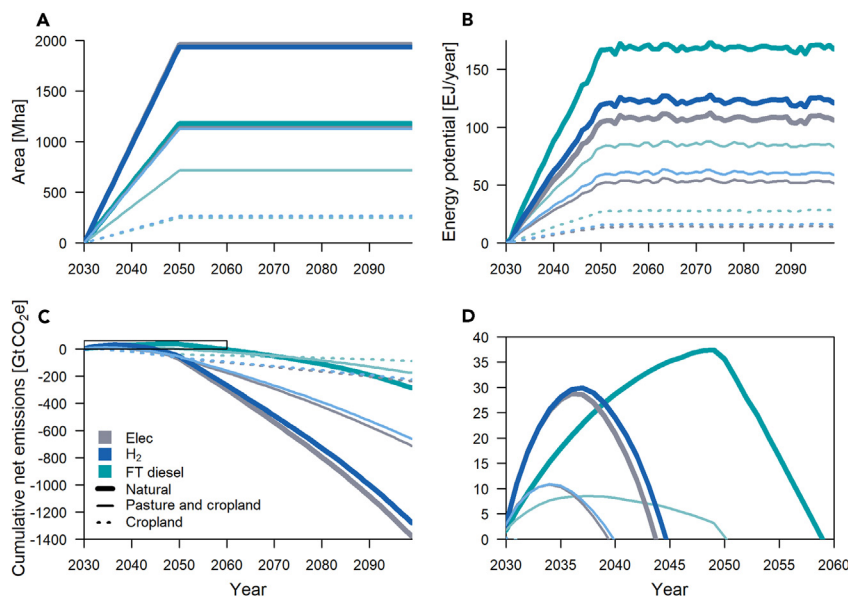


Figure 5. Temporal development of BECCS potentials

(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 of the subplots show BECCS maximum negative emission potential via electricity, hydrogen, and FT diesel production over 3 land categories: natural areas (from *Expand*), all of the 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 (A).

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 (LUC) 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, then 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 CO₂ 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 CO₂. Afterward, natural succession could more slowly store in the biosphere and pedosphere any excess CO₂ (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, such as some rangelands (rangelands were evaluated

within pastures in this study and represent ~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, CO₂ storage, and more. A fundamental uncertainty is timeliness when bioenergy crops replace pastures, mainly due to unknown SOC changes and initial plant carbon 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, then breakeven time and overshoot ratio may resemble more the transition from feed crops to bioenergy crops (Figure 6). In addition, 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 soil⁶⁸; 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 CO₂. 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.

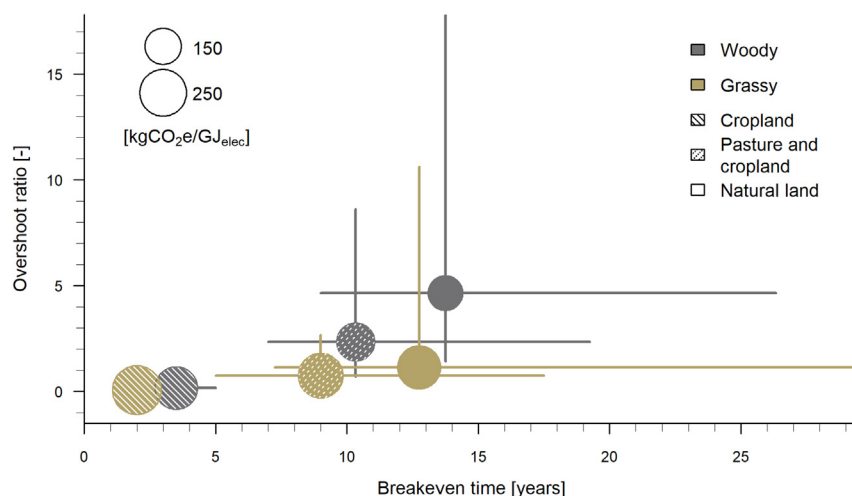


Figure 6. Overshoot ratio and breakeven time for electricity production through BECCS

Woody and grassy bioenergy crops replace 3 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 (see Figure 5A).

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 technoeconomic to sociopolitical, for scaling up CCS technologies and CO₂ 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 CO₂ is especially challenging because realistic storage capacities remain highly uncertain; at this point, further delaying the planning process may also delay CCS deployment, including that of BECCS.⁷³

Future research could provide a more nuanced assessment of emissions, crop yields, and land use requirements that is 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 APs. Our approach for replacing animal products is likely conservative for land use because it is based on conventional alternatives such as pulses, which will likely use more land than emerging alternatives such as 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 dividend²⁰; 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 APs.

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. Such potentials cannot be taken for granted, however. On the one hand, future replacement levels of animal products, the adoption of specific AP 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 of the data shown in the figures and all original code have been deposited at Zenodo under <https://doi.org/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 SSP2, representative concentration pathway 2.6. Concretely, the scenarios use land-use data from the Inter-Sectoral Impact Model Inter-comparison Project (ISIMIP) 2b, created by the integrated assessment model REMIND-MAGPIE.⁷⁶ The land-use data are processed by the dynamic global vegetation model LPJmL, together with climate input from four GCMs: HadGEM2-ES, MIROC5, GFDL-ESM2M, and 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 APs 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,^{8,23,29} 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 75% of the total feed supply (by weight¹⁹); 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 obtain 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.

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 2050¹⁹ and a moderate yield growth of 0.53%/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% by 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 integrated assessment models,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 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 research¹⁹ 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 Food and Agriculture Organization Statistics (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 categories⁷⁷ (year 2019), and the maximum increase of barley was only 4.8%, also in line with Hayek et al.¹⁹ Since the spatial data of maize and barley do 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). In addition, we excluded steep slopes (>30%)⁸³ where agriculture may be unfeasible and areas of high conservation value: protected areas⁸⁴ (International Union for Conservation of Nature protected area categories I–IV), wetlands and water bodies (Global Lakes and Wetlands Database-3),⁸⁵ key biodiversity areas,⁸⁶ Last of the Wild areas,⁸⁷ and locations of rare plant species (above median Margalef rarity index⁸⁸). 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 review⁵; hydrogen production uses biomass gasification and water-gas shift technology⁸⁹; and production of Fischer-Tropsch diesel requires that the feedstock is gasified and the resulting synthesis gas is catalytically converted to hydrocarbons⁹⁰ (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 kgCO₂e) equal BECCS net sequestered carbon (Net_{BE}) minus the difference in carbon stocks at the end of the evaluation period (2100). For all of the 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).

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

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

$$LUC_{i,x} = \Delta CV_{i,x} + \Delta SOC_{i,x} \quad (\text{Equation 3})$$

Net_{BE} is the balance of the total sequestered carbon (Seq_{CCS}), minus fertilizer N₂O emissions (Em_{Fert}) and other supply chain emissions (including CH₄) 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 is harvested); and ΔSOC is natural vegetation SOC minus bioenergy crops SOC (at depths up to 200 centimeters [cm]) in 2100 (the end of the evaluation period). Equations 4, 5, and 6 describe the components of the BECCS emissions balance (Net_{BE}).

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

$$Em_{Fert,i,x} = em_{Fert,i} \times Y_{i,x} \times A_x \quad (\text{Equation 5})$$

$$Em_{SC,ij,x} = em_{SC,ij} \times Y_{i,x} \times A_x \times f_{loss} \times (\eta_{ij} - \pi_{ij}) \quad (\text{Equation 6})$$

Y is the total bioenergy crop yield over the evaluation period (in tonnes of dry matter [tDM] per hectare [ha]), A the area (in hectares), f_{loss} the biomass loss correction factor (dimensionless), η the conversion efficiency from biomass to final carrier (in gigajoules [GJ] per 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 CO₂ to carbon (44/12), and κ the carbon capture efficiency of CCS (tCO₂ captured per tCO₂ emitted) during the production of the energy carrier. em_{CCS} are the additional supply chain emissions from CCS per energy produced (in kgCO₂/GJ), em_{Fert} the fertilizer emissions per biomass produced (in kgCO₂e/tDM), and em_{SC} other supply chain emissions per energy produced (in kgCO₂e/GJ). Finally, Equation 7 shows the calculation of total energy (E , in GJ).

$$E_{ij,x} = Y_{i,x} \times A_x \times f_{loss} \times (\eta_{ij} - \pi_{ij}) \quad (\text{Equation 7})$$

Table S2 presents the data used for most of the 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 LPJmL²³ 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 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, and IPSL-CM5A-LR) that we used to define our two land scenarios, *Replace* and *Expand*. For both scenarios, we prioritize securing water supply for HIL 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 EFR scheme of 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 the daily available water for irrigation of grid cells through the EFR scheme, which aimed to preserve 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, respectively. EFRs are 30-year averages, based on historical land use⁹⁶ and climate for the period 1970–1999. We prioritize securing water for HIL. If EFRs are transgressed in a river basin since the first step, then 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 of the crops, then irrigation water is distributed among all of the crops (energy and nonenergy crops) according to the respective crop cultivation area. As Stenzel et al.³⁰ reported, global yields could decrease by ~3.5% under our EFR scheme. Yield drops could be compensated for 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.^{25,93,97,98} 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, parametrized 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 8 years, with replantation after a maximum of 40 years. Bioenergy crop yields have been compared against field data by Beringer et al.²⁵ and Heck et al.⁹⁷ Although new data^{71,99} on bioenergy crops are 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 of the cases, we excluded areas with low yields (yearly yields <1.25 tDM/ha).

Natural regrowth and LUC emissions

To understand the BECCS-added climate mitigation value, we estimated 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 vegetation⁹² and soil.¹⁰¹

Equations 8 and 9 (based on the work of Cook-Patton et al.⁹¹) describe plant carbon accumulation in the nine biomes we considered. Table S3 specifies which formula is used for each biome.

$$f(\text{age})_{b,l,x} = (a_b + c_{b,l,x} \times ar_b) \times \text{age}_x + (b_b + c_{b,l,x} \times br_b) \quad (\text{Equation 8})$$

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

where $f(\text{age})$ 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 the available data on initial carbon stocks (P_{t_0}).

$$P_{t,b,l,x} = P_{t_0} + [f(\text{age}_t)_{b,l,x} - f(\text{age}_{t_0})_{b,l,x}] \quad (\text{Equation 10})$$

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 forgone 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. For pastureland, which also becomes natural, we assumed that the whole belowground and 50% of the aboveground biomass would remain after abandonment. For both pasture and cropland, we assumed a moderate growth (0.53%/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. Whereas 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 because 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 (Ramankutty et al.¹⁰³ for pasture; Winkler et al.¹⁰⁴ for cropland and natural land) with the spatial data of current stocks and natural regrowth. 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 CO₂ 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 (Figures 2B and 2C), 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 (Figures 2B and 2C).

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 SOC.^{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, SOC₀ 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 NoLU as SOC₀ 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).

$$SOC_{0,d,j,x} = SOC_{NoLU,d,x} \times (1 - L_{T,d,j}) \quad (\text{Equation 11})$$

$$f(t)_{d,j,x} = \begin{cases} SOC_{0,d,j,x} \times \left(1 - \frac{t}{t_{loss}} \times L_{T,d,j,j}\right), & t < t_{loss} \\ SOC_{0,d,j,x} \times (1 - L_{T,d,j,j}), & t \geq t_{loss} \end{cases} \quad (\text{Equation 12})$$

$$f(t)_{b,d,j,x} = SOC_{0,d,j,x} + t \times acc_{b,d} \quad (\text{Equation 13})$$

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 an 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 AP adoption level

In *Replace*, we evaluated BECCS total energy and negative emission potentials by replacing all of the 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 because 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 the total animal agriculture area of each cell. 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).

$$\max \sum_{x_a=1}^{m_a} c_{a,x_a} z_{a,x_a} \quad (\text{Equation 14.1})$$

$$\begin{aligned} \text{s.t.} \quad & - \sum_{x_a=1}^{m_a} p_{a,x_a} z_{a,x_a} \geq (1 - AP) \times P_{Tot,a} - \sum_{y_a=1}^{n_a} p_{a,y_a} \\ & - \sum_{x_a=1}^{m_a} p_{a,x_a} z_{a,x_a} \text{ binary} \end{aligned} \quad (\text{Equation 14.2})$$

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 tCO₂e) over cells with location x , where the binary decision variable z results in 1. 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 tonnes) is the production of the animal agriculture product a in a cell, AP (fraction) the market share of APs (i.e., the animal products displaced), and P_{Tot} (in tonnes) 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 disproportionately 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 originate 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 of the 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 the estimated area and energy of every cell by the resulting z values from the optimizations. For all of the 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 (MRIO) analysis

To measure the control of countries over the fate of their animal agriculture land, we estimated the fraction domestic/total land impacts from the countries' consumption of animal products. We traced land-use impacts through an MRIO analysis using EXIOBASE.¹⁰⁸ EXIOBASE data link final consumption to environmental impacts, considering trade. It provided us data on the regional land-use impacts (pasture and cropland) resulting from the final consumption of all animal product categories of the nations. The data were 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 CO₂ storage and source-sink match

Among different alternatives for CO₂ 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 CO₂ storage in basins remains uncertain.⁷³ Even ambitious initiatives to evaluate storage capacity in regions such as the United States, 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 CO₂ storage because it correlates with the prospectivity of hydrocarbon potential.^{73,112}

Given the high uncertainty on the amount of CO₂ that each site can store, we implemented a simple but uniform quantification method at a global level¹¹¹; and to leverage the correlation between the prospectivities of hydrocarbons and CO₂, we painstakingly matched global maps of sedimentary basins¹¹³ and highly prospective hydrocarbon provinces.¹¹² We used the method proposed by Kearns et al.¹¹¹ to estimate storage capacity. Kearns et al. follow an approach similar to that of others to estimate approximate storage capacities with limited data. The International Energy Agency¹¹⁴ and a recent study¹⁰⁹ 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 the International Energy Agency¹¹⁴ and Wei et al.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 the formation volume, which was estimated to explain 83%–89% of the variation in the storage capacity estimates. Therefore, we followed the method of Kearns et al., assuming that sedimentary formation volume is proportional to storage capacity. We took the lowest proposed coefficient, 0.037 GtCO₂/1,000 km³,¹¹¹ to account for likely limiting injection rates. Our selected coefficient leads to capacity estimates ~7 and 14 times lower than volumetric estimates from the US Geological Survey and the US Department of Energy.^{111,116,117} Despite the uncertainty, the order of the estimates seems reasonable because past research indicated that dynamic estimates may be a factor of 10 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 the work of the GEBCO Compilation Group¹¹⁹), as Kearns et al. proposed. Moreover, we considered only highly prospective basins; as a result, our global layout of CO₂ storage sites is in agreement with past research.^{112,120} We defined highly prospective basins based on Robertson CGG¹¹³ and Bradshaw and Dance,¹¹² excluding impractical offshore areas, and integrating sedimentary thickness data¹¹⁵ to estimate the volume.

Unlike crops and storage sites, power plants could have a more flexible but uncertain location. Hence, to measure the regions' source-sink match potential, we present an optimization model that minimizes the transport distance between bioenergy crops (source) and highly prospective storage sites (sinks). Specifically, we optimally allocated sequestered 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 entire world.

$$\min \sum_i \sum_j d_{ij} x_{ij} \quad (\text{Equation 15.1})$$

$$\text{s.t. } \sum_i x_{ij} = s_i \quad \text{for all } i \quad (\text{Equation 15.2})$$

$$\sum_j x_{ij} \leq c_j \quad \text{for all } j \quad (\text{Equation 15.3})$$

$$x_{ij} \geq 0 \quad \text{for all } i, j \quad (\text{Equation 15.4})$$

In the minimization model (Equations 15.1–15.4), *d* represents the minimum distance (in kilometers) between bioenergy crop location *i* and sedimentary basin *j*. *x* is the CO₂ flow (in MtCO₂), *s* the source of the sequestered CO₂ 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 CO₂ 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 CO₂ storage with other sources (e.g., industry, fossil fuel energy). Therefore, if BECCS potential is fully used, then transport distances would increase. On the contrary, if CCS potential is not fully used and there is low storage competition, then source-sink distances may decrease, especially if bioenergy crop locations closer to basins are prioritized.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.oneear.2023.12.016>.

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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.M., A.T., and F.S.; visualization, O.R.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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