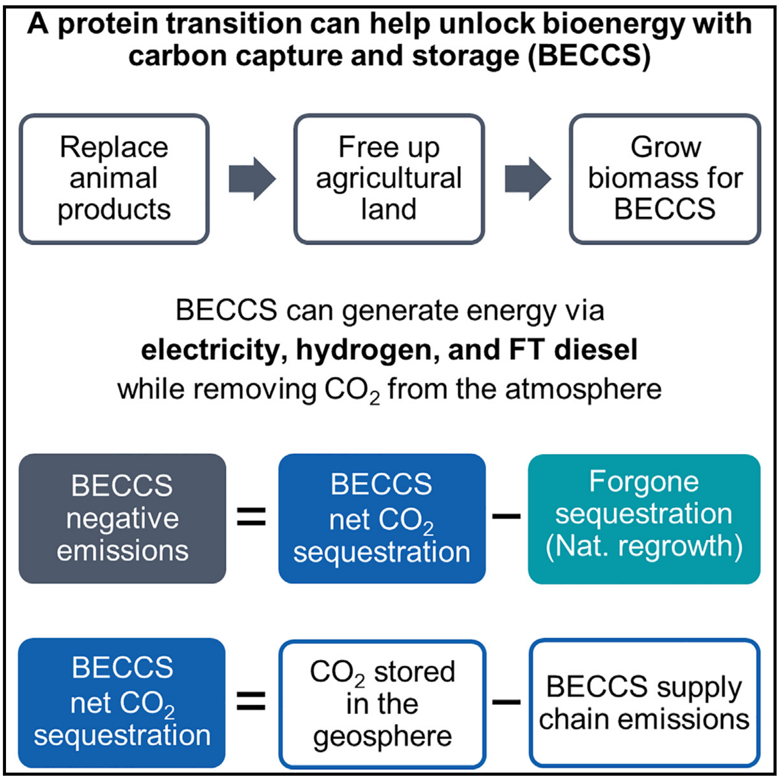
One Earth

Article

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

Graphical abstract



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 H_2 can provide substantial energy and negative emissions
- BECCS FT diesel has a high energy potential but a limited mitigation potential

Authors

Oscar Rueda, José M. Mogollón, Fabian Stenzel, Arnold Tukker, Laura Scherer

Correspondence

o.rueda@cml.leidenuniv.nl

In brief

Bioenergy with carbon capture and storage (BECCS) could help stabilize the climate by removing CO_2 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.

Rueda et al., 2024, One Earth 7, 1–18
February 16, 2024
https://doi.org/10.1016/j.oneear.2023.12.016

CellPress

Please cite this article in press as: Rueda et al., A protein transition can free up land to tap vast energy and negative emission potentials, One Earth (2023), https://doi.org/10.1016/j.oneear.2023.12.016

One Earth

CellPress

Article

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

Oscar Rueda,[1,4,*] José M. Mogollón,[1] Fabian Stenzel,[2] Arnold Tukker,[1,3] and Laura Scherer[1]
[1]Institute of Environmental Sciences (CML), Leiden University, 2333 CC Leiden, the Netherlands
[2]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, P.O. Box 60 12 03, 14412 Potsdam, Germany
[3]Netherlands Organisation for Applied Scientific Research (TNO), 2595 DA The Hague, the Netherlands
[4]Lead contact
*Correspondence: o.rueda@cml.leidenuniv.nl
https://doi.org/10.1016/j.oneear.2023.12.016

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 $GtCO_2e$/year from the atmosphere, almost what coal power emits today.

INTRODUCTION

Carbon dioxide (CO_2) 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 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, which focus 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 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 EJ_{elec}/year, the scale of coal power today (35 EJ_{elec}/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 $GtCO_2e$/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 $GtCO_2e$/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 8.2–10.6 $GtCO_2e$/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– S9. Considering that today's global electricity production E is ~100 EJ/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), ~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 ~700 $GtCO_2e$ (~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 ~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 EJ_{elec}/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 ~50% of 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 ~90% of today's global electricity from coal and gas[35]; and achieve ~12 $GtCO_2$/year of negative emissions, also ~90% of today's global emissions from coal and gas electricity.[36] High-income

Please cite this article in press as: Rueda et al., A protein transition can free up land to tap vast energy and negative emission potentials, One Earth (2023), https://doi.org/10.1016/j.oneear.2023.12.016

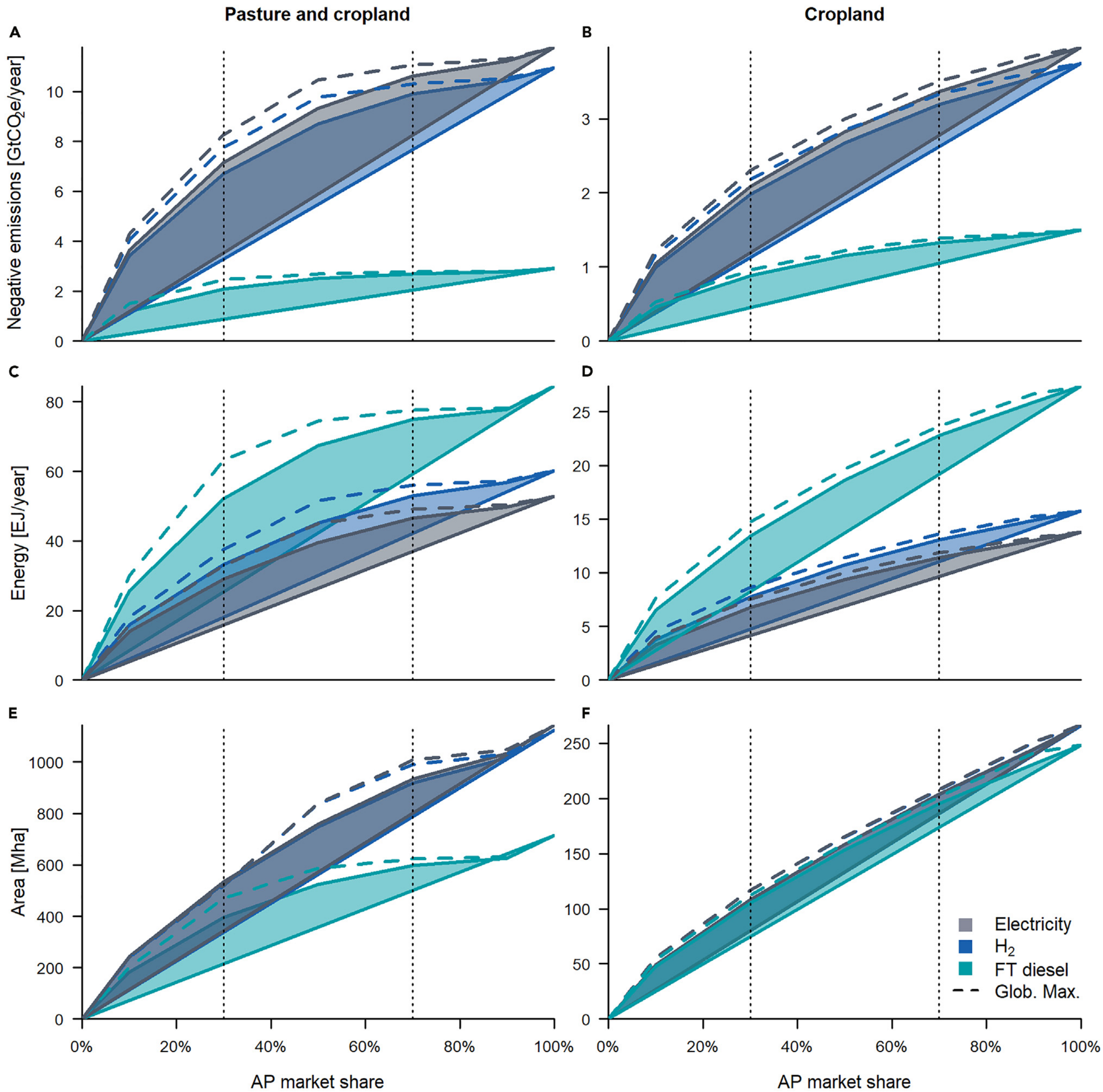


Figure 1. Global potentials under different levels of AP adoption

(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 "leafs" (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

One Earth
Article

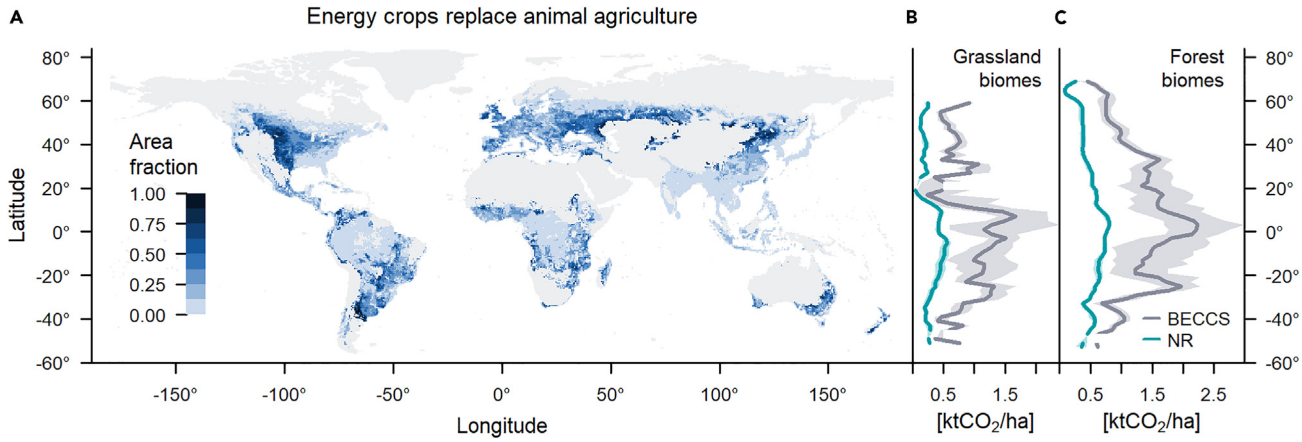


Figure 2. Negative emissions of BECCS replacing animal agriculture

(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 CO_2 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 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.

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 $GtCO_2$ for electricity and hydrogen by 2100, with very low (0.19 $GtCO_2$) 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 $GtCO_2$ for electricity and hydrogen), but with initial excess emissions (~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 ~710 and 660 $GtCO_2$ for electricity and hydrogen, respectively. Initial excess emissions could reach ~10 $GtCO_2$, 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 $GtCO_2/GtCO_2$) 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, 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

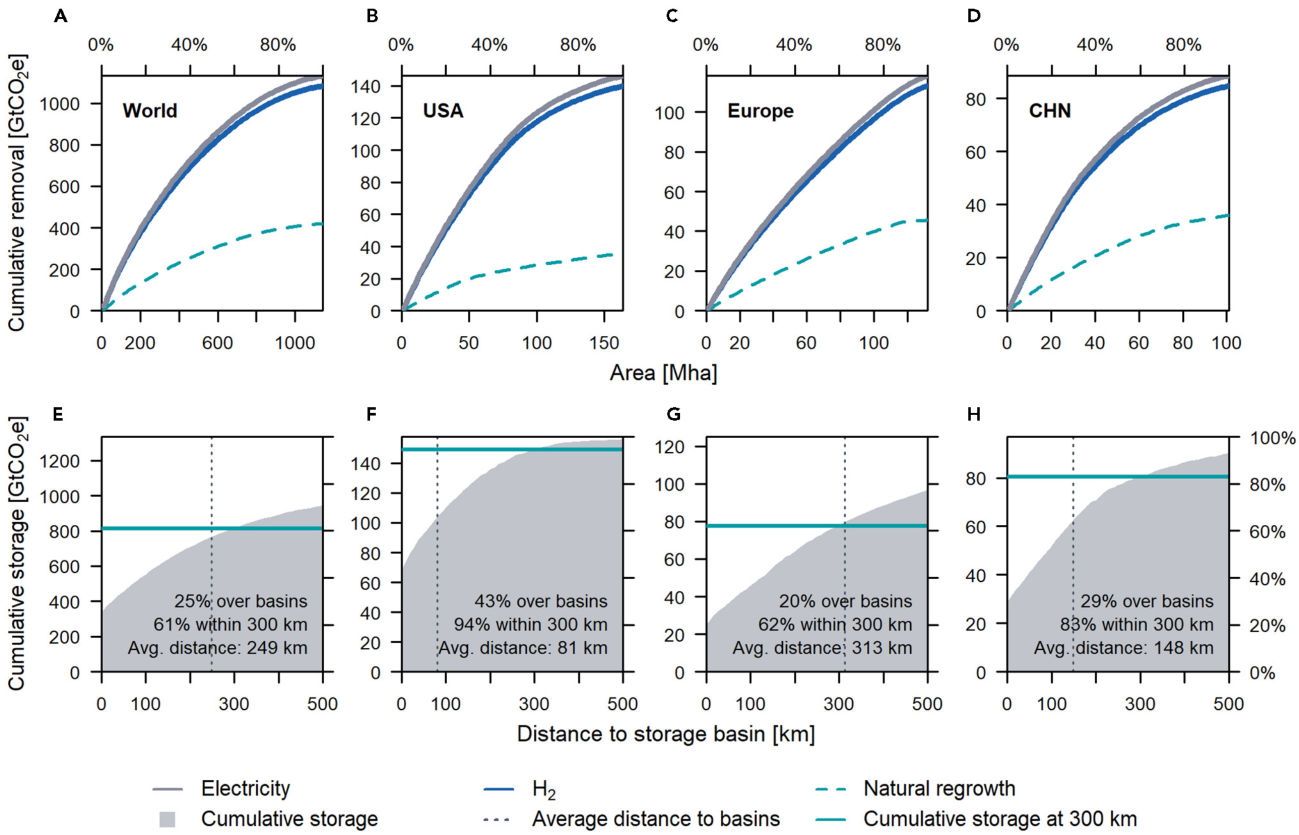


Figure 3. Cumulative removal and storage

(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 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, 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 areas[48] 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 consumption[51]; in commerce, it may give countries a competitive edge in the global hydrogen

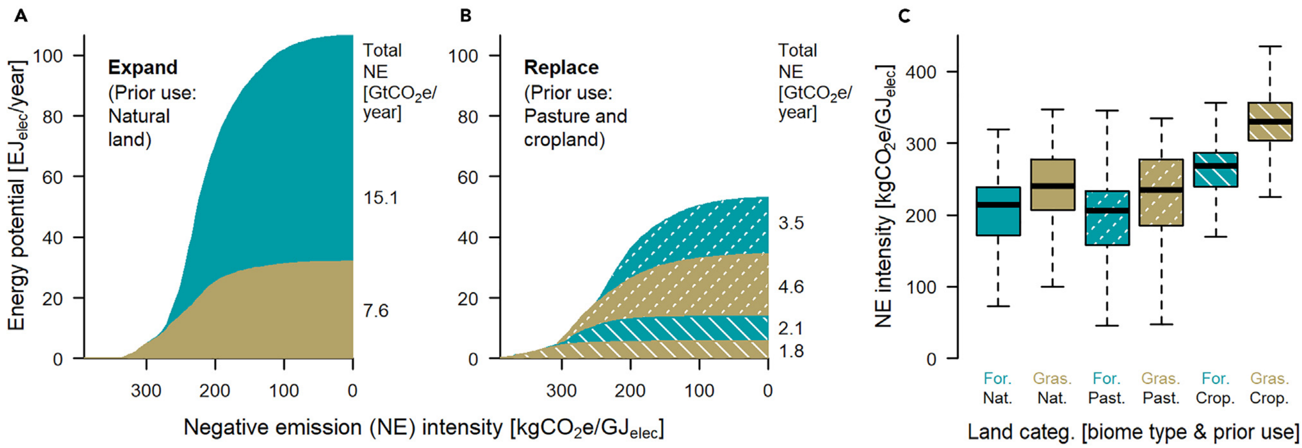


Figure 4. Cumulative energy and negative emission (NE) potential by emission intensity for 2 scenarios

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).

market[37]; in the 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 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 Humpenöder 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

Please cite this article in press as: Rueda et al., A protein transition can free up land to tap vast energy and negative emission potentials, One Earth (2023), https://doi.org/10.1016/j.oneear.2023.12.016

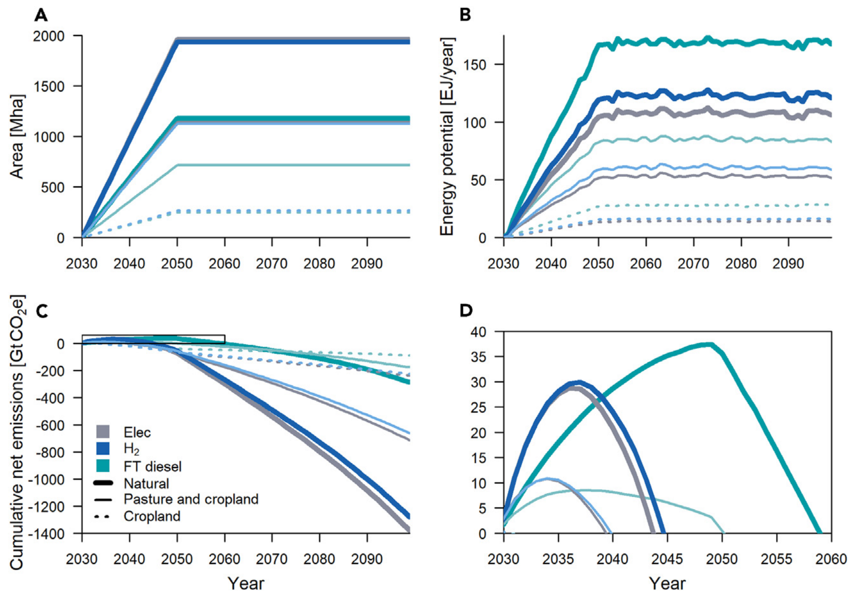


Figure 5. Temporal development of BECCS potentials

(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 CO_2 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, 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, CO_2 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 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.

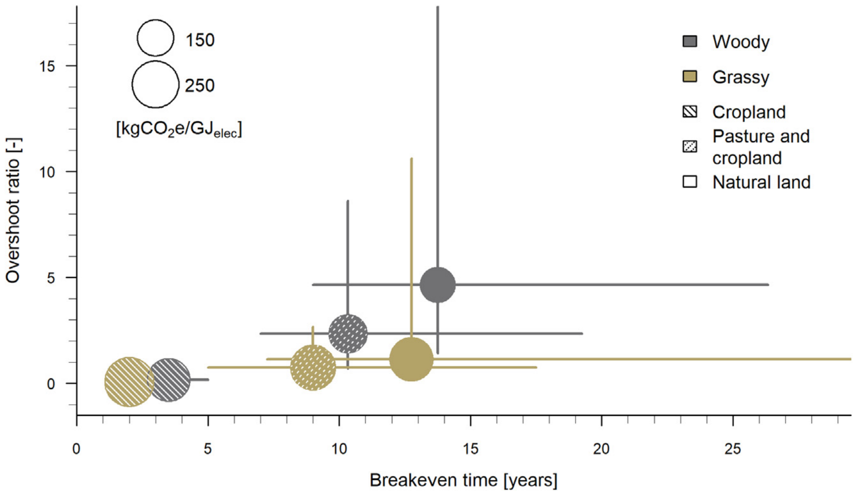


Figure 6. Overshoot ratio and breakeven time for electricity production through BECCS

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 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 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 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 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 Intercomparison 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 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 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 2050[19] 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 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 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 categories[77] (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 areas[84] (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 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 is 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 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).

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

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

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

Net_{BE} is the balance of the total 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 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}).

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

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

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

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 CO_2 to carbon (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 per energy produced (in $kgCO_2$/GJ), em_{Fert} the fertilizer emissions per biomass produced (in $kgCO_2e$/tDM), and em_{SC} other supply chain emissions per energy produced (in $kgCO_2e$/GJ). Finally, Equation 7 shows the calculation of total energy (E, in GJ).

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

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 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] 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 use[96] 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 vegetation[92] 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.

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

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

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 the available data on initial carbon stocks (P_{t_0}).

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

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 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 (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, 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 NoLU 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).

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

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

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

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).

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

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

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 tCO_2e) 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 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 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 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 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 CO_2 storage because it correlates with the 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 an approach similar to that of others to estimate approximate storage capacities with limited data. The International Energy Agency[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 the International Energy Agency[114] 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 $GtCO_2/1{,}000\ km^3$,[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 Group[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 Robertson CGG[113] and Bradshaw and Dance,[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 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 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 entire world.

$$\min \sum_i \sum_j d_{i,j} x_{i,j} \quad \text{(Equation 15.1)}$$

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

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

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

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 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, 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.

ACKNOWLEDGMENTS

We thank Susan Cook-Patton and Matthew N. Hayek for the data and clarifications provided. We are also grateful for the reviewers' time in providing detailed feedback and suggestions to improve the study.

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.

Received: August 12, 2022
Revised: September 26, 2023
Accepted: December 19, 2023
Published: February 7, 2024

REFERENCES

1. Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., and Kriegler, E. (2018). Mitigation pathways compatible with 1.5 C in the context of sustainable development Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. In the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, and R. Pidcock, et al., eds., pp. 93–174.
2. Riahi, K., Bertram, C., Huppmann, D., Rogelj, J., Bosetti, V., Cabardos, A.-M., Deppermann, A., Drouet, L., Frank, S., Fricko, O., et al. (2021). Cost and attainability of meeting stringent climate targets without overshoot. Nat. Clim. Chang. *11*, 1063–1069.
3. Obersteiner, M., Bednar, J., Wagner, F., Gasser, T., Ciais, P., Forsell, N., Frank, S., Havlik, P., Valin, H., Janssens, I.A., et al. (2018). How to spend a dwindling greenhouse gas budget. Nat. Clim. Chang. *8*, 7–10.
4. Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environ. Change *42*, 153–168.
5. Hanssen, S.V., Daioglou, V., Steinmann, Z.J.N., Doelman, J.C., van Vuuren, D.P., and Huijbregts, M.A.J. (2020). The climate change mitigation potential of bioenergy with carbon capture and storage. Nat. Clim. Chang. *10*, 1023–1029.
6. Fajardy, M., Köberle, A., Mac Dowell, N., and Fantuzzi, A. (2019). BECCS Deployment: A Reality Check (Grantham Institute briefing). paper 28 (Imperial College London).
7. Stenzel, F., Greve, P., Lucht, W., Tramberend, S., Wada, Y., and Gerten, D. (2021). Irrigation of biomass plantations may globally increase water stress more than climate change. Nat. Commun. *12*, 1512.
8. Creutzig, F., Erb, K.-H., Haberl, H., Hof, C., Hunsberger, C., and Roe, S. (2021). Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments. GCB Bioenergy *13*, 510–515.
9. Haberl, H., Erb, K.-H., Krausmann, F., Bondeau, A., Lauk, C., Müller, C., Plutzar, C., and Steinberger, J.K. (2011). Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. Biomass & bioenergy *35*, 4753–4769.
10. Morach, B., Witte, B., Walker, D., von Koeller, E., Grosse-Holz, F., Rogg, J., Brigl, M., Dehnert, N., Obloj, P., Koktenturk, S., and Schulze, U. (2021). Food for Thought: The Protein Transformation. Ind. Biotechnol. *17*, 125–133.
11. Klerk, E. (2021). The Global Food System: Identifying Sustainable Solutions.
12. Dongoski, R. (2021). Protein Reimagined: Challenges and Opportunities in the Alternative Meat Industry.
13. Gerhardt, C., Warschun, M., Donnan, D., and Ziemßen, F. (2019). When consumers go vegan, how much meat will be left on the table for agribusiness?.
14. Hansen, J., Sparleanu, C., Liang, Y., Büchi, J., Bansal, S., Caro, M.Á., and Staedtler, F. (2021). Exploring cultural concepts of meat and future predictions on the timeline of cultured meat. Future Foods *4*, 100041.

15. Pointke, M., Ohlau, M., Risius, A., and Pawelzik, E. (2022). Plant-Based Only: Investigating Consumers' Sensory Perception, Motivation, and Knowledge of Different Plant-Based Alternative Products on the Market. Foods *11*.

16. Poore, J., and Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science (New York, N.Y.) *360*, 987–992.

17. Smetana, S., Mathys, A., Knoch, A., and Heinz, V. (2015). Meat alternatives: life cycle assessment of most known meat substitutes. Int. J. Life Cycle Assess. *20*, 1254–1267.

18. Parodi, A., Leip, A., De Boer, I.J.M., Slegers, P.M., Ziegler, F., Temme, E.H.M., Herrero, M., Tuomisto, H., Valin, H., van Middelaar, C.E., et al. (2018). The potential of future foods for sustainable and healthy diets. Nat. Sustain. *1*, 782–789.

19. Hayek, M.N., Harwatt, H., Ripple, W.J., and Mueller, N.D. (2020). The carbon opportunity cost of animal-sourced food production on land. Nat. Sustain. *4*, 21–24.

20. Sun, Z., Scherer, L., Tukker, A., Spawn-Lee, S.A., Bruckner, M., Gibbs, H.K., and Behrens, P. (2022). Dietary change in high-income nations alone can lead to substantial double climate dividend. Nat. Food *3*, 29–37.

21. Clark, M.A., Domingo, N.G.G., Colgan, K., Thakrar, S.K., Tilman, D., Lynch, J., Azevedo, I.L., and Hill, J.D. (2020). Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science (New York, N.Y.) *370*, 705–708.

22. van Vuuren, D.P., Stehfest, E., Gernaat, D.E., Doelman, J.C., van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y., et al. (2017). Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environ. Change *42*, 237–250.

23. Heck, V., Gerten, D., Lucht, W., and Popp, A. (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. Nat. Clim. Chang. *8*, 151–155.

24. Smith, P., Haberl, H., Popp, A., Erb, K.-H., Lauk, C., Harper, R., Tubiello, F.N., de Siqueira Pinto, A., Jafari, M., Sohi, S., et al. (2013). How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Glob. Chang. Biol. *19*, 2285–2302.

25. Beringer, T., Lucht, W., and Schaphoff, S. (2011). Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. GCB Bioenergy *3*, 299–312.

26. Bonsch, M., Humpenöder, F., Popp, A., Bodirsky, B., Dietrich, J.P., Rolinski, S., Biewald, A., Lotze-Campen, H., Weindl, I., Gerten, D., and Stevanovic, M. (2016). Trade-offs between land and water requirements for large-scale bioenergy production. GCB Bioenergy *8*, 11–24.

27. Ai, Z., Hanasaki, N., Heck, V., Hasegawa, T., and Fujimori, S. (2021). Global bioenergy with carbon capture and storage potential is largely constrained by sustainable irrigation. Nat. Sustain. *4*, 884–891.

28. Baik, E., Sanchez, D.L., Turner, P.A., Field, C.B., Benson, S.M., and Mach, K.J. (2018). Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States. Proc. Natl. Acad. Sci. USA *115*, 3290–3295.

29. Rockström, J., Edenhofer, O., Gaertner, J., and DeClerck, F. (2020). Planet-proofing the global food system. Nat. Food *1*, 3–5.

30. Stenzel, F., Gerten, D., Werner, C., and Jägermeyr, J. (2019). Freshwater requirements of large-scale bioenergy plantations for limiting global warming to 1.5 °C. Environ. Res. Lett. *14*, 84001.

31. Fajardy, M., and Mac Dowell, N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? Energy Environ. Sci. *10*, 1389–1426.

32. U.S. Geological Survey (2013). Geologic Carbon Dioxide Storage Resources Assessment Team. National Assessment of Geologic Carbon Dioxide Storage Resources: Results, *1386* (Reston, VA: U.S. Geological Survey Circular).

33. Australia. Department of Resources (2009). Energy and Tourism. Carbon Storage Taskforce. National Carbon Mapping and Infrastructure Plan : Australia : Concise Report/Carbon Storage Taskforce (Canberra: Department of Resources, Energy and Tourism). Carbon Storage Taskforce).

34. Rütters, H.; CGS Europe partners (2013). State of Play on CO2 Geological Storage in 28 European Countries.

35. IEA (2002). Electricity Generation by Fuel, p. 2022. https://www.iea.org/data-and-statistics/charts/electricity-generation-by-fuel-2002-2022.

36. IEA (2000). CO2 Emissions from Electricity and Heat Production by Fuel, and Share by Fuel, p. 2021. https://www.iea.org/data-and-statistics/charts/co2-emissions-from-electricity-and-heat-production-by-fuel-and-share-by-fuel-2000-2021.

37. IRENA (2022). Geopolitics of the Energy Transformation: The Hydrogen Factor. (Abu Dhabi).

38. Ember (4 September 2023). Annual electricity data, https://ember-climate.org/data-catalogue/yearly-electricity-data/.

39. Metz, B., Davidson, O., Coninck, H.C. de, Loos, M., and Meyer, L. (2005). IPCC Special Report on Carbon Dioxide Capture and Storage (Cambridge: Cambridge University Press).

40. Hepburn, C., Adlen, E., Beddington, J., Carter, E.A., Fuss, S., Mac Dowell, N., Minx, J.C., Smith, P., and Williams, C.K. (2019). The technological and economic prospects for CO2 utilization and removal. Nature *575*, 87–97.

41. Fridahl, M., and Lehtveer, M. (2018). Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers. Energy Res. Soc. Sci. *42*, 155–165.

42. Friedlingstein, P., Jones, M.W., O'Sullivan, M., Andrew, R.M., Bakker, D.C.E., Hauck, J., Le Quéré, C., Peters, G.P., Peters, W., Pongratz, J., et al. (2021). Global Carbon Budget 2021. Earth Syst. Sci. Data Discuss. 1–191.

43. Elshout, P.M.F., van Zelm, R., Balkovic, J., Obersteiner, M., Schmid, E., Skalsky, R., van der Velde, M., and Huijbregts, M.A.J. (2015). Greenhouse-gas payback times for crop-based biofuels. Nat. Clim. Chang. *5*, 604–610.

44. Creutzig, F., Ravindranath, N.H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucchi, M., Faaij, A., et al. (2015). Bioenergy and climate change mitigation: an assessment. GCB Bioenergy *7*, 916–944.

45. Daioglou, V., Doelman, J.C., Stehfest, E., Müller, C., Wicke, B., Faaij, A., and van Vuuren, D.P. (2017). Greenhouse gas emission curves for advanced biofuel supply chains. Nat. Clim. Chang. *7*, 920–924.

46. Guo, L.B., and Gifford, R.M. (2002). Soil carbon stocks and land use change: a meta analysis. Global Change Biol. *8*, 345–360.

47. Harris, Z.M., Spake, R., and Taylor, G. (2015). Land use change to bioenergy: A meta-analysis of soil carbon and GHG emissions. Biomass & bioenergy *82*, 27–39.

48. Whitehead, D. (2020). Management of Grazed Landscapes to Increase Soil Carbon Stocks in Temperate, Dryland Grasslands. Front. Sustain. Food Syst. *4*.

49. Sanchez, D.L., Nelson, J.H., Johnston, J., Mileva, A., and Kammen, D.M. (2015). Biomass enables the transition to a carbon-negative power system across western North America. Nat. Clim. Chang. *5*, 230–234.

50. Mac Dowell, N., and Fajardy, M. (2017). Inefficient power generation as an optimal route to negative emissions via BECCS? Environ. Res. Lett. *12*, 045004.

51. Scherer, L., Behrens, P., and Tukker, A. (2019). Opportunity for a Dietary Win-Win-Win in Nutrition, Environment, and Animal Welfare. One Earth *1*, 349–360.

52. Donnison, C., Holland, R.A., Harris, Z.M., Eigenbrod, F., and Taylor, G. (2021). Land-use change from food to energy: meta-analysis unravels effects of bioenergy on biodiversity and cultural ecosystem services. Environ. Res. Lett. *16*, 113005.

53. Humpenöder, F., Bodirsky, B.L., Weindl, I., Lotze-Campen, H., Linder, T., and Popp, A. (2022). Projected environmental benefits of replacing beef with microbial protein. Nature *605*, 90–96.

54. Kalt, G., Mayer, A., Theurl, M.C., Lauk, C., Erb, K.-H., and Haberl, H. (2019). Natural climate solutions versus bioenergy: Can carbon benefits of natural succession compete with bioenergy from short rotation coppice? GCB Bioenergy *11*, 1283–1297.

55. Rueda, O., Mogollón, J., Tukker, A., and Scherer, L. (2021). Negative-emissions technology portfolios to meet the 1.5 °C target. Global Environ. Change *67*, 102238.

56. Scott, V., Haszeldine, R.S., Tett, S.F.B., and Oschlies, A. (2015). Fossil fuels in a trillion tonne world. Nat. Clim. Chang. *5*, 419–423.

57. IEA (2021). The Role of Low-Carbon Fuels in the Clean Energy Transitions of the Power Sector.

58. Lehmann, J., Cowie, A., Masiello, C.A., Kammann, C., Woolf, D., Amonette, J.E., Cayuela, M.L., Camps-Arbestain, M., and Whitman, T. (2021). Biochar in climate change mitigation. Nat. Geosci. *14*, 883–892.

59. Creutzig, F., Breyer, C., Hilaire, J., Minx, J., Peters, G.P., and Socolow, R. (2019). The mutual dependence of negative emission technologies and energy systems. Energy Environ. Sci. *12*, 1805–1817.

60. Lehtveer, M., and Emanuelsson, A. (2021). BECCS and DACCS as Negative Emission Providers in an Intermittent Electricity System: Why Levelized Cost of Carbon May Be a Misleading Measure for Policy Decisions. Front. Clim. *3*.

61. Rosa, L., Sanchez, D.L., and Mazzotti, M. (2021). Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. Energy Environ. Sci. *14*, 3086–3097.

62. Powell, T.W.R., and Lenton, T.M. (2012). Future carbon dioxide removal via biomass energy constrained by agricultural efficiency and dietary trends. Energy Environ. Sci. *5*, 8116–8133.

63. Anderson, K., and Peters, G. (2016). The trouble with negative emissions. Science (New York, N.Y.) *354*, 182–183.

64. Rogelj, J., Huppmann, D., Krey, V., Riahi, K., Clarke, L., Gidden, M., Nicholls, Z., and Meinshausen, M. (2019). A new scenario logic for the Paris Agreement long-term temperature goal. Nature *573*, 357–363.

65. Holl, K.D., and Brancalion, P.H.S. (2020). Tree planting is not a simple solution. Science (New York, N.Y.) *368*, 580–581.

66. Hua, F., Bruijnzeel, L.A., Meli, P., Martin, P.A., Zhang, J., Nakagawa, S., Miao, X., Wang, W., McEvoy, C., and Peña-Arancibia, J.L. (2022). The Biodiversity and Ecosystem Service Contributions and Trade-Offs of Forest Restoration Approaches (New York, N.Y.: Science), pp. eabl4649.

67. Poorter, L., Craven, D., Jakovac, C.C., van der Sande, M.T., Amissah, L., Bongers, F., Chazdon, R.L., Farrior, C.E., Kambach, S., Meave, J.A., et al. (2021). Multidimensional tropical forest recovery. Science *374*, 1370–1376.

68. Case, S.D.C., McNamara, N.P., Reay, D.S., and Whitaker, J. (2014). Can biochar reduce soil greenhouse gas emissions from a M iscanthus bioenergy crop? GCB Bioenergy *6*, 76–89.

69. Beusen, A., Doelman, J.C., van Beek, L., van Puijenbroek, P., Mogollón, J., van Grinsven, H., Stehfest, E., van Vuuren, D.P., and Bouwman, A.F. (2022). Exploring river nitrogen and phosphorus loading and export to global coastal waters in the Shared Socio-economic pathways. Global Environ. Change *72*, 102426.

70. Cadoux, S., Riche, A.B., Yates, N.E., and Machet, J.-M. (2012). Nutrient requirements of Miscanthus x giganteus: Conclusions from a review of published studies. Biomass & bioenergy *38*, 14–22.

71. Li, W., Ciais, P., Stehfest, E., van Vuuren, D., Popp, A., Arneth, A., Di Fulvio, F., Doelman, J., Humpenöder, F., Harper, A.B., et al. (2020). Mapping the yields of lignocellulosic bioenergy crops from observations at the global scale. Earth Syst. Sci. Data *12*, 789–804.

72. Wu, Z., and Zhai, H. (2021). Consumptive life cycle water use of biomass-to-power plants with carbon capture and sequestration. Appl. Energy *303*, 117702.

73. Lane, J., Greig, C., and Garnett, A. (2021). Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. Nat. Clim. Chang. *11*, 925–936.

74. Scherer, L., Rueda, O., and Smetana, S. (2023). Environmental Impacts of Meat and Meat Replacements. In Meat and Meat Replacements. An Interdisciplinary Assessment of Current Status and Future Directions, H.L. Meiselman and J.M. Lorenzo, eds. (Elsevier).

75. Sinke, P., Swartz, E., Sanctorum, H., van der Giesen, C., and Odegard, I. (2023). Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030. Int. J. Life Cycle Assess. *28*, 234–254.

76. Chini, L.P., Hurtt, G.C., Sahajpal, R., Frolking, S., Frieler, K., Popp, A., Bodirsky, B., Humpenoeder, F., Stevanovic, M., Calvin, K., et al. (2020). LUH2-ISIMIP2b Harmonized Global Land Use for the Years 2015-2100 (ORNL Distributed Active Archive Center).

77. FAO (2022). FAOSTAT. https://www.fao.org/faostat/en/#data/FBS.

78. Monfreda, C., Ramankutty, N., and Foley, J.A. (2008). Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem. Cycles *22*, n. /a-n/a.

79. Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., et al. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Global Environ. Change *42*, 251–267.

80. Valin, H., Sands, R.D., van der Mensbrugghe, D., Nelson, G.C., Ahammad, H., Blanc, E., Bodirsky, B., Fujimori, S., Hasegawa, T., Havlik, P., et al. (2014). The future of food demand: understanding differences in global economic models. Agric. Econ. *45*, 51–67.

81. Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.P., Doelmann, J.C., Gusti, M., et al. (2017). Land-use futures in the shared socio-economic pathways. Global Environ. Change *42*, 331–345.

82. Xie, W., Xiong, W., Pan, J., Ali, T., Cui, Q., Guan, D., Meng, J., Mueller, N.D., Lin, E., and Davis, S.J. (2018). Decreases in global beer supply due to extreme drought and heat. Nat. Plants *4*, 964–973.

83. FAO (2021). Harmonized World Soil Database V 1.2. https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/.

84. UNEP-WCMC (2020). World Database on Protected Areas. https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA.

85. WWF. Global. Lakes and Wetlands Database. https://www.worldwildlife.org/pages/global-lakes-and-wetlands-database.

86. BirdLife International and Conservation International (2018). Key Biodiversity Area (KBA) Digital Boundaries: September 2018 Version. http://www.keybiodiversityareas.org/.

87. Allan, J., Venter, O., and Watson, J.E.M. (2018). Data from: Temporally Inter-comparable Maps of Terrestrial Wilderness and the Last of the Wild (Dryad).

88. Enquist, B.J., Feng, X., Boyle, B., Maitner, B., Newman, E.A., Jørgensen, P.M., Roehrdanz, P.R., Thiers, B.M., Burger, J.R., Corlett, R.T., et al. (2019). The commonness of rarity: Global and future distribution of rarity across land plants. Sci. Adv. *5*, eaaz0414.

89. Bui, M., Zhang, D., Fajardy, M., and Mac Dowell, N. (2021). Delivering carbon negative electricity, heat and hydrogen with BECCS – Comparing the options. Int. J. Hydrogen Energy *46*, 15298–15321.

90. van Vliet, O.P., Faaij, A.P., and Turkenburg, W.C. (2009). Fischer–Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis. Energy Convers. Manag. *50*, 855–876.

91. Cook-Patton, S.C., Leavitt, S.M., Gibbs, D., Harris, N.L., Lister, K., Anderson-Teixeira, K.J., Briggs, R.D., Chazdon, R.L., Crowther, T.W., Ellis, P.W., et al. (2020). Mapping carbon accumulation potential from global natural forest regrowth. Nature *585*, 545–550.

92. Erb, K.-H., Kastner, T., Plutzar, C., Bais, A.L.S., Carvalhais, N., Fetzel, T., Gingrich, S., Haberl, H., Lauk, C., Niedertscheider, M., et al. (2018).

Unexpectedly large impact of forest management and grazing on global vegetation biomass. Nature *553*, 73–76.

93. Schaphoff, S., von Bloh, W., Rammig, A., Thonicke, K., Biemans, H., Forkel, M., Gerten, D., Heinke, J., Jägermeyr, J., Knauer, J., et al. (2018). LPJmL4 – a dynamic global vegetation model with managed land – Part 1: Model description. Geosci. Model Dev. (GMD) *11*, 1343–1375.

94. Jägermeyr, J., Gerten, D., Heinke, J., Schaphoff, S., Kummu, M., and Lucht, W. (2015). Water savings potentials of irrigation systems: global simulation of processes and linkages. Hydrol. Earth Syst. Sci. *19*, 3073–3091.

95. Pastor, A.V., Ludwig, F., Biemans, H., Hoff, H., and Kabat, P. (2014). Accounting for environmental flow requirements in global water assessments. Hydrol. Earth Syst. Sci. *18*, 5041–5059.

96. Jägermeyr, J., Pastor, A., Biemans, H., and Gerten, D. (2017). Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. Nat. Commun. *8*, 15900.

97. Heck, V., Gerten, D., Lucht, W., and Boysen, L.R. (2016). Is extensive terrestrial carbon dioxide removal a 'green' form of geoengineering? A global modelling study. Global Planet. Change *137*, 123–130.

98. Fader, M., Rost, S., Müller, C., Bondeau, A., and Gerten, D. (2010). Virtual water content of temperate cereals and maize: Present and potential future patterns. J. Hydrol. *384*, 218–231.

99. Li, W. (2019). Mapping the Yields of Lignocellulosic Bioenergy Crops from Observations at the Global Scale (Zenodo).

100. Spawn, S.A., Sullivan, C.C., Lark, T.J., and Gibbs, H.K. (2020). Harmonized global maps of above and belowground biomass carbon density in the year 2010. Sci. Data *7*, 112.

101. Sanderman, J., Hengl, T., and Fiske, G.J. (2017). Soil carbon debt of 12,000 years of human land use. Proc. Natl. Acad. Sci. USA *114*, 9575–9580.

102. Poulter, B., Aragão, L., Andela, N., Bellassen, V., Ciais, P., Kato, T., Lin, X., Nachin, B., Luyssaert, S., Pederson, N., et al. (2019). The Global Forest Age Dataset and its Uncertainties (GFADv1.1) (PANGAEA - Data Publisher for Earth & Environmental Science).

103. Ramankutty, N., Evan, A.T., Monfreda, C., and Foley, J.A. (2008). Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Global Biogeochem. Cycles *22*, n. /a-n/a.

104. Winkler, K., Fuchs, R., Rounsevell, M., and Herold, M. (2021). Global land use changes are four times greater than previously estimated. Nat. Commun. *12*, 2501.

105. Koch, A., and Kaplan, J.O. (2022). Tropical forest restoration under future climate change. Nat. Clim. Chang. *12*, 279–283.

106. Strassburg, B.B.N., Iribarrem, A., Beyer, H.L., Cordeiro, C.L., Crouzeilles, R., Jakovac, C.C., Braga Junqueira, A., Lacerda, E., Latawiec, A.E., Balmford, A., et al. (2020). Global priority areas for ecosystem restoration. Nature *586*, 724–729.

107. Theussl, S., and Hornik, K. (2019). Rglpk: R/GNU Linear Programming Kit Interface. https://CRAN.R-project.org/package=Rglpk.

108. Stadler, K., Wood, R., Bulavskaya, T., Södersten, C., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., et al. (2018). EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. J. Ind. Ecol. *22*, 502–515.

109. Wei, Y.-M., Kang, J.-N., Liu, L.-C., Li, Q., Wang, P.-T., Hou, J.-J., Liang, Q.-M., Liao, H., Huang, S.-F., and Yu, B. (2021). A proposed global layout of carbon capture and storage in line with a 2 °C climate target. Nat. Clim. Chang. *11*, 112–118.

110. IEA (2021). About CCUS.

111. Kearns, J., Teletzke, G., Palmer, J., Thomann, H., Kheshgi, H., Chen, Y.-H.H., Paltsev, S., and Herzog, H. (2017). Developing a Consistent Database for Regional Geologic CO2 Storage Capacity Worldwide. Energy Proc. *114*, 4697–4709.

112. Bradshaw, J., and Dance, T. (2005). - Mapping geological storage prospectivity of CO2 for the world's sedimentary basins and regional source to sink matching. In Greenhouse Gas Control Technologies 7, E. Rubin, D. Keith, C. Gilboy, M. Wilson, T. Morris, J. Gale, and K. Thambimuthu, eds. (Oxford: Elsevier Science Ltd)), pp. 583–591.

113. Robertson CGG (2019). Sedimentary Basins of the World. https://www.arcgis.com/home/item.html?id=9845f1f30a1641efbe54dd1f9c8c668b.

114. International Energy Agency Greenhouse Gas R&D Programme (2005). Building the Cost Curves for CO2 Storage: European Sector.

115. Laske, G., Ma, Z., Masters, G., and Pasyanos, M. (2014). Crust 1.0: A New Global Crustal Model at 1x1 Degrees. http://igppweb.ucsd.edu/~gabi/crust1.html.

116. U.S. Geological Survey (2013). National Assessment of Geologic Carbon Dioxide Storage Resources—Results. ver. 1.1.

117. Gray, K. (2015). Carbon Storage Atlas.

118. Gorecki, C.D., Sorensen, J.A., Bremer, J.M., Knudsen, D., Smith, S.A., Steadman, E.N., and Harju, J.A. (2009). Development of Storage Coefficients for Determining the Effective CO2 Storage Resource in Deep Saline Formations. SPE-126444-MS.

119. GEBCO Compilation Group (2020). GEBCO 2020 Grid.

120. Kelemen, P., Benson, S.M., Pilorgé, H., Psarras, P., and Wilcox, J. (2019). An Overview of the Status and Challenges of CO2 Storage in Minerals and Geological Formations. Front. Clim. *1*.

121. Berkelaar, M., and others. (2020). lpSolve: Interface to 'Lp_solve' V. 5.5 to Solve. Linear/Integer Programs. https://CRAN.R-project.org/package=lpSolve.

One Earth, Volume *7*

Supplemental information

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

Oscar Rueda, José M. Mogollón, Fabian Stenzel, Arnold Tukker, and Laura Scherer

Supplemental figures

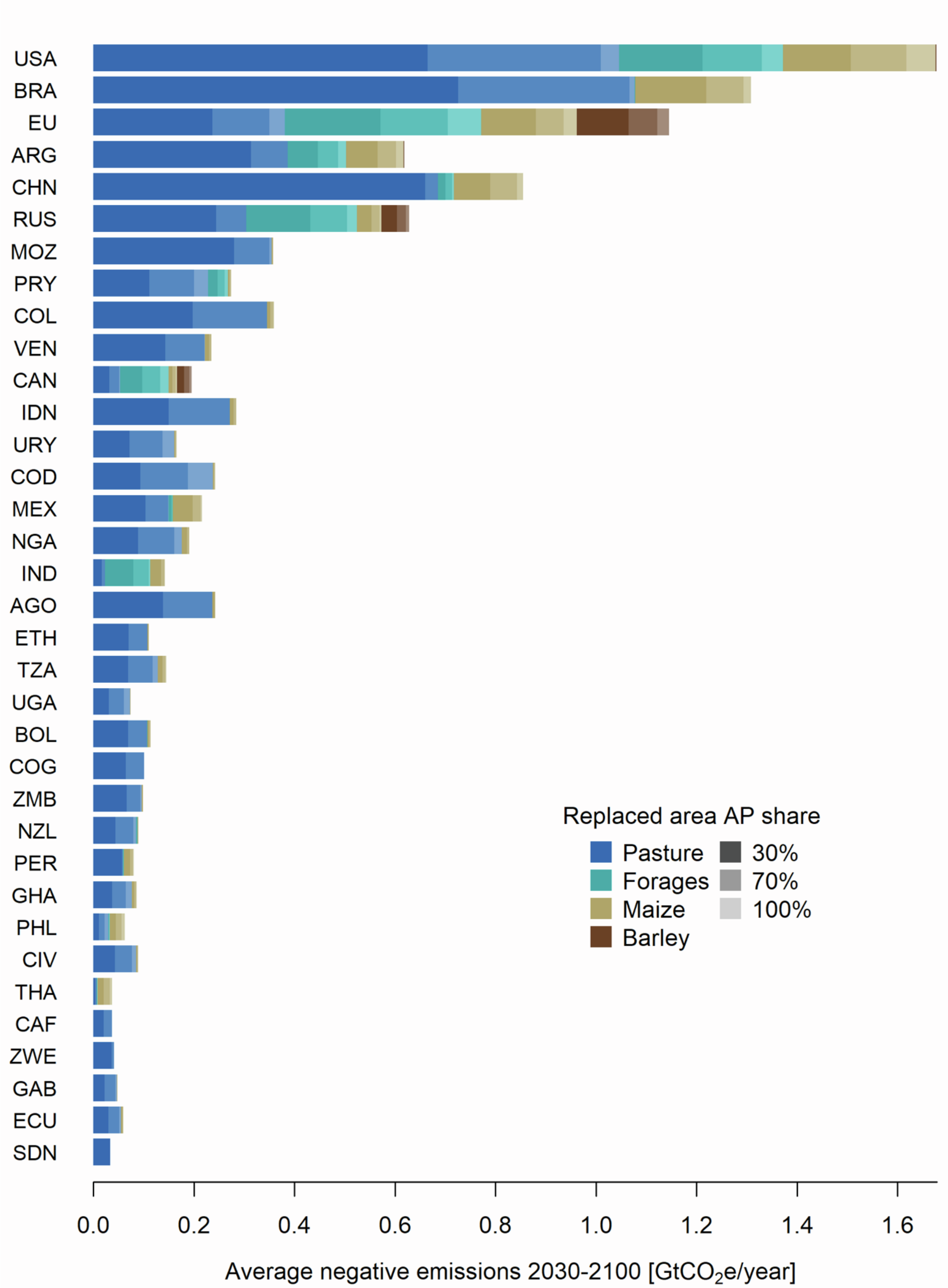


Figure S1. Negative emission potential of countries (only Europe as a whole) at three levels of alternative protein (AP) adoption for BECCS electricity. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

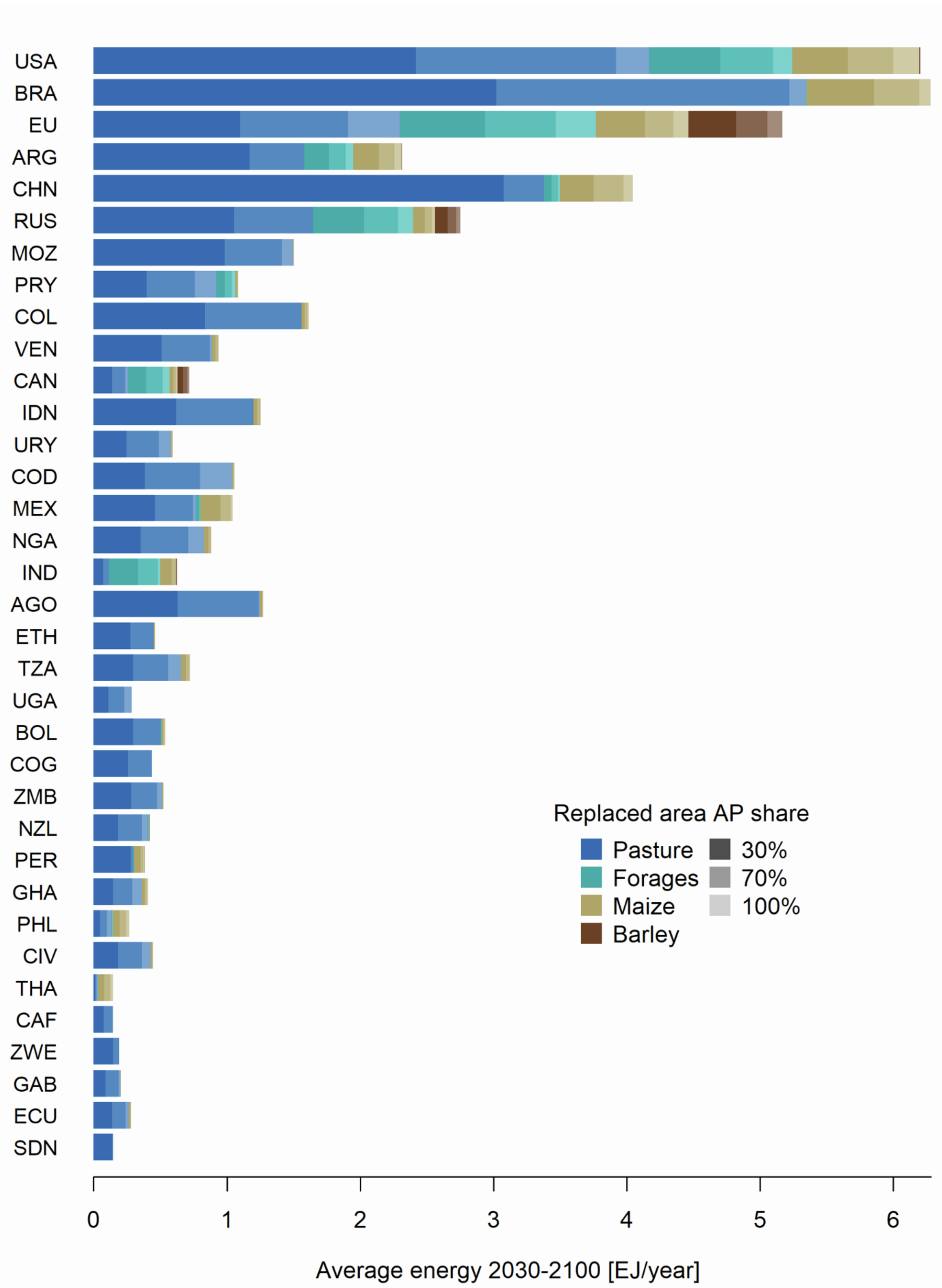


Figure S2. Energy potential for BECCS electricity of countries (only Europe as a whole) when maximizing negative emissions at three levels of alternative protein (AP) adoption. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

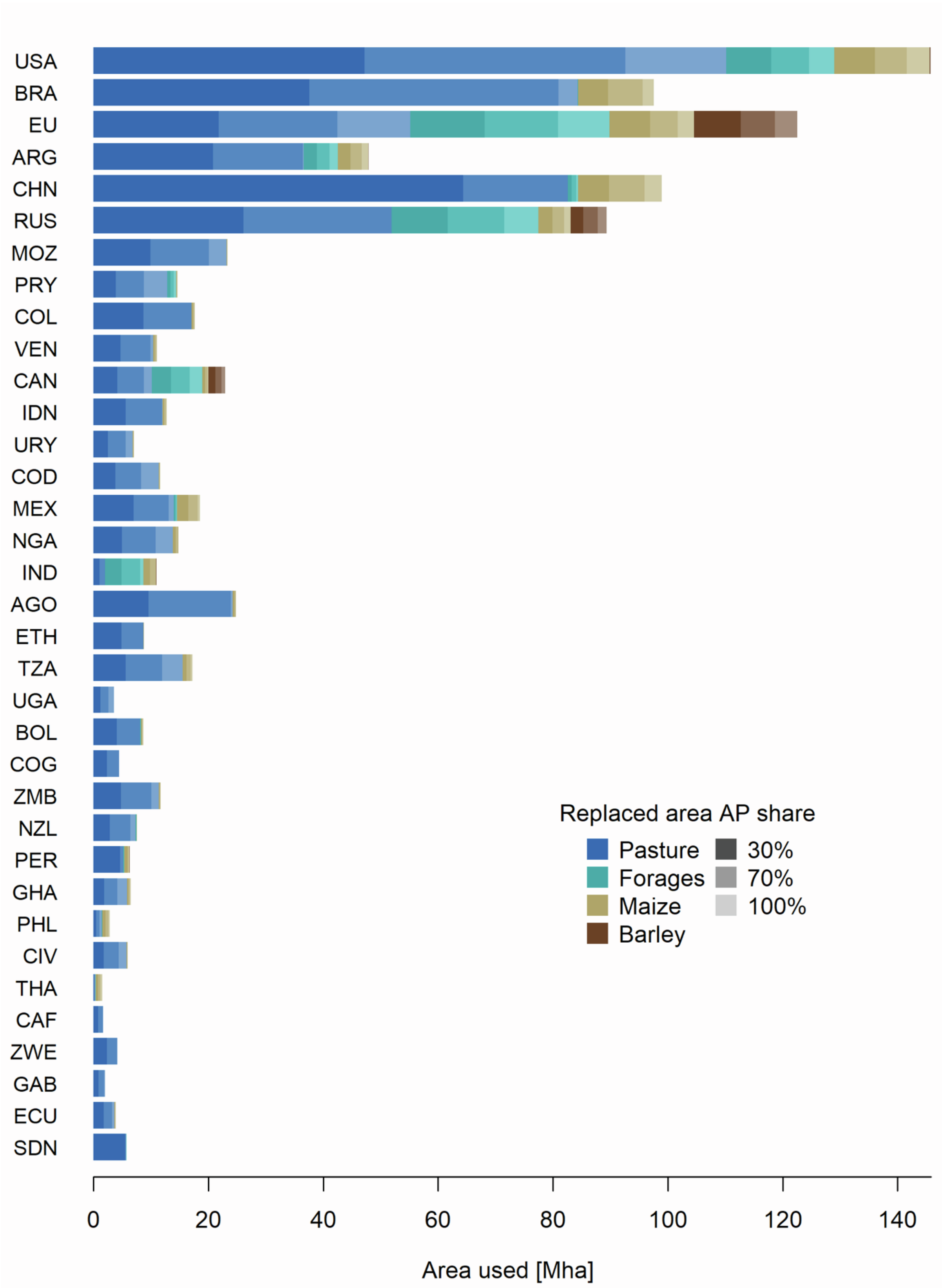


Figure S3. Area used for BECCS electricity of countries (only Europe as a whole) when maximizing negative emissions at three levels of alternative protein (AP) adoption. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

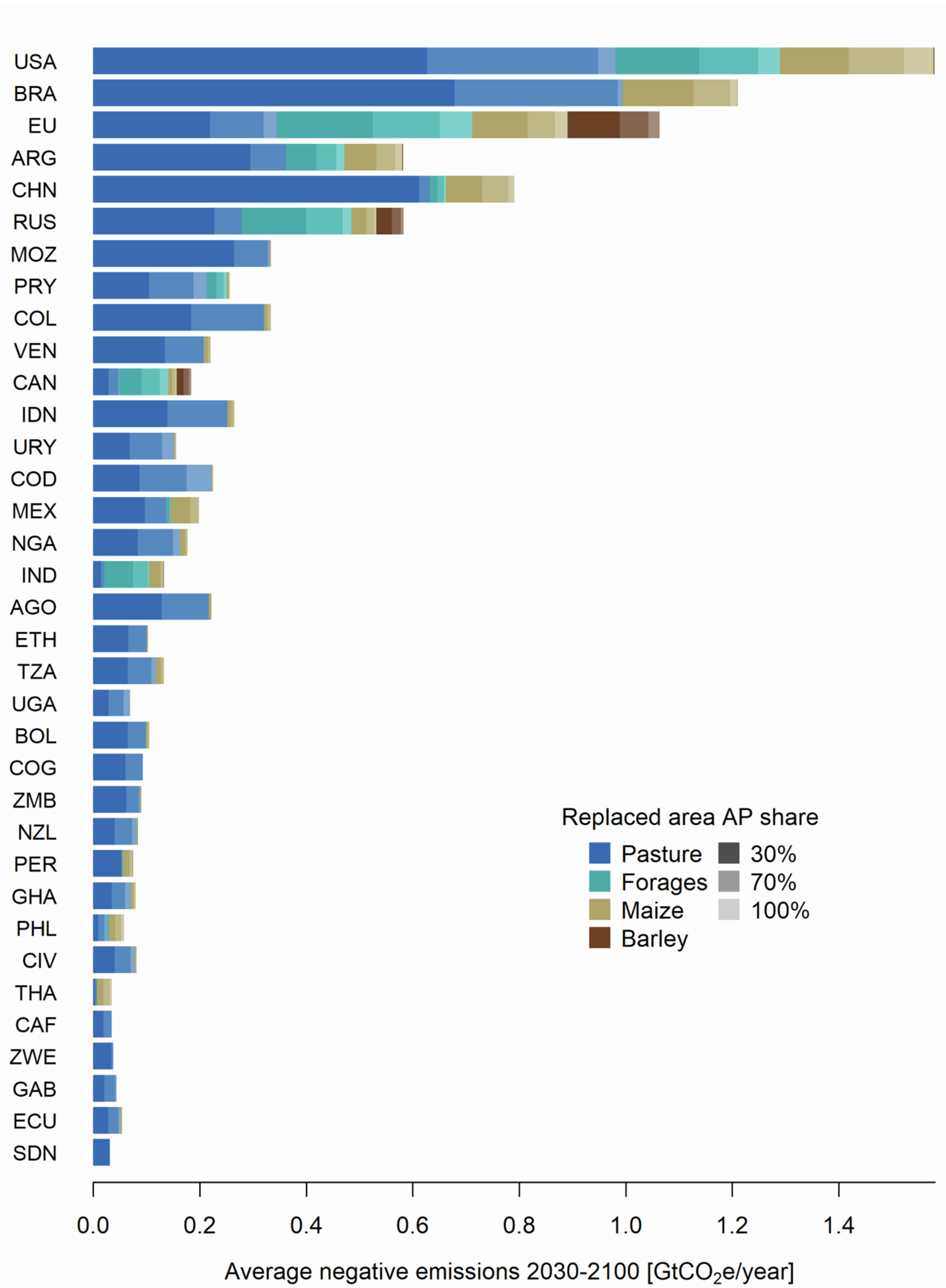


Figure S4. Negative emission potential of countries (only Europe as a whole) at three levels of alternative protein (AP) adoption for BECCS hydrogen. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

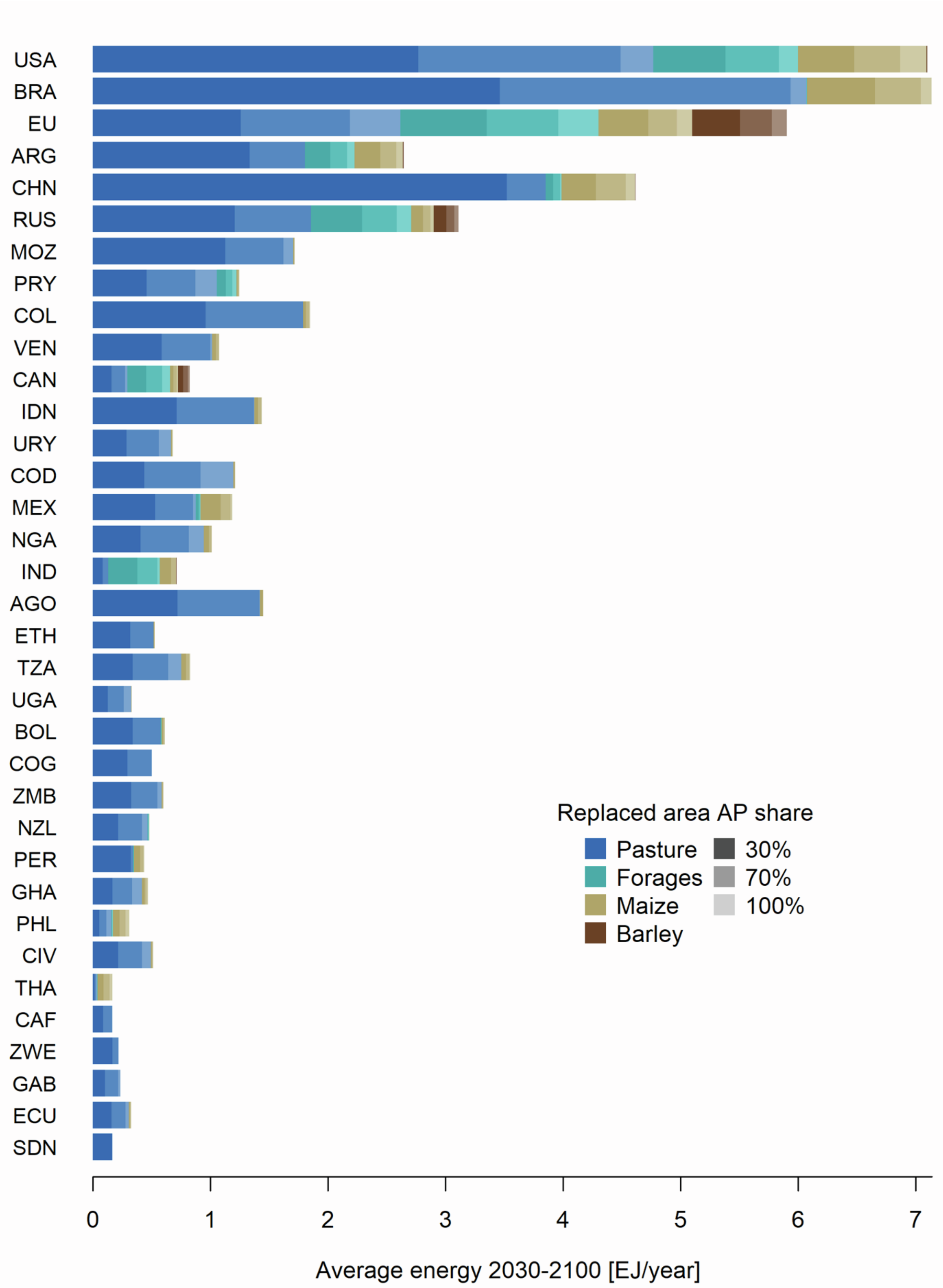


Figure S5. Energy potential for BECCS hydrogen of countries (only Europe as a whole) when maximizing negative emissions at three levels of alternative protein (AP) adoption. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

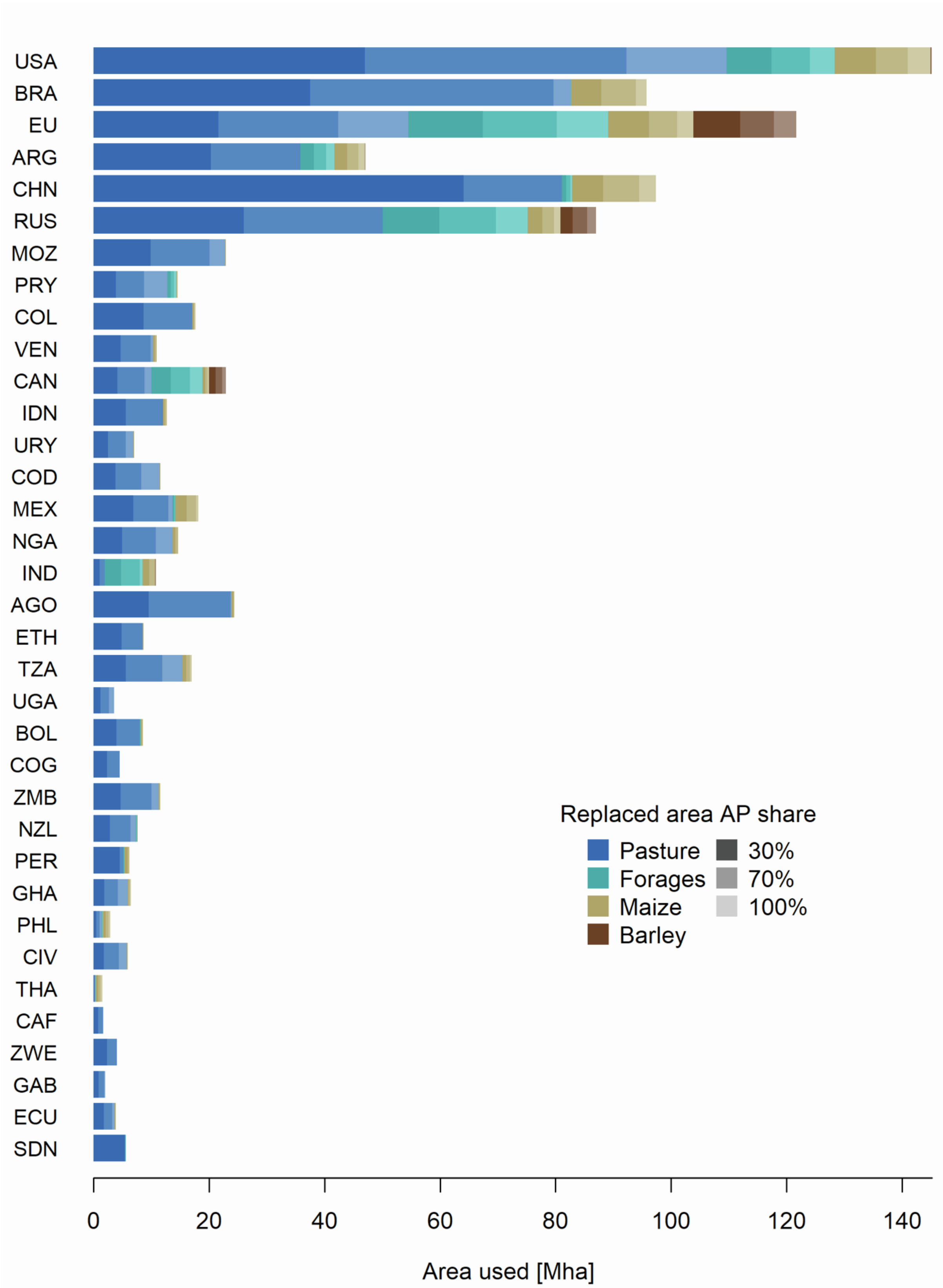


Figure S6. Area used for BECCS hydrogen of countries (only Europe as a whole) when maximizing negative emissions at three levels of alternative protein (AP) adoption. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

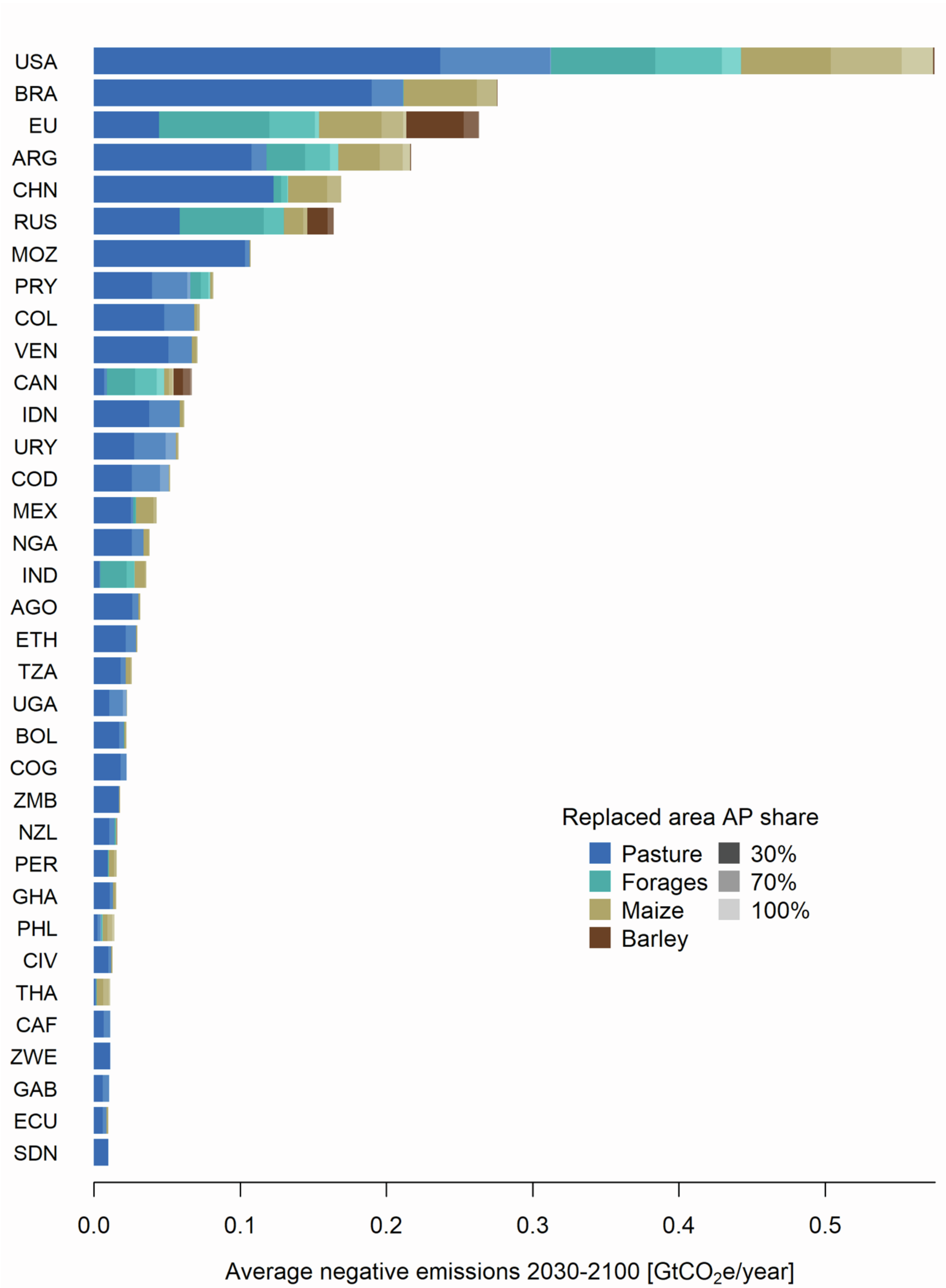


Figure S7. Negative emission potential of countries (only Europe as a whole) at three levels of alternative protein (AP) adoption for BECCS FT diesel. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

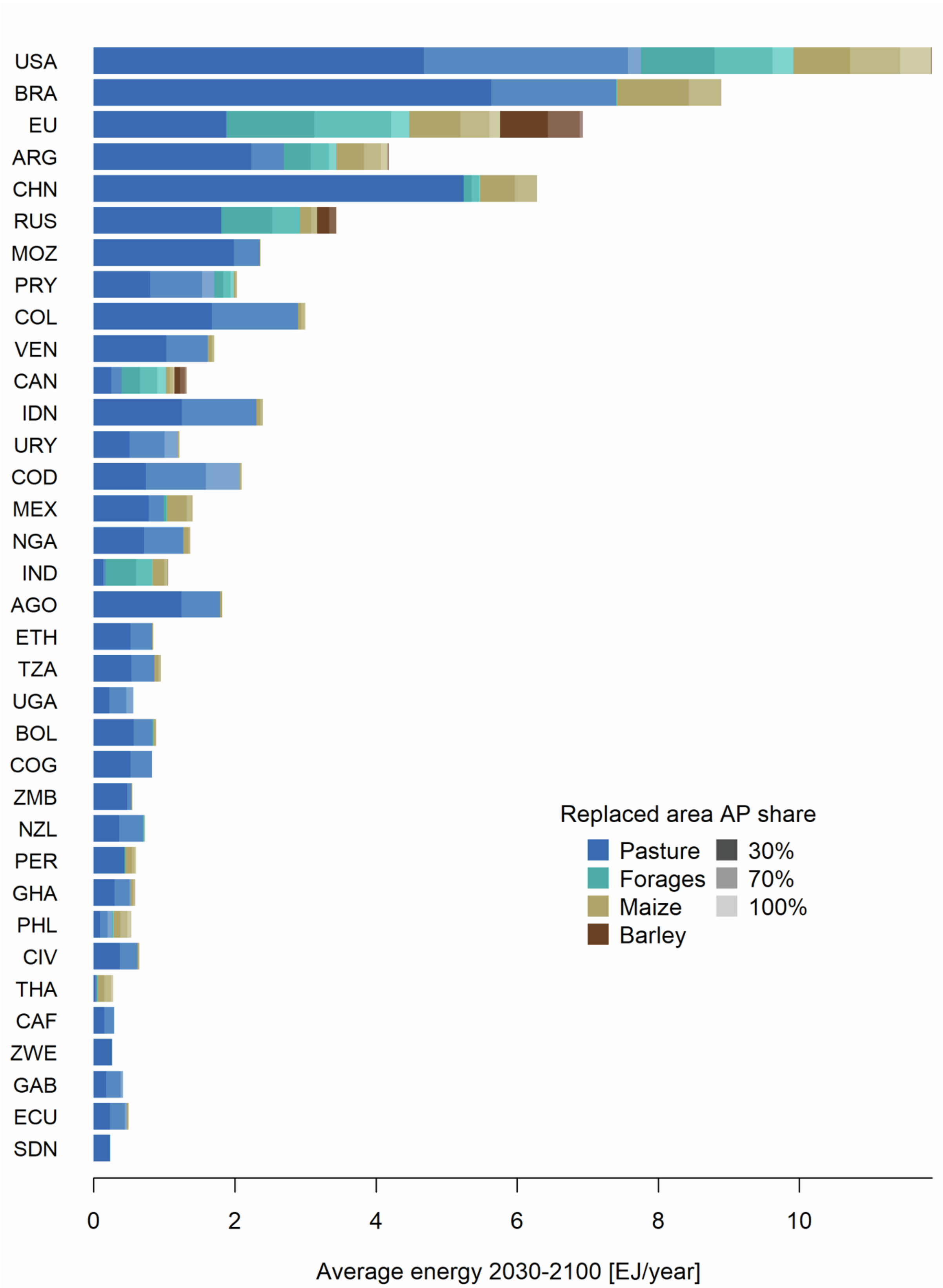


Figure S8. Energy potential for BECCS FT diesel of countries (only Europe as a whole) when maximizing negative emissions at three levels of alternative protein (AP) adoption. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

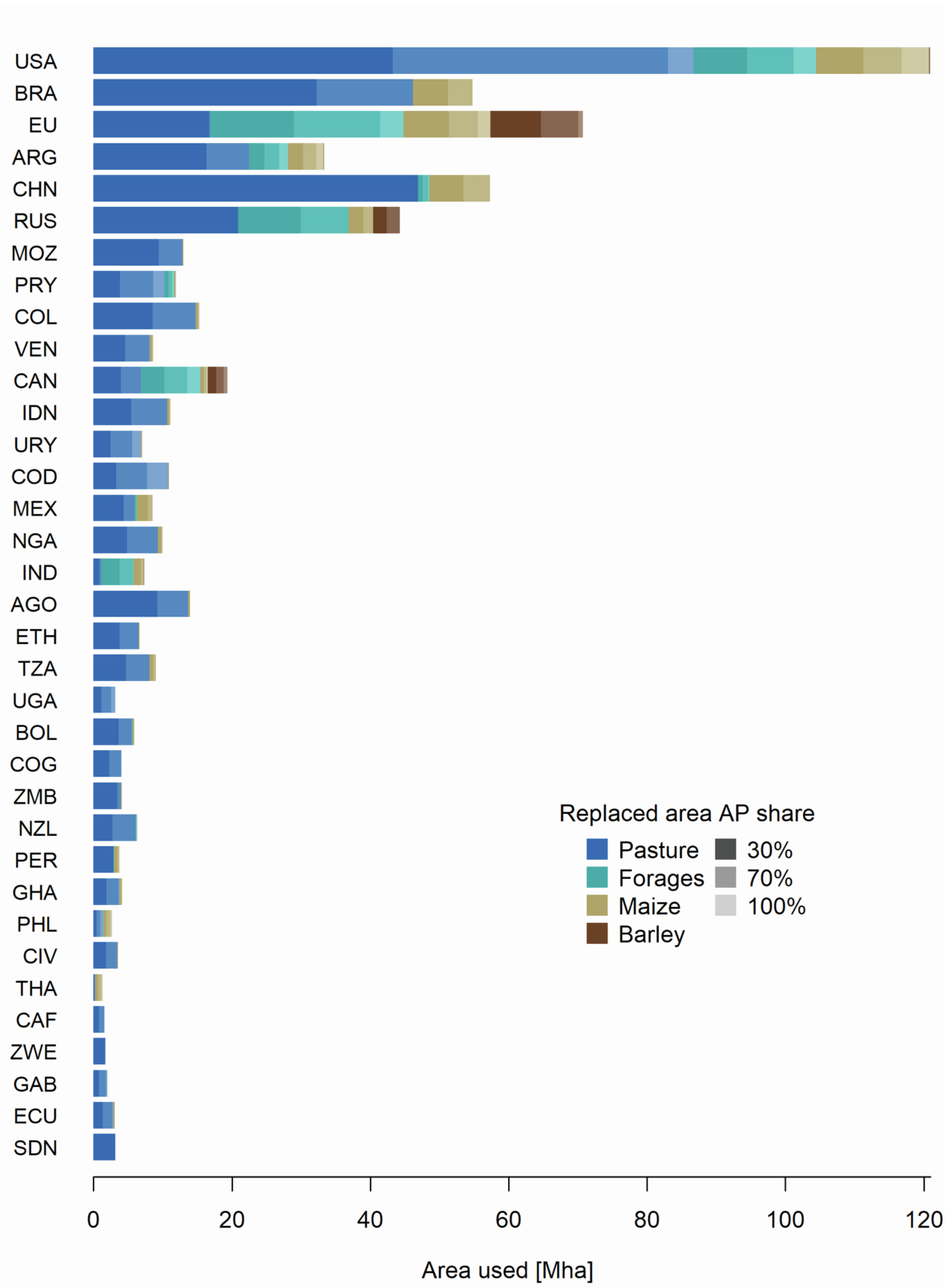


Figure S9. Area used for BECCS FT diesel of countries (only Europe as a whole) when maximizing negative emissions at three levels of alternative protein (AP) adoption. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

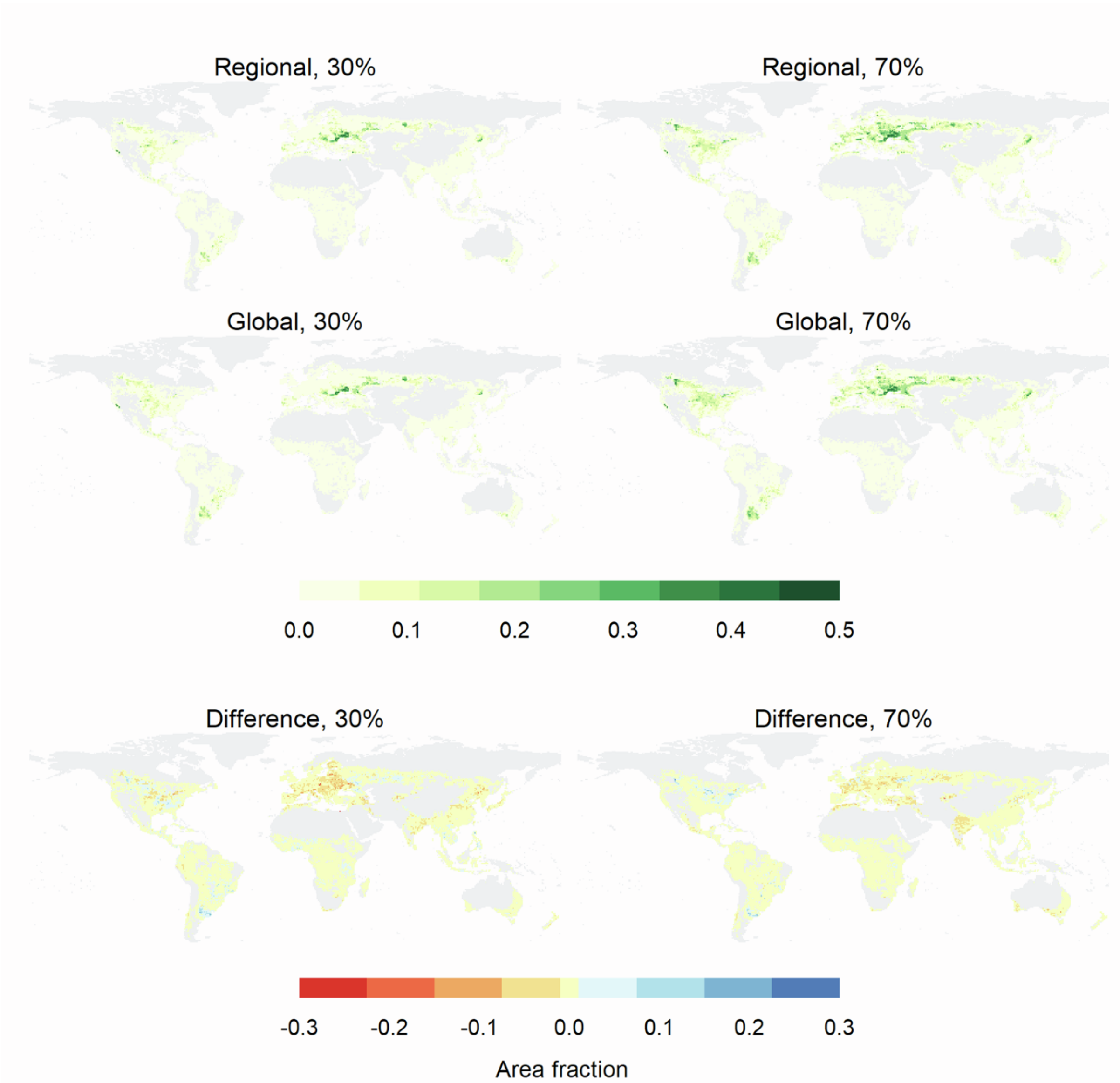


Figure S10. Feed crop areas where bioenergy crops for BECCS electricity could achieve negative emissions. *Replacement levels of animal products include 30% and 70%. Areas for bioenergy crops were optimized at the global and regional level (by country, considering only Europe as a whole) to maximize negative emissions, while still ensuring the supply of the remaining animal products. The subplots at the bottom show the difference between areas (global minus regional). Related to Figure 2.*

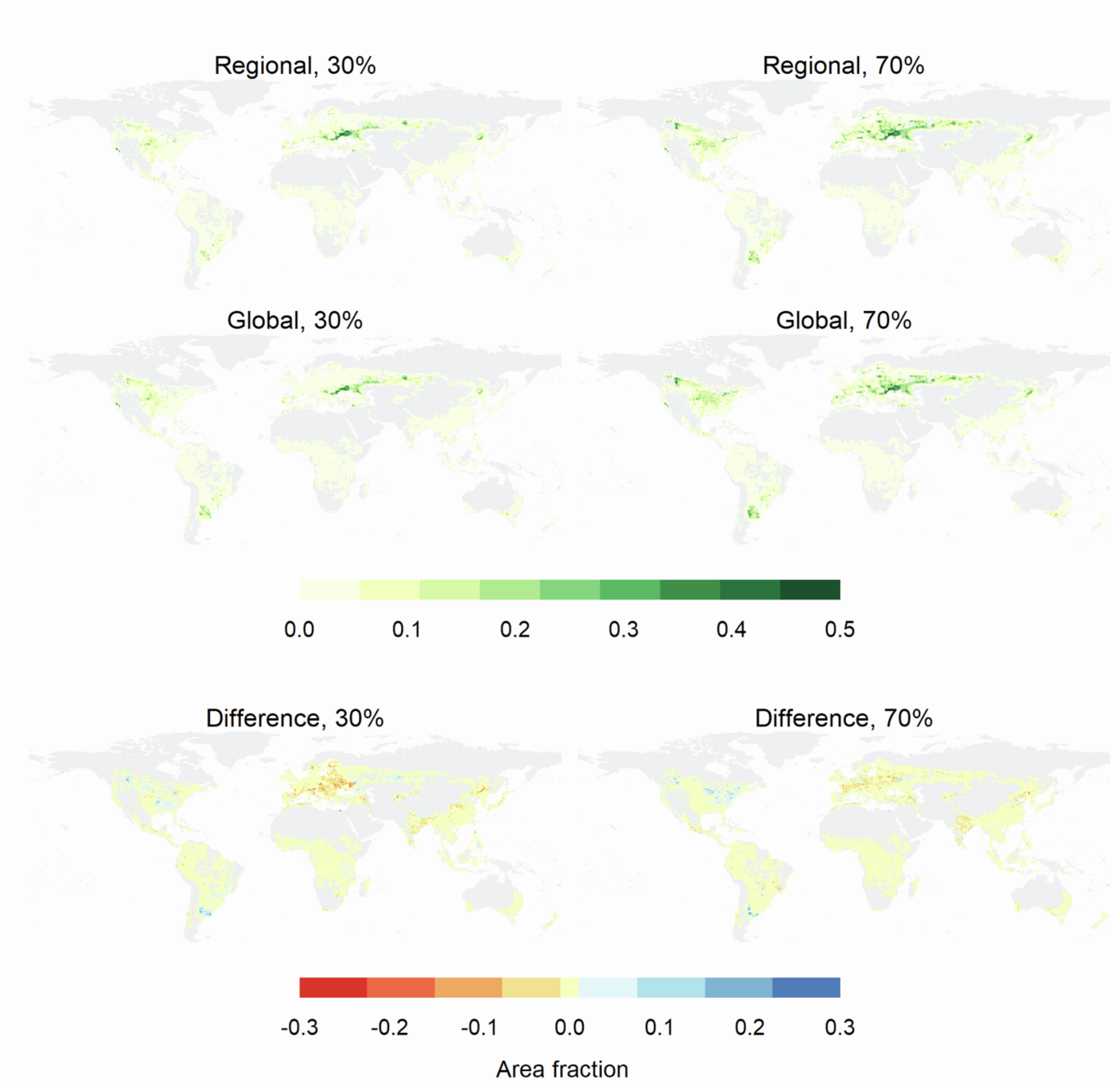


Figure S11. Feed crop areas where bioenergy crops for BECCS FT-diesel could achieve negative emissions. *Replacement levels of animal products include 30% and 70%. Areas for bioenergy crops were optimized at the global and regional level (by country, considering only Europe as a whole) to maximize negative emissions, while still ensuring the supply of the remaining animal products. The subplots at the bottom show the difference between areas (global minus regional). Related to Figure 2.*

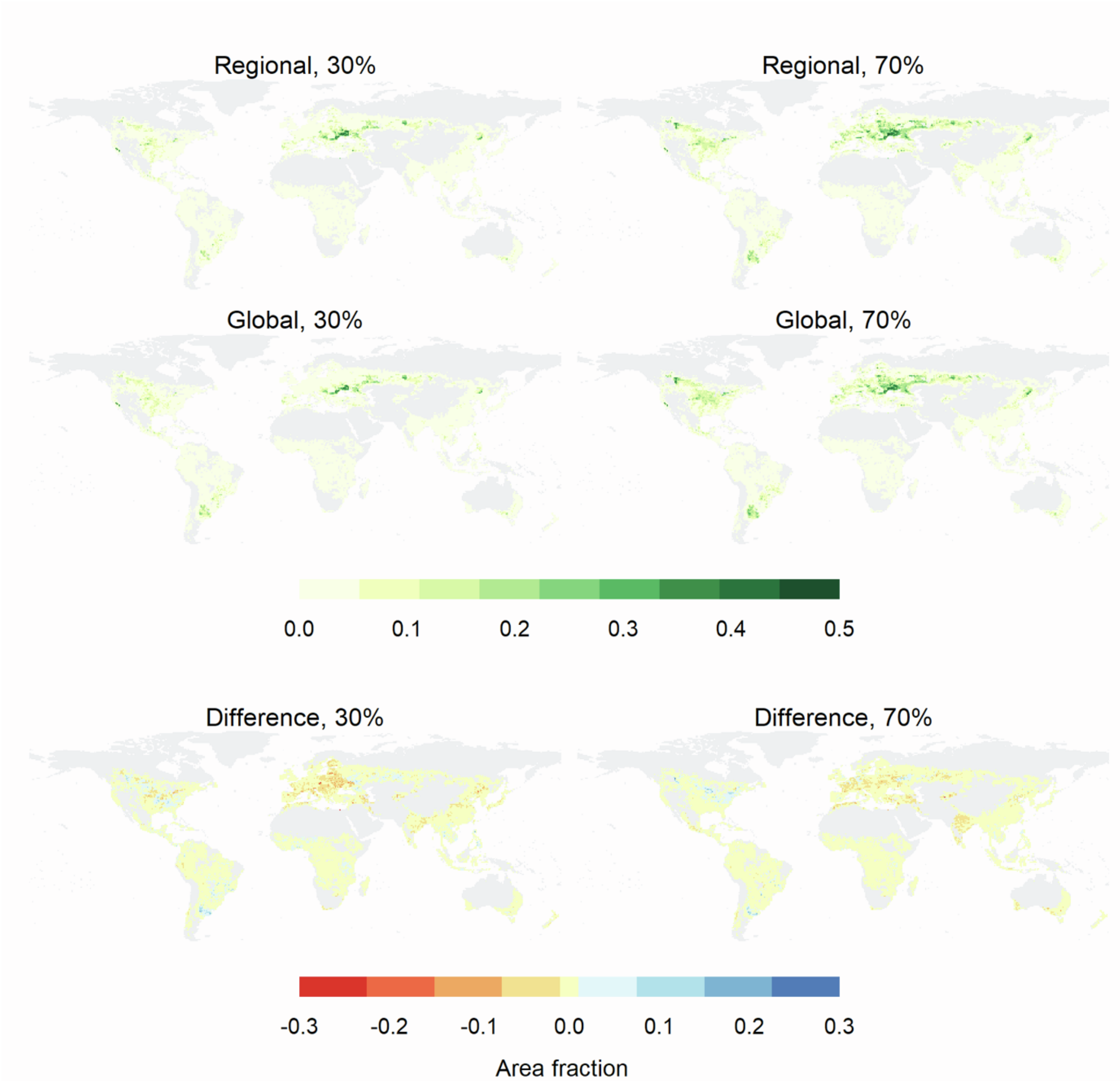


Figure S12. Feed crop areas where bioenergy crops for BECCS hydrogen could achieve negative emissions. *Replacement levels of animal products include 30% and 70%. Areas for bioenergy crops were optimized at the global and regional level (by country, considering only Europe as a whole) to maximize negative emissions, while still ensuring the supply of the remaining animal products. The subplots at the bottom show the difference between areas (global minus regional). Related to Figure 2.*

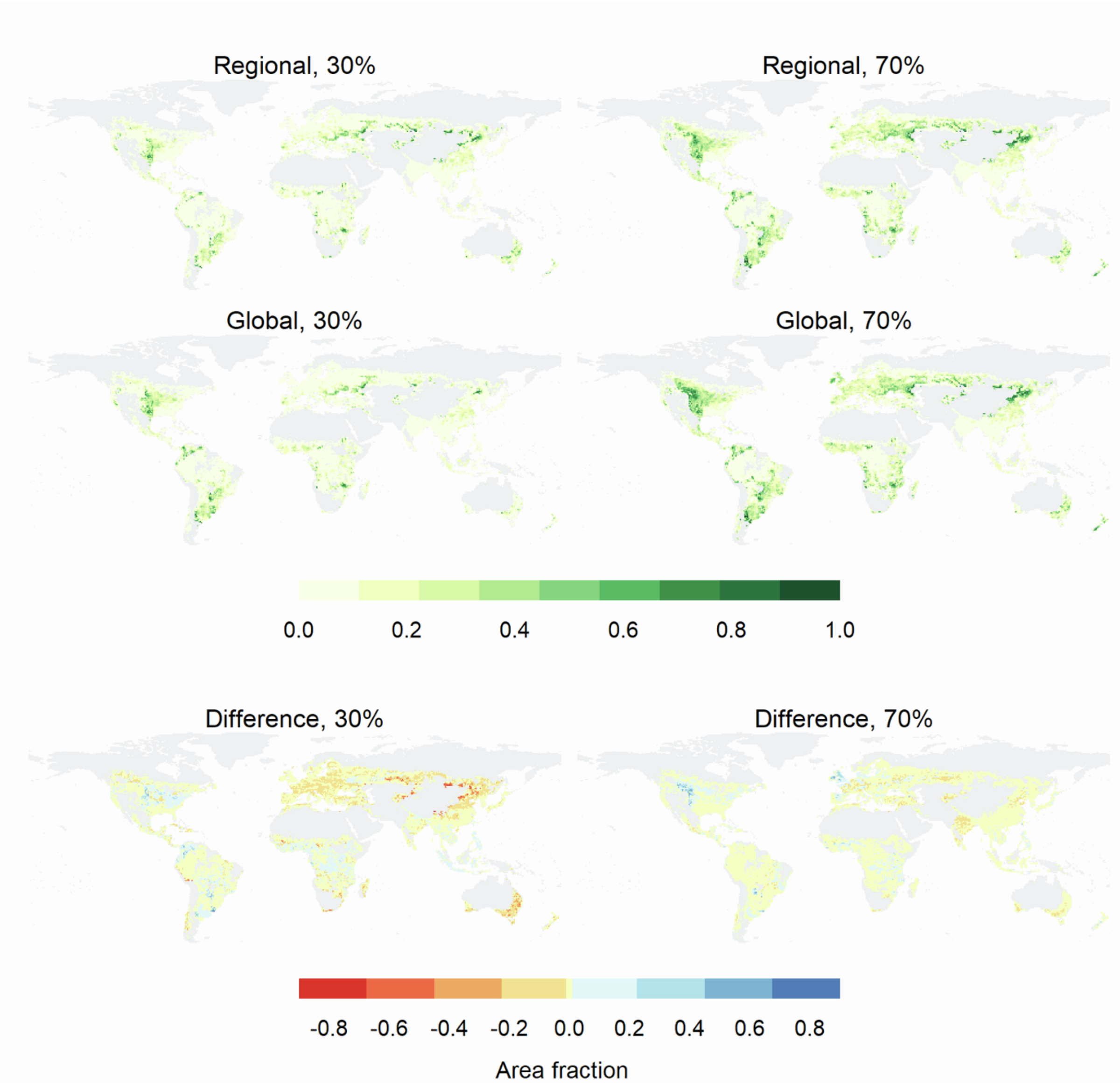


Figure S13. Feed crop and pasture areas where bioenergy crops for BECCS electricity could achieve negative emissions. *Replacement levels of animal products include 30% and 70%. Areas for bioenergy crops were optimized at the global and regional level (by country, considering only Europe as a whole) to maximize negative emissions, while still ensuring the supply of the remaining animal products. The subplots at the bottom show the difference between areas (global minus regional). Related to Figure 2.*

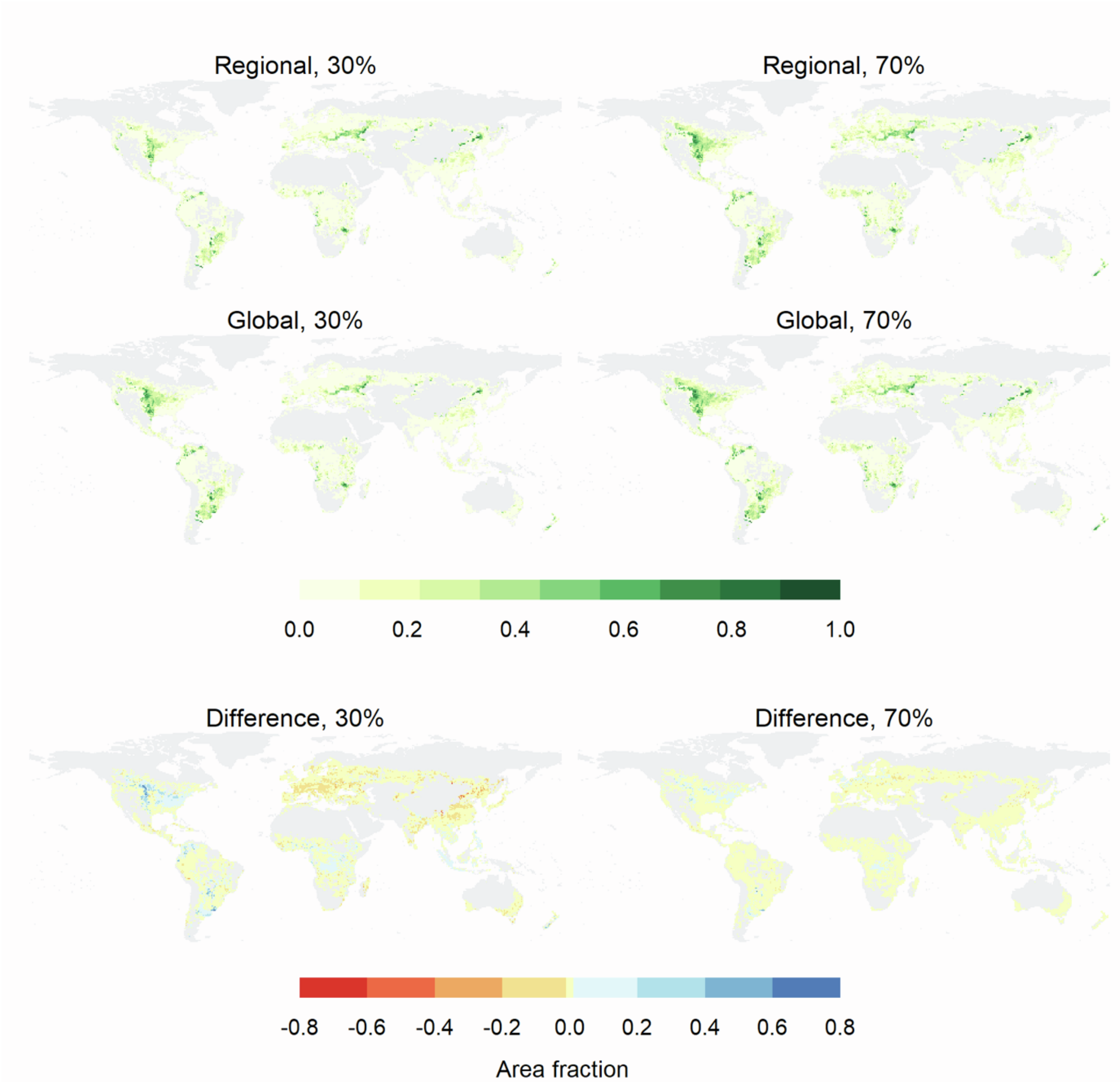


Figure S14. Feed crop and pasture areas where bioenergy crops for BECCS FT-diesel could achieve negative emissions. *Replacement levels of animal products include 30% and 70%. Areas for bioenergy crops were optimized at the global and regional level (by country, considering only Europe as a whole) to maximize negative emissions, while still ensuring the supply of the remaining animal products. The subplots at the bottom show the difference between areas (global minus regional). Related to Figure 2.*

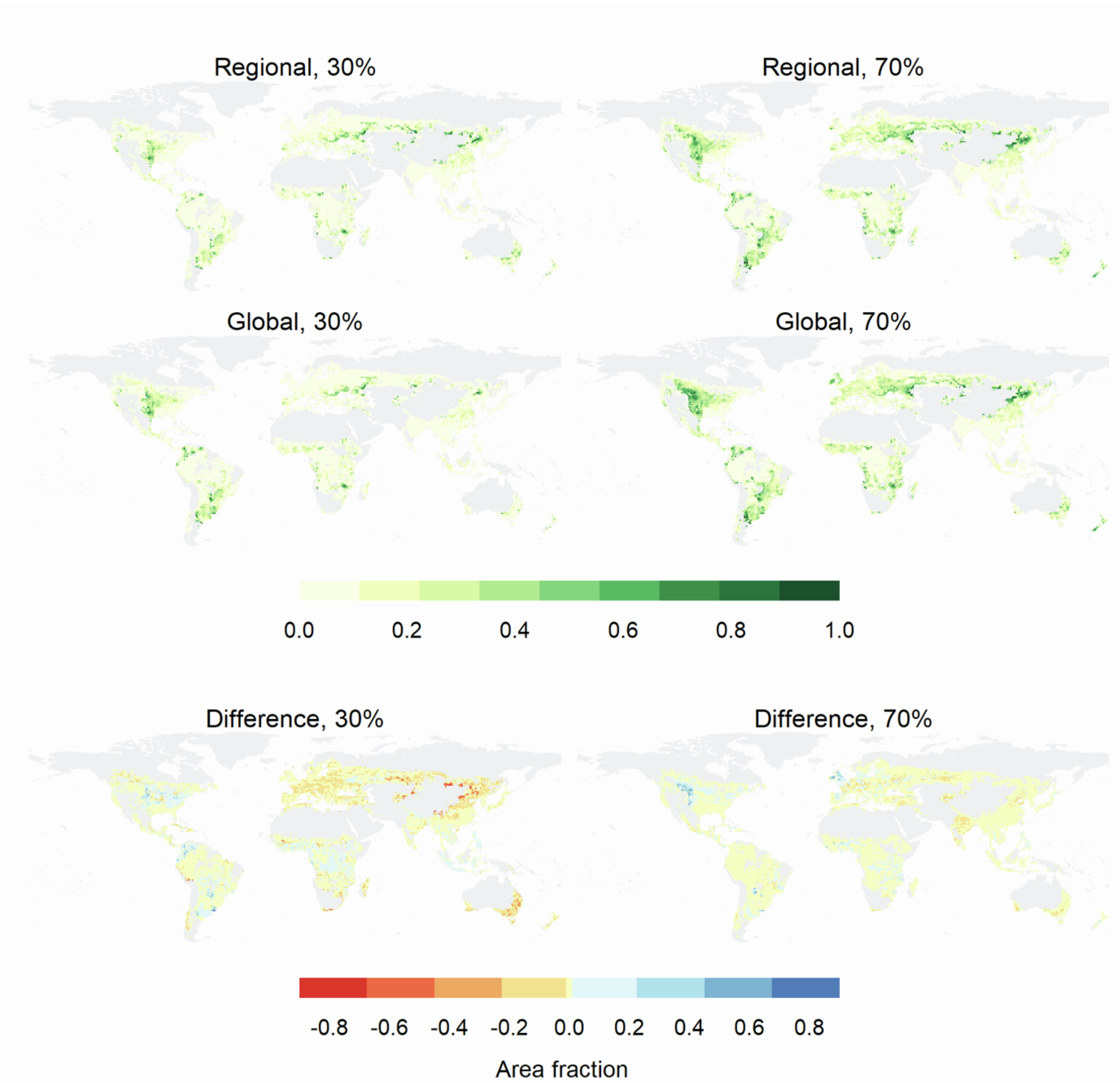


Figure S15. Feed crop and pasture areas where bioenergy crops for BECCS hydrogen could achieve negative emissions. *Replacement levels of animal products include 30% and 70%. Areas for bioenergy crops were optimized at the global and regional level (by country, considering only Europe as a whole) to maximize negative emissions, while still ensuring the supply of the remaining animal products. The subplots at the bottom show the difference between areas (global minus regional). Related to Figure 2.*

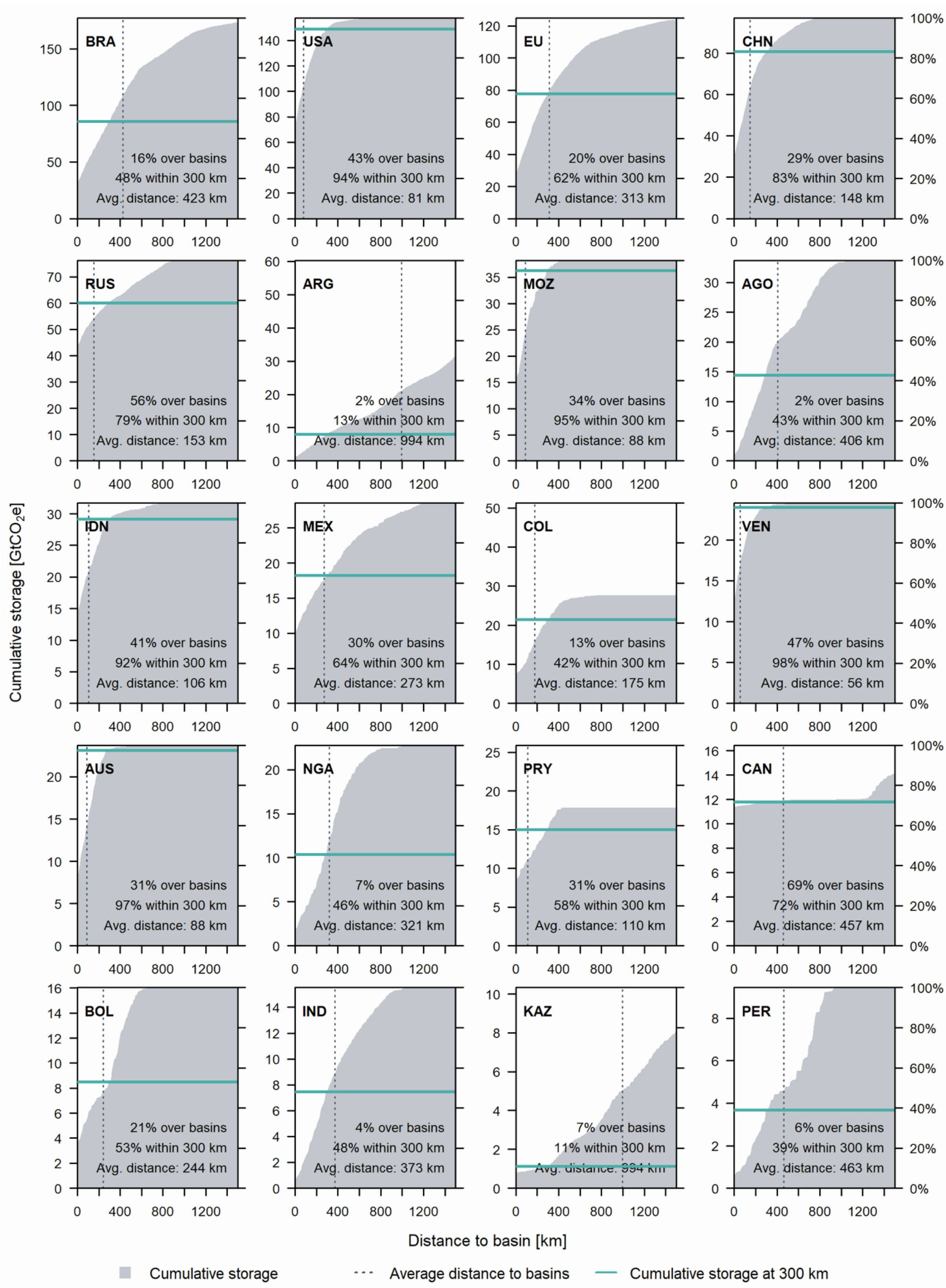


Figure S16. Source-sink distance between bioenergy crops and CO_2 storage sites for electricity production through BECCS. *Negative emissions are the difference between the net carbon removal from BECCS and the forgone carbon stock through natural regrowth. BECCS potential is the average of 4 climate models and natural regrowth 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 (Figure 4a). Related to Figure 3.*

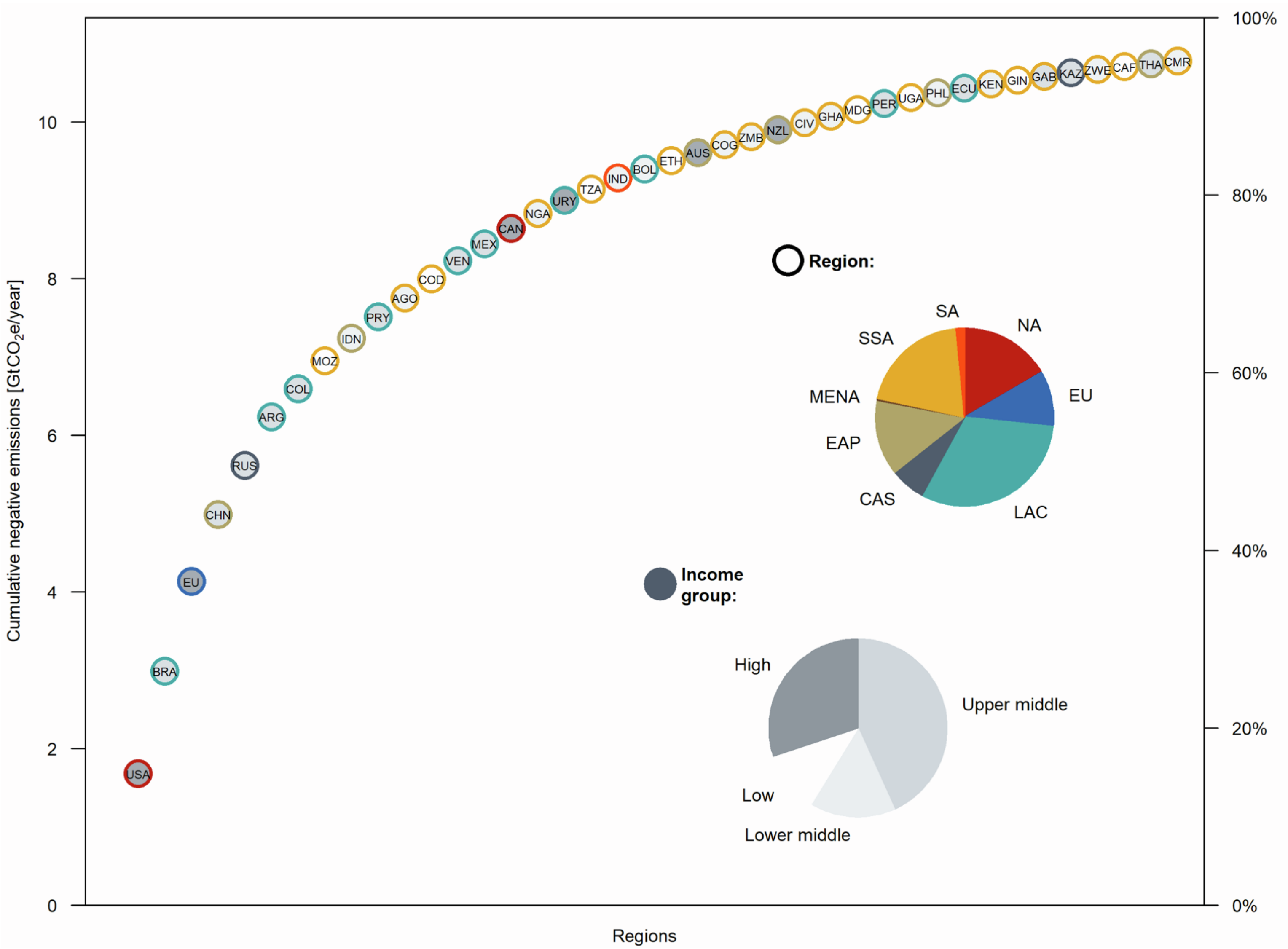


Figure S17. Negative emissions through BECCS electricity by country and country group. *Main plot shows cumulative negative emissions of countries (only Europe as a whole) with the highest potentials. Inset plots indicate breakdown by region and income group. The evaluation period is 2030-2100 with 20 years of ramp-up time (Figure 4a). Related to Figure 4.*

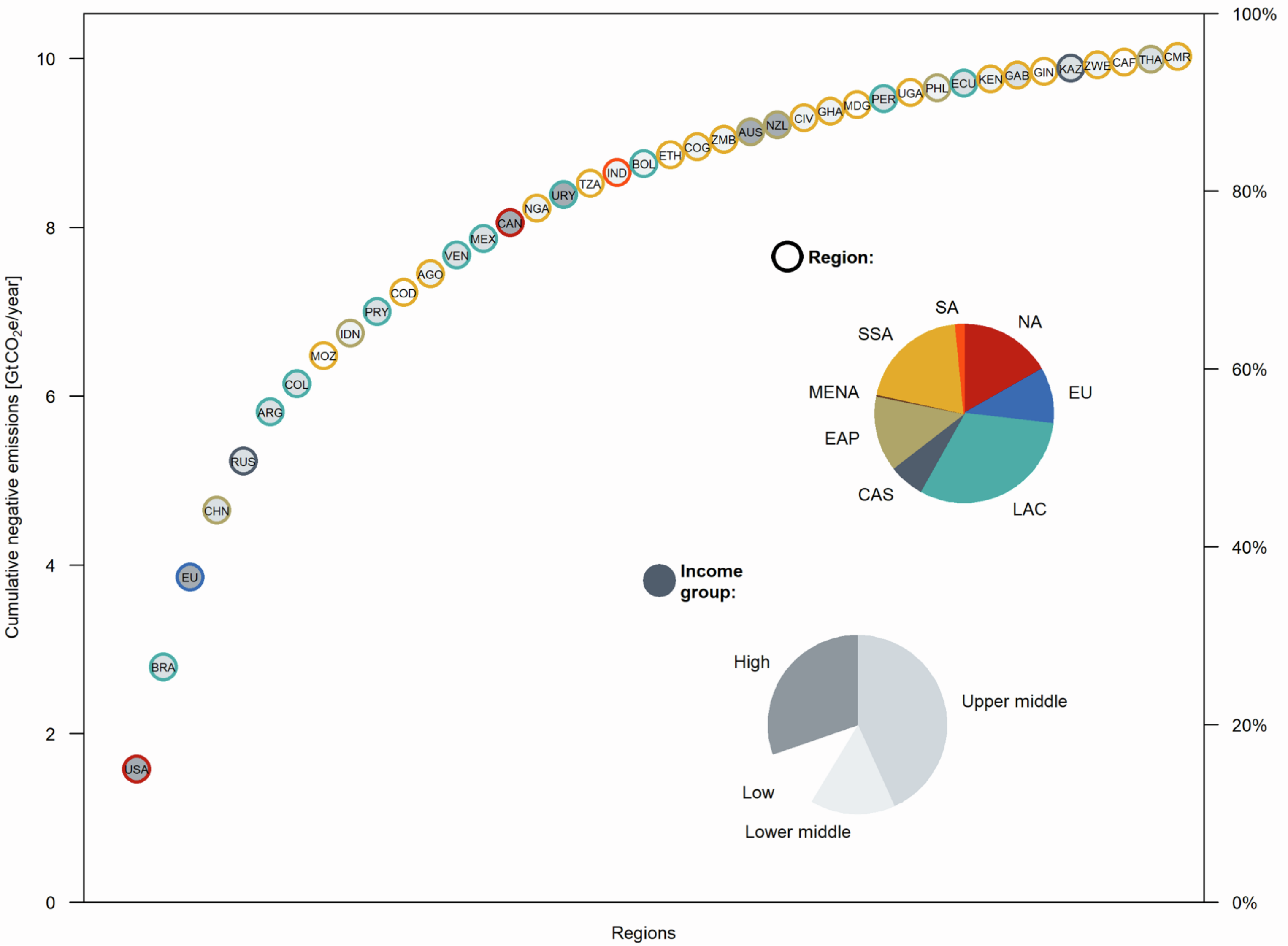


Figure S18. Negative emissions through BECCS hydrogen by country and country group. *Main plot shows cumulative negative emissions of countries (only Europe as a whole) with the highest potentials. Inset plots indicate breakdown by region and income group. The evaluation period is 2030-2100 with 20 years of ramp-up time (Figure 4a). Related to Figure 4.*

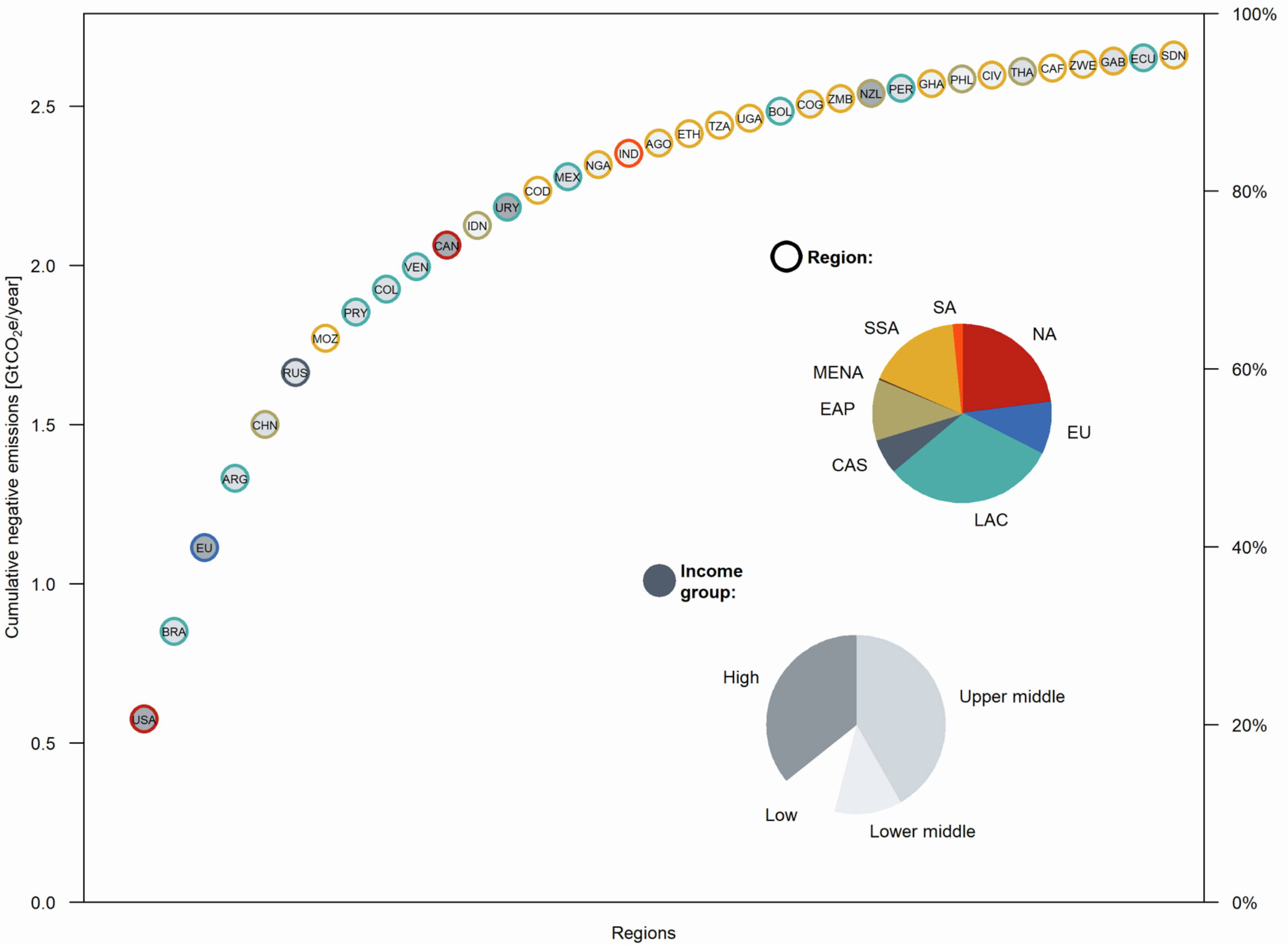


Figure S19. Negative emissions through BECCS FT diesel by country and country group. *Main plot shows cumulative negative emissions of countries (only Europe as a whole) with the highest potentials. Inset plots indicate breakdown by region and income group. The evaluation period is 2030-2100 with 20 years of ramp-up time (Figure 4a). Related to Figure 4.*

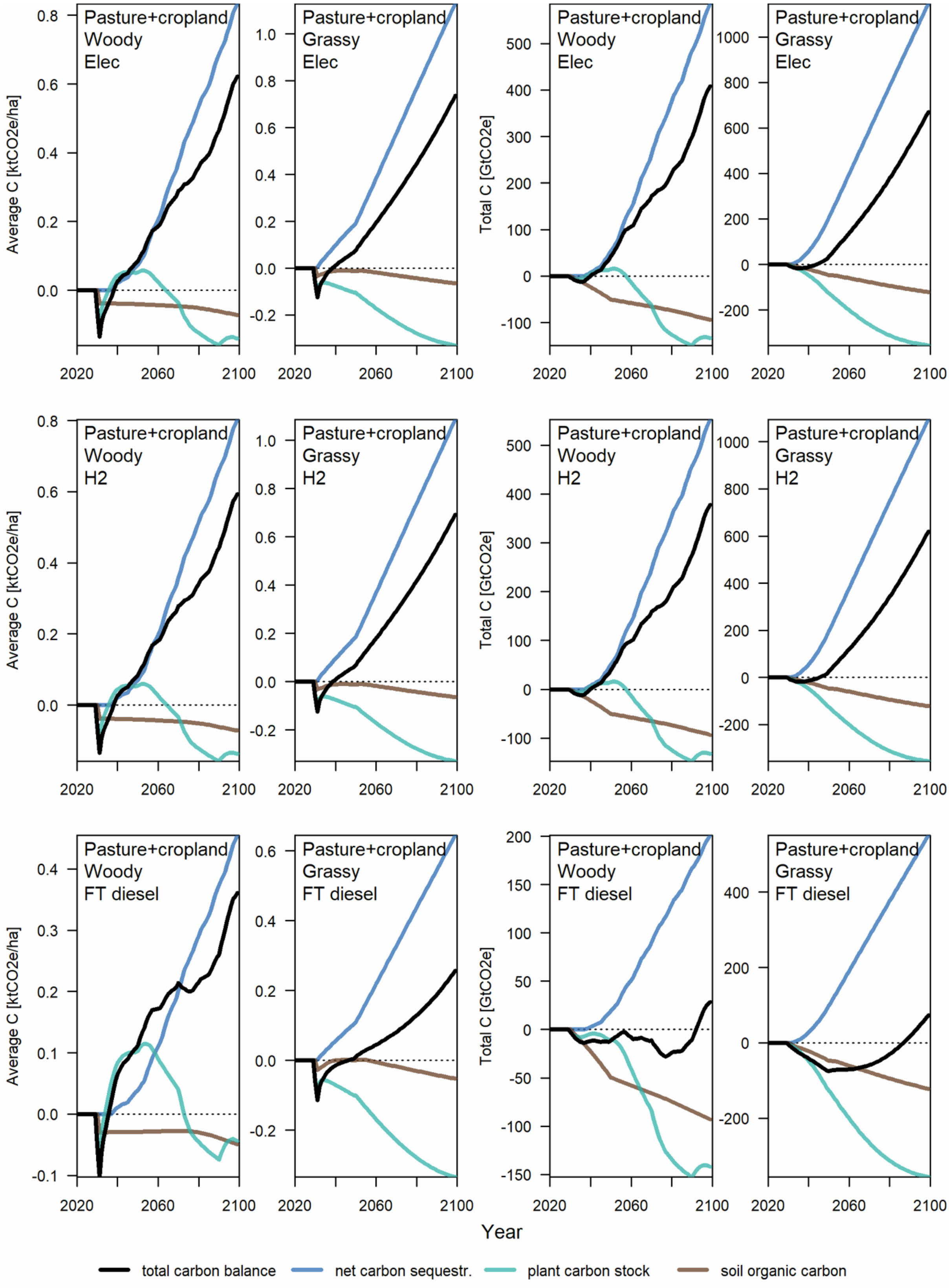


Figure S20. Global carbon balance for all areas in the Replace scenario (pasture and feed cropland). *Average (left half) and total (right half). Total carbon balance represents net negative emissions, equal to the sum of all flows: BECCS net carbon sequestration and plant and soil stocks. Stocks represent BECCS minus natural regrowth stocks (i.e., forgone sequestration). Related to Figure 6.*

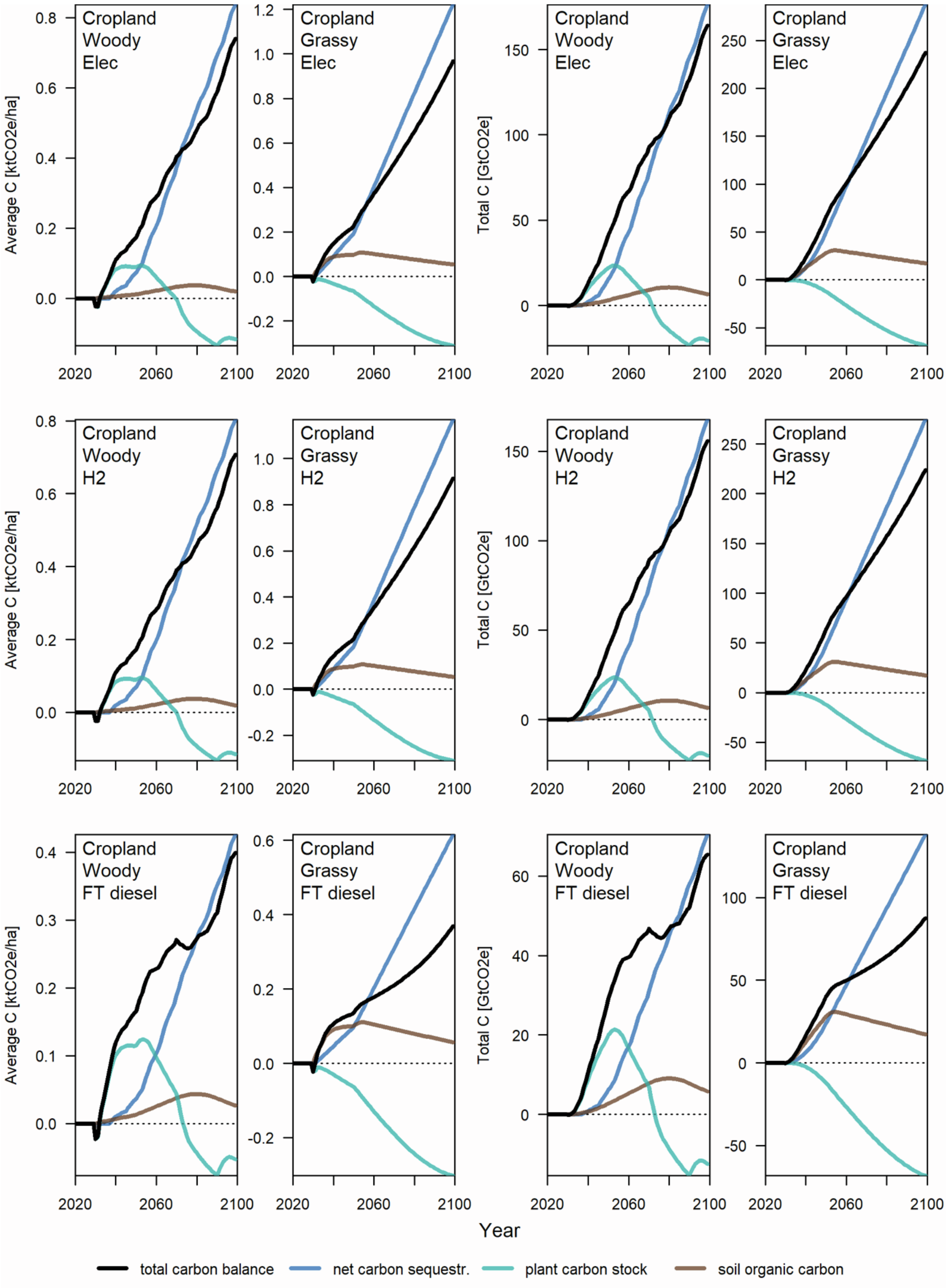


Figure S21. Global carbon balance for feed cropland in the Replace scenario. *Average (left half) and total (right half). Total carbon balance represents net negative emissions, equal to the sum of all flows: BECCS net carbon sequestration and plant and soil stocks. Stocks represent BECCS minus natural regrowth stocks (i.e., forgone sequestration). Related to Figure 6.*

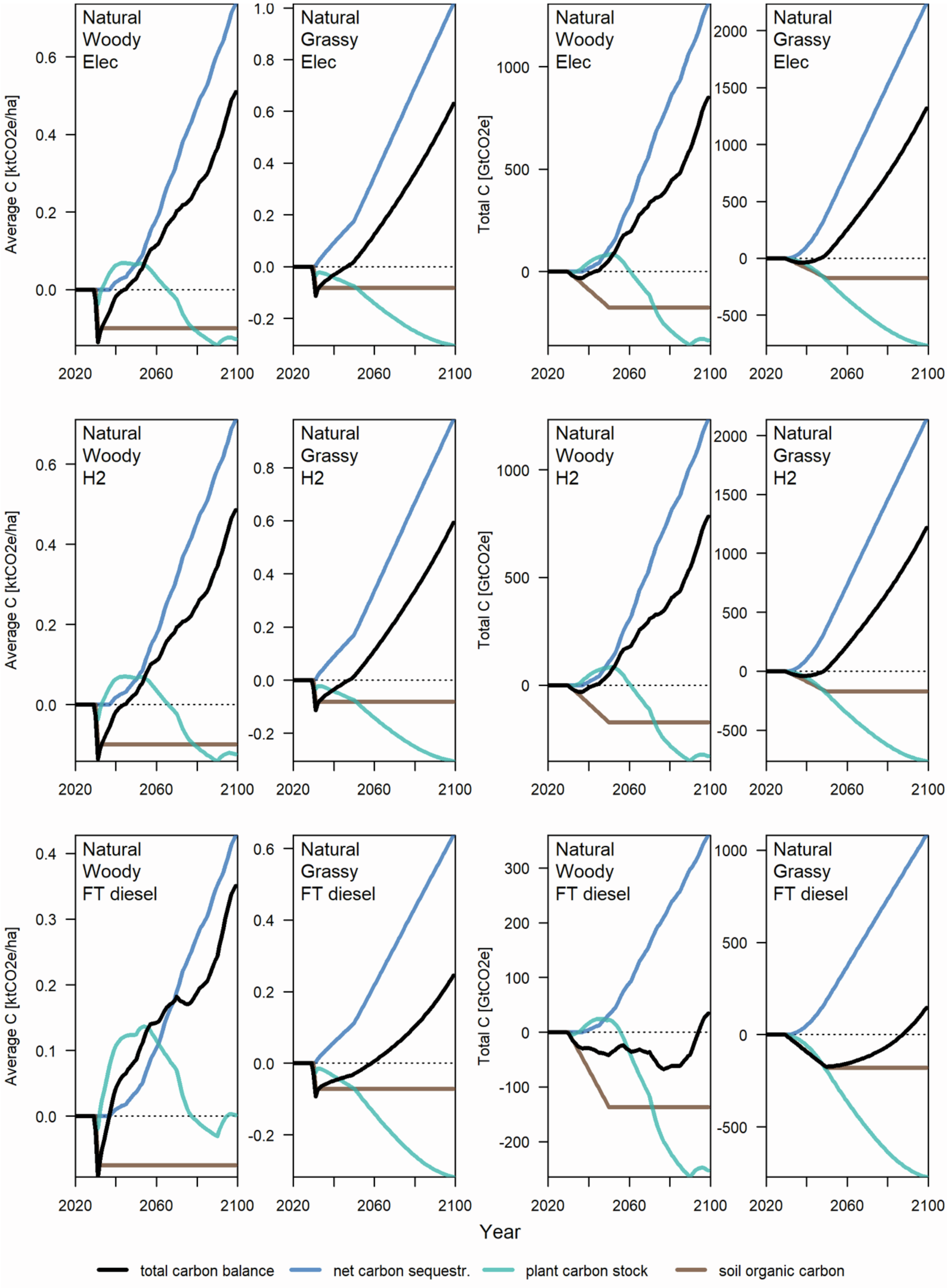


Figure S22. Global carbon balance for all areas in the Expand scenario (natural areas, excluding areas with the highest conservation value). *Average (left half) and total (right half). Total carbon balance represents net negative emissions, equal to the sum of all flows: BECCS net carbon sequestration and plant and soil stocks. Stocks represent BECCS minus natural regrowth stocks (i.e., forgone sequestration). Related to Figure 6.*

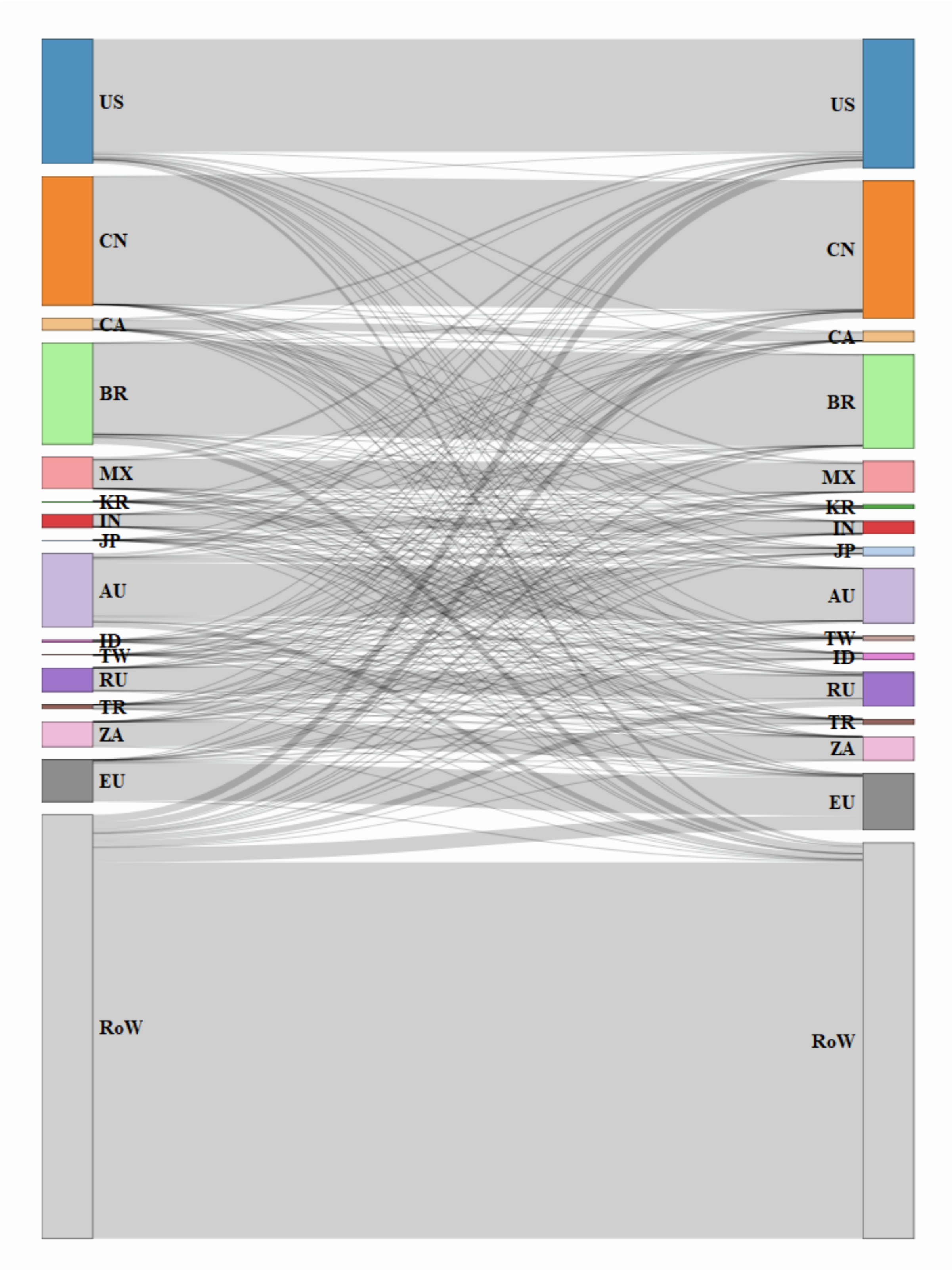


Figure S23. Land-use impacts (pasture and cropland) from the consumption of animal products in different regions. *The left side represents the production and the right side the consumption. RoW stands for Rest of the World. Related to Discussion.*

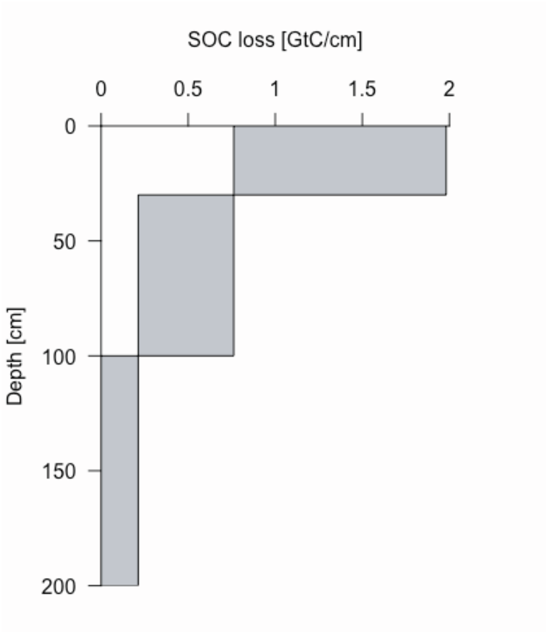


Figure S24. Soil organic carbon (SOC) loss profile. *Related to experimental procedures. Figure modified from reference.*[1]

Supplemental tables

Table S1. Overview of source-sink match potentials in main regions. *Results represent electricity production for the Replace scenario. Source is the CO_2 that could be captured from domestic bioenergy crops. Sink is the storage potential of sedimentary basins. Stored and Not stored represent estimated potentials when only domestic storage is allowed. Related to Figure 3 and Figure S16.*

Code	Region	Source [$MtCO_2$]	Sink [$MtCO_2$]	Sink/Source [-]	Not stored [$MtCO_2$]	Stored [$MtCO_2$]
BRA	Brazil	177,206	231,260	1.3	-	177,206
USA	United States of America	157,660	446,215	2.8	-	157,660
EU	Europe	124,961	210,326	1.7	-	124,961
CHN	China	96,923	264,318	2.7	-	96,923
RUS	Russian Federation	76,188	929,854	12.2	-	76,188
ARG	Argentina	60,266	42,126	0.7	18,140	42,126
MOZ	Mozambique	38,226	93,385	2.4	-	38,226
AGO	Angola	33,685	48,396	1.4	-	33,685
IDN	Indonesia	31,730	121,147	3.8	-	31,730
MEX	Mexico	28,580	148,846	5.2	-	28,580
COL	Colombia	51,344	27,494	0.5	23,851	27,494
VEN	Venezuela	24,575	42,023	1.7	-	24,575
AUS	Australia	23,741	371,223	15.6	-	23,741
NGA	Nigeria	22,775	48,129	2.1	-	22,775
PRY	Paraguay	25,914	17,751	0.7	8,163	17,751
CAN	Canada	16,446	97,576	5.9	-	16,446
BOL	Bolivia	16,036	16,183	1.0	-	16,036
IND	India	15,523	49,767	3.2	-	15,523
KAZ	Kazakhstan	10,328	214,785	20.8	-	10,328
PER	Peru	9,444	50,034	5.3	-	9,444
ECU	Ecuador	7,247	12,896	1.8	-	7,247
COG	Congo	13,067	6,675	0.5	6,392	6,675
GAB	Gabon	6,398	35,431	5.5	-	6,398
ZAF	South Africa	6,075	52,904	8.7	-	6,075
URY	Uruguay	15,079	5,587	0.4	9,492	5,587
PHL	Philippines	6,148	5,510	0.9	638	5,510
SDN	Sudan	6,665	5,465	0.8	1,200	5,465
NZL	New Zealand	10,100	4,988	0.5	5,112	4,988
TZA	Tanzania	17,788	4,012	0.2	13,776	4,012
THA	Thailand	3,404	17,280	5.1	-	3,404
GHA	Ghana	9,694	3,153	0.3	6,541	3,153
GIN	Guinea	7,608	2,694	0.4	4,914	2,694
COD	DR Congo	24,921	2,683	0.1	22,238	2,683
CHL	Chile	2,494	9,205	3.7	-	2,494

Table S2. BECCS parameters for Equations 1–7. *Related to experimental procedures.*

Var.	Units	Value: Electricity[a] Woody	Electricity[a] Grassy	Hydrogen[b,c] Woody	Hydrogen[b,c] Grassy	FT diesel[a] Woody	FT diesel[a] Grassy	Description
η	GJ/tDM	5.8	5.7	6.4	6.3	8.1	8	Biomass to e. carrier conv. Eff.
π	GJ/tDM	1.8		1.8		0		Con. Eff. penalty due to CCS
em_{Fert}	$kgCO_2e/tDM$	55	54	55	54	55	54	Fertilizer emissions
em_{SC}	$kgCO_2e/GJ$	13	16	24.7	27.4	19	18	Supply chain emissions[d]
em_{CCS}	$kgCO_2e/GJ$	11		9.9		3		Add. supply chain em. CCS
κ	-	0.9		0.9		0.52		Carbon capture efficiency
cc	tC/tDM	0.5						Biomass carbon content
f_{loss}	-	0.92						Loss factor

a Most values are based on an extensive literature review, presented in detail in Table S1 from reference [2]
b Biomass to energy carrier conversion efficiency and carbon capture efficiency from reference [3]
c Supply chain emissions consider hydrogen production, purification, and transportation from reference [4]
d Supply chain emissions represent cradle-to-factory-gate for electricity and well-to-tank for hydrogen and FT diesel. Supply chain emissions have large technological and geographical variability. If biomass is sourced domestically, as we propose, estimates may be conservative.

Table S3. Natural regrowth parameters for Equations 8, 9, and 13. *SE is the standard error. Related to experimental procedures.*

	Biome	Vegetation[a]: Slope *a*	Slope SE *ar*	Type	Intercept *b*	Intcp. SE *br*	SOC: Acc. Rate [tCha-1y-1]
1	Trop. & Subtrop. Dry Broadleaf Forests	35.927	1.658	ln	-56.558	7.369	0.4[c]
2	Trop. & Subtrop. Moist Broadleaf Forests	2.200	0.082	linear	28.360	2.818	0.4[c]
3	Temperate Broadleaf & Mixed Forests	1.662	0.093	linear	-0.740	6.520	0.3[d]
4	Temperate Conifer Forests	1.765	0.107	linear	-5.464	6.815	0.3[d]
5	Boreal Forest	23.284	3.261	ln	-35.756	12.633	0.3[d]
6	Trop. & Subtrop. Grass., Sav. & Shrub.	1.668	0.156	linear	0.969	6.997	0.4[c]
7	Temperate Grass., Sav. & Shrub.	0.981	0.094	linear	-8.530	5.749	0.3[d]
8	Mediterr. Forests, Woodlands & Scrub.[b]	1.668	0.156	linear	0.969	6.997	0.2[d]
9	Tropical & Subtropical Conifer Forests[b]	1.765	0.107	linear	-5.464	6.815	0.3[d]

a Data based on reference [5], downloaded on April 20, 2021 from reference [6]
b Vegetation parameters for biomes 8 and 9 are assumed as biomes 6 and 4
c Based on literature review [7]
d Based on literature review [8]

Table S4. Soil organic carbon (SOC) change parameters for Equations 11 and 12. *Avg as % change from native soil, n as number of observations, and t as time to change in years. Related to experimental procedures.*

Transitions to agricultural land (cropland or pasture)[1]

Native forest	Converted to cropland	pasture
Data at 30 cm depth		
Avg	-29.25	-19.75
n	37	13
Data at 100 cm depth		
Avg	-16.7	-10.4
n	13	5

Native grassland	Converted to cropland	pasture
Data at 30 cm depth		
Avg	-27.53	-19.96
n	56	24
Data at 100 cm depth		
Avg	-20.25	-5.25
n	35	3

Transitions to bioenergy crops (woody or grassy)

Native forest	Converted to grassy	woody[9]
Data at 30 cm depth		
Avg	-11.07	-13
n	(calc.)	30
t	1	1

Nat., Mng. grassland	Converted to grassy[10]	woody[9]
Data at 30 cm depth		
Avg	-10.90	-10
n	(43 studies)	83
t	1	1

Cropland	Converted to grassy[10]	woody[9]
Data at 30 cm depth		
Avg	25.7	18
n	(63 studies)	29
t	6	40

Supplemental references

1. Sanderman, J., Hengl, T., and Fiske, G.J. (2017). Soil carbon debt of 12,000 years of human land use. Proceedings of the National Academy of Sciences of the United States of America *114,* 9575–9580.
2. Hanssen, S.V., Daioglou, V., Steinmann, Z.J.N., Doelman, J.C., van Vuuren, D.P., and Huijbregts, M.A.J. (2020). The climate change mitigation potential of bioenergy with carbon capture and storage. Nature Climate Change *10,* 1023–1029.
3. Bui, M., Di Zhang, Fajardy, M., and Mac Dowell, N. (2021). Delivering carbon negative electricity, heat and hydrogen with BECCS – Comparing the options. International Journal of Hydrogen Energy *46,* 15298–15321.
4. Li, G., Cui, P., Wang, Y., Liu, Z., Zhu, Z., and Yang, S. (2020). Life cycle energy consumption and GHG emissions of biomass-to-hydrogen process in comparison with coal-to-hydrogen process. Energy *191,* 116588.
5. Cook-Patton, S.C., Leavitt, S.M., Gibbs, D., Harris, N.L., Lister, K., Anderson-Teixeira, K.J., Briggs, R.D., Chazdon, R.L., Crowther, T.W., and Ellis, P.W., et al. (2020). Mapping carbon accumulation potential from global natural forest regrowth. Nature *585,* 545–550.
6. Cook-Patton, S.C., Leavitt, S.M., Gibbs, D., Harris, N.L., Lister, K., Anderson-Teixeira, K.J., Briggs, R.D., Chazdon, R.L., Crowther, T.W., Ellis, P.W., Griscom, H.P., Herrmann, V., Holl, K.D., Houghton, R.A., Larrosa, C., Lomax, G., Lucas, R., Madsen, P., Malhi, Y., Paquette, A., Parker, J.D., Paul, K., Routh, D., Roxburgh, S., Saatchi, S., van den Hoogen, J., Walker, W.S., Wheeler, C.E., Wood, S.A., Xu, L. and Griscom, B.W. Biome rates from publication on "Mapping carbon accumulation potential from global natural forest regrowth", https://tnc.app.box.com/s/togss3bk7fsavgqavfmh5a471o8s69hv.
7. Silver, W.L., Ostertag, R., and Lugo, A.E. (2000). The Potential for Carbon Sequestration Through Reforestation of Abandoned Tropical Agricultural and Pasture Lands. Restor Ecology *8,* 394–407.
8. Post, W.M., and Kwon, K.C. (2000). Soil carbon sequestration and land-use change: processes and potential. Global change biology *6,* 317–327.
9. Guo, L.B., and Gifford, R.M. (2002). Soil carbon stocks and land use change: a meta analysis. Glob Change Biol *8,* 345–360.
10. Harris, Z.M., Spake, R., and Taylor, G. (2015). Land use change to bioenergy: A meta-analysis of soil carbon and GHG emissions. Biomass and Bioenergy *82,* 27–39.