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The climate change mitigation potential of bioenergy with carbon capture and storage

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Bioenergy with carbon capture and storage (BECCS) can act as a negative emission technology and is considered crucial in many climate change mitigation pathways that limit global warming to 1.5–2 °C; however, the negative emission potential of BECCS has not been rigorously assessed. Here we perform a global spatially explicit analysis of life-cycle GHG emissions for lignocellulosic crop-based BECCS. We show that negative emissions greatly depend on biomass cultivation location, treatment of original vegetation, the final energy carrier produced and the evaluation period considered. We find a global potential of 28 EJ per year for electricity with negative emissions, sequestering 2.5 $GtCO_2$ per year when accounting emissions over 30 years, which increases to 220 EJ per year and 40 $GtCO_2$ per year over 80 years. We show that BECCS sequestration projected in IPCC SR1.5 °C pathways can be approached biophysically; however, considering its potentially very large land requirements, we suggest substantially limited and earlier deployment.

Most climate change mitigations pathways that limit global warming to 1.5 °C or 2 °C rely on negative emission technologies, in particular bioenergy with carbon capture and storage (BECCS)[1–7], which has the benefit of combining the energy generation based on existing technologies with the geological storage of sequestered atmospheric carbon[8–10].

However, concerns have been raised on the biophysical feasibility, environmental effects and biodiversity impacts of large-scale BECCS deployment, which stem from its intensive land, water and nutrient use[5,10–15]. Moreover, BECCS cost estimates vary widely[5,16] and BECCS implementation may prove to be socio-politically difficult[17], among other issues due to the challenge of accounting and rewarding negative emissions[18–20].

Given that BECCS is considered a crucial technology in many mitigation pathways, but also has major drawbacks, it is essential to assess its effectiveness as a climate change mitigation strategy. Two previous studies report that BECCS electricity can result in both net-negative and -positive GHG emissions, mainly depending on the required land-use change (LUC) and the efficiency of the bioenergy supply chain[21,22]. Earlier work stresses that the climate change mitigation potential of bioenergy is highly dependent on biomass cultivation location and conversion technology[22–24], and that bioenergy crop yields may not suffice to achieve ambitious carbon sequestration targets via BECCS[15]. However, spatially explicit GHG emissions for bioelectricity and liquid biofuels with CCS have not been estimated yet, despite being essential in evaluating the contribution of BECCS in mitigation pathways.

Emission factors (EFs) express the amount of GHG emissions per unit bioenergy produced. Here we quantified spatially explicit EFs and determined the global potential supply of BECCS at increasing EF levels, producing so-called emission–supply curves. Emission factors and supply potentials were calculated using the global vegetation model, LPJml, which was combined with full life-cycle GHG emission data. The EFs include emissions from LUC, the lost carbon sequestration capacity of natural vegetation (foregone sequestration), bioenergy supply chain emissions including fertilizers and CO_2 sequestered through CCS over a set evaluation period. Agricultural areas (cropland and pastures), including projected additional land requirements, are excluded from our analysis, as employing them could lead to indirect land-use change (iLUC) effects[25,26] or threaten food security[27–29]. We assessed bioelectricity and liquid biofuels (Fischer–Tropsch (FT) diesel and bioethanol) produced with CCS, and considered lignocellulosic biomass from fast-growing grasses (*Miscanthus* and switchgrass) and woody bioenergy crops (short-rotation poplar, willow and *Eucalyptus*), as well as sugarcane (for bioethanol only), with all crops being rainfed. We used a 30-year evaluation period that reflects typical plantation lifetimes and short- to medium-term mitigation without carbon budget overshoot, as well as an 80-year evaluation period that corresponds with mitigation pathways towards 2100. Biomass present before plantation establishment (initial biomass) was assumed to be burned, consistent with previous analyses[23,24,30], but we also quantified EFs and energy supply potential under the assumption that initial biomass is used to produce bioenergy or biomaterials. Our emission–supply curves provide new insights into the amount of BECCS energy that can be produced with negative emissions or with EFs below those of alternative energy generation, allowing evaluation of BECCS's climate change mitigation potential.

Bioelectricity

For a 30-year evaluation period, the global lignocellulosic crop-based BECCS electricity potential with negative emissions is 28 EJ_{elec} per year (Fig. 1a), which equals around 32% of the current global electricity production[31] and would entail net sequestration of 2.5 $GtCO_2e$ per year (Supplementary Table 5) based on a 90% carbon capture rate (Supplementary Table 1). At EFs above zero, BECCS electricity does not result in net-negative emissions, but GHG emissions would be reduced when replacing electricity

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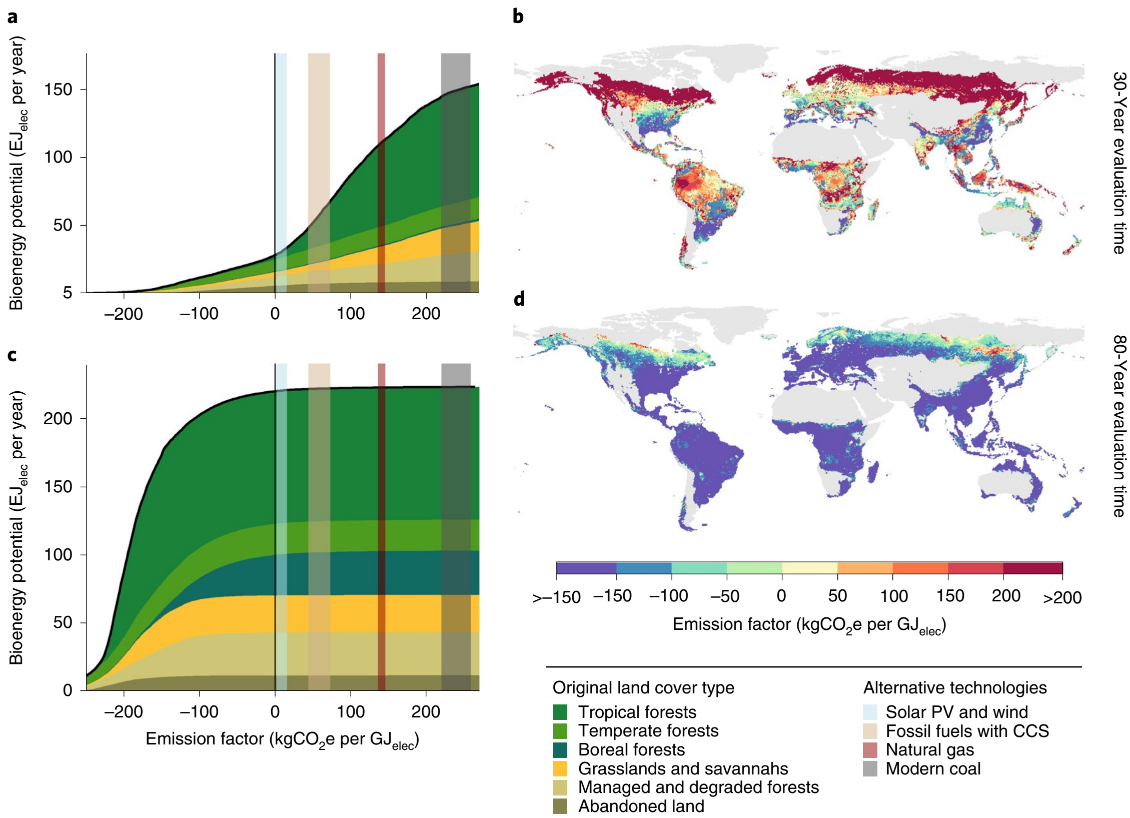

Fig. 1 | Global emission–supply curve and emission factor map of bioelectricity with CCS. a, An emission–supply curve of bioelectricity with CCS over a 30-year evaluation period (black solid line), split over different original land cover types (coloured areas) and excluding agricultural land. Shaded columns indicate EF ranges for alternative electricity generation technologies[55,56]. **b**, An emission factor map of bioelectricity with CCS over a 30-year evaluation period. **c**,**d**, An emission–supply curve (**c**) and emission factor map (**d**) of bioelectricity with CCS over an 80-year evaluation period.

generation technologies with higher EFs. Bioenergy with carbon capture and storage electricity typically achieves lower EFs on agricultural lands that are abandoned or are projected to be abandoned (abandoned lands), but electricity supply potential with negative EFs on these abandoned lands is limited to around 6 EJ_{elec} per year. Emission factors are usually higher on natural forest and grasslands, and on managed and degraded forests that have recently been logged or burnt and are regrowing (managed and degraded forests; see Methods). Net-negative EFs are furthermore typically achieved in subtropical and warmer temperate areas (Fig. 1b), which often sustain high yields (Supplementary Fig. 1) but do not have the large carbon stocks and the associated initial LUC emissions of natural tropical and boreal forests. In large parts of the globe, however, purpose-grown biomass use for BECCS electricity would result in (considerable) positive EFs over this 30-year evaluation period, stressing that BECCS's mitigation potential is highly dependent on the location of biomass cultivation. The geographical pattern we observe is in line with earlier geospatially explicit results on biofuels without CCS[23,24], although Elshout and colleagues[23] do deem boreal areas suitable on the basis of more optimistic estimates of both high crop yields and limited soil carbon losses in these regions.

Longer evaluation periods lead to substantially higher BECCS energy potential at low EFs (Fig. 1c, Supplementary Fig. 8), predominantly as initial LUC emissions are amortized over longer periods, and to a lesser extent due to projected yield increases and levelling off of foregone carbon sequestration in the natural vegetation benchmark scenario. At an 80-year evaluation period (2020–2100), almost the entire global BECCS electricity potential (that is, 220 EJ_{elec} per year) has EFs below zero (Fig. 1d), which entails a large sequestration potential (40 $GtCO_2e$ per year; Supplementary Table 5). The increase in the BECCS's electricity supply potential is predominantly realized on natural forest and grasslands. On abandoned lands and on managed and degraded forests, the electricity supply potential with negative emissions is limited to 12 and 31 EJ_{elec} per year, respectively. Care should be taken when drawing conclusions based on longer evaluation periods, as BECCS capacity that is installed later in the century may only achieve net-negative emissions beyond the target year 2100. The results shown here represent lignocellulosic crops in general (grass and woody crop-specific results are provided in Supplementary Figs. 5–7). Furthermore, we also investigated a shorter, 20-year evaluation period, which reduces electricity potentials by about 60% compared to 30-year evaluation period results (Supplementary Fig. 9).

Liquid biofuels

Lignocellulosic FT-diesel with CCS has the highest energy and sequestration potentials of the investigated liquid biofuel routes; however, over a 30-year evaluation period, the FT-diesel supply with negative emissions is minimal (Fig. 2a, Supplementary Table 5). As there is substantial supply potential at EFs below those of fossil diesel (67 EJ_{fuel} per year), replacing the entire current global diesel consumption of 60 EJ_{fuel} per year (including gas oil)[32] could theoretically result in GHG emission savings of approximately 5.5 $GtCO_2e$ per year, although this is not the same as net sequestration. Savings could also be achieved if FT-diesel and FT-synthetic kerosene[33] are used to replace fossil shipping and aviation fuels. At an 80-year evaluation period, the global supply potential of

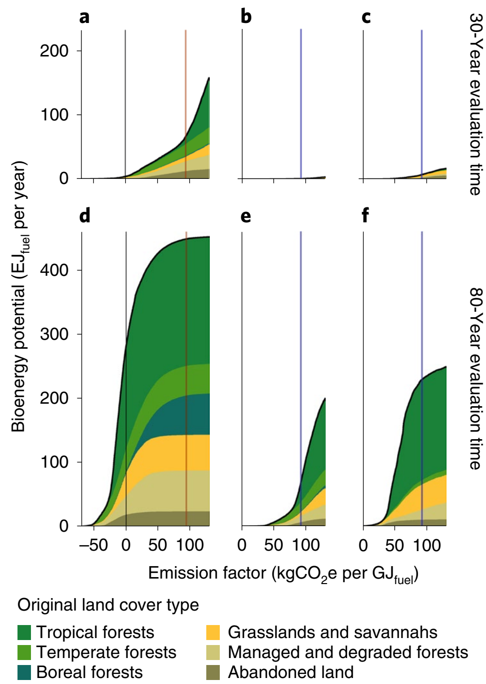

Fig. 2 | Global emission–supply curves of liquid biofuels with CCS. **a**–**c**, Global emission–supply curves of lignocellulosic FT-diesel (**a**), lignocellulosic ethanol (**b**) and sugarcane ethanol (**c**), all with CCS, over a 30-year evaluation period. **d**–**f**, The corresponding global emission–supply curves of these liquid biofuels with CCS over an 80-year evaluation period. The orange and blue lines indicate the EFs of fossil diesel (94 kgCO_2e per GJ_{fuel}) and petrol (92 kgCO_2e per GJ_{fuel})[57], respectively. Note that electricity, FT-diesel and bioethanol potentials cannot be summed, as they are based on overlapping locations.

lignocellulosic FT-diesel with negative emissions is large (282 EJ_{fuel} per year; Fig. 2d), but the resulting global net sequestration potential of 4.8 GtCO_2e per year is about eight-times lower than for BECCS electricity over the same evaluation period (Supplementary Table 5), predominantly due to FT-diesel's lower carbon capture rate of 52% (Supplementary Table 1). The relative geographic and crop-specific patterns for EFs of FT-diesel with CCS are, however, similar to those of BECCS electricity for both evaluation periods (Supplementary Figs. 6 and 10). Over both a 30- and 80-year evaluation period, the bioethanol pathways with CCS do not result in net-negative emissions (Fig. 2b–f). This is primarily due to their low carbon capture rates (12 and 24% for lignocellulosic and sugarcane ethanol, respectively, see Methods and Supplementary Table 1).

Initial biomass

In line with previous work[23,24], we conservatively assumed that the original vegetation is burned when a bioenergy crop plantation is established, releasing all carbon in the initial biomass to the atmosphere as CO_2; however, part of this initial biomass could also be used to produce bioenergy (Fig. 3a). Using initial biomass for bioenergy increases overall BE(CCS) energy potential and sequestration (as also suggested by Harper and colleagues[22]), and decreases EFs as emissions are allocated over more energy generated. If 80% (ref. [34]) of all initial stem biomass is used and 90% of its carbon content is captured, BECCS electricity potential becomes approximately 4.5 times larger at EFs below zero, increasing from 28 to 125 EJ_{elec} per year over a 30-year evaluation period (Fig. 3b). Carbon sequestration increases from 2.5 to 5.9 GtCO_2e per year (Supplementary Table 5).

Alternatively, the initial biomass can be used in other sectors to create more valuable products such as timber and paper[34]. In this scenario, part of the initial carbon is stored in these products and allocated to them when it is ultimately emitted. Under this assumption, initial LUC emissions of BE(CCS) are lower, thus lowering EFs. If 80% of initial stem biomass is used in other sectors, the potential of BECCS electricity increases from 28 to 129 EJ_{elec} per year at EFs below zero (Fig. 3c) and sequestration increases sharply from 2.5 to 11 GtCO_2e per year (Supplementary Table 5).

It is evidently better to use initial biomass for energy or materials rather than burning it, as is also reflected by the lower EFs in both cases; however, the increased energy and sequestration potential of BECCS at negative EFs would also come from converting additional natural forests and savannahs, which have substantial initial stem biomass. At longer evaluation periods, the influence of using initial biomass for bioenergy or other products is limited (Supplementary Fig. 11), as emissions from initial biomass are amortized over longer time periods and have a smaller effect on EFs. Patterns for FT-diesel with CCS are similar to those of bioelectricity with CCS (Supplementary Fig. 12).

BECCS in mitigation pathways

We used our spatially explicit EFs and energy and sequestration potentials for BECCS to analyse global carbon sequestration until 2100 following the phased deployment of BECCS in two illustrative mitigation pathways of the IPCC SR1.5 °C report: the S2 middle-of-the-road pathway and the S5 fossil fuel and BECCS-intensive pathway[7,35] (see Methods). In our analysis, we deployed land starting with the best locations (lowest EFs; excluding agricultural land) and we matched prescribed BECCS deployment rates either in terms of pathway-prescribed energy generation or pathway-required sequestration. We used a dynamic evaluation period up until 2100 for the installed BECCS capacity (for example, a 40-year evaluation period for capacity installed in 2060) and assumed that the initial vegetation is burned.

As we determine EFs from a full life-cycle perspective and include foregone sequestration, we typically find less carbon sequestration per unit BECCS energy than in mitigation pathways. Following energy-based BECCS deployment rates thus resulted in lower carbon sequestration than projected in the pathways (Fig. 4a). Following pathway-required annual sequestration, BECCS electricity from lignocellulosic crops only can keep up net sequestration until the year 2066 for S2 and the year 2050 for S5 (Fig. 4a), after which additional land conversion does not provide negative emissions over the remaining period to 2100. When first deploying all biomass residues that are available for energy (based on IMAGE shared socio-economic pathway 2 (SSP2), see Methods) to BECCS before using lignocellulosic crops, these points are postponed to the year 2076 and 2058 for S2 and S5 (Fig. 4a).

Over the century, the estimated sequestration that could be achieved using lignocellulosic crops alone (250 and 1,008 Gt for S2 and S5) is 61–84% of total projected sequestration (408 and 1,207 Gt for S2 and S5; Fig. 4b). This is in line with an earlier, crop yield-based exploration of BECCS' global sequestration potential, which found that 59% of the sequestration required in a limited global warming scenario (representative concentration pathway 2.6) may be achieved[15]. When also including biomass residues, we find that projected sequestration is approached to 88–94%, but not fully achieved (360 and 1,132 Gt for S2 and S5; Fig. 4b). In this estimate 0.8 to 2.4 Gha of land is required by 2100 to grow crops for BECCS (for S2 and S5 respectively), which equals 5.1% and 16% of the total land surface area on Earth and of which 53% and 72% are currently natural forests and grasslands. It is important to note that these extreme levels of land demand partly arise due to the time profile of, in particular, the S2 pathway, and from our assumption to use residues before crops. The cumulative sequestration these

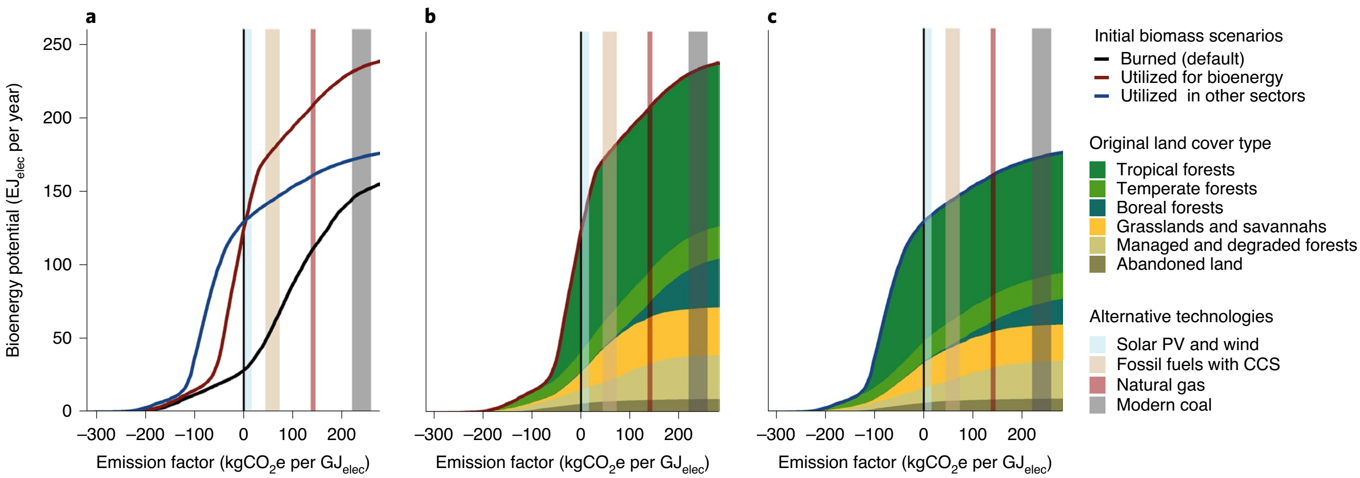

Fig. 3 | Global emission–supply curves of BECCS electricity with different initial biomass use scenarios over a 30-year evaluation period. a, An overview of emission–supply curves for three initial biomass scenarios. **b**, An emission–supply curve of BECCS electricity, with 80% of the initial stem biomass used to produce additional BECCS electricity (red solid line), split over different original land cover types. **c**, An emission–supply curve of BECCS electricity with 80% of initial stem biomass used in other sectors (blue solid line). Shaded columns indicate EF ranges for alternative electricity generation technologies[55,56].

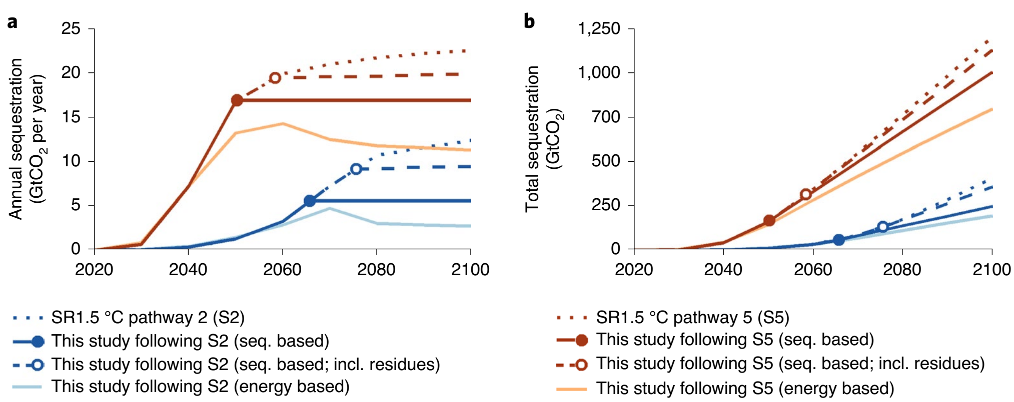

Fig. 4 | Carbon sequestration potential of BECCS electricity in climate change mitigation pathways. Carbon sequestration refers to negative emissions. **a**, Annual sequestration through BECCS electricity. **b**, Total (cumulative) sequestration through BECCS electricity. Dots indicate the point at which pathway-prescribed sequestration can no longer be kept up with, as additional land conversion no longer results in negative emissions over the remaining (evaluation) time until 2100. seq., sequestration; incl., including.

pathways demand by 2100 could biophysically be achieved with lower land requirements if deployment of crop-based BECCS starts even earlier on, as indicated by the importance of evaluation periods in our analysis (see Supplementary Fig. 8). In any scenario, sequestration potential is drastically increased when deploying BECCS earlier, as also suggested in earlier work[36].

Sensitivities and limitations

Figure 5 shows how emission–supply curves of BECCS electricity are influenced by three key parameters. First, keeping bioenergy crop yields constant at their 2020 values decreases BECCS electricity supply potential at negative EFs by 25–32%, whereas enhanced yield improvement (that is, global improvement of agricultural management to current best practice, representing SSP1) increases it by 6–11% (Fig. 5a,e). Second, in line with previous studies[21,22], BECCS electricity supply potential is sensitive to electricity conversion efficiency: a literature-based 5–7% change in conversion efficiency (Supplementary Table 1) changes supply potential with negative emissions by 6–8% (Fig. 5b,f). Carbon sequestration potential is, however, unaffected as the carbon capture rate is not influenced by conversion efficiency. Third, more arable lands become available for bioenergy if less land is required for conventional agriculture. Following the SSP1 scenario (with a smaller population and low meat diet, see Methods), BECCS electricity potential at EFs below zero increases by 21–93% (Fig. 5c,g). When all three parameters are combined into a best- and worst-case scenario, BECCS energy potential at negative EFs approximately doubles or halves from the default (Fig. 5d,h). These patterns are similar for lignocellulosic FT-diesel (Supplementary Fig. 13). Our results are less sensitive to variation in other parameters. Doubling supply chain emissions, for instance, only resulted in a 1–5% reduction of BECCS electricity supply potential at negative EFs (Supplementary Fig. 14), although liquid biofuel EFs are more strongly affected (Supplementary Fig. 15).

There are several possible limitations to the biophysical climate change mitigation potential of BECCS. First, our analysis focuses on high-yielding lignocellulosic bioenergy crops and sugarcane. In the boreal forest region, however, yields would typically be low and natural carbon stock losses high, meaning that lower EFs may be

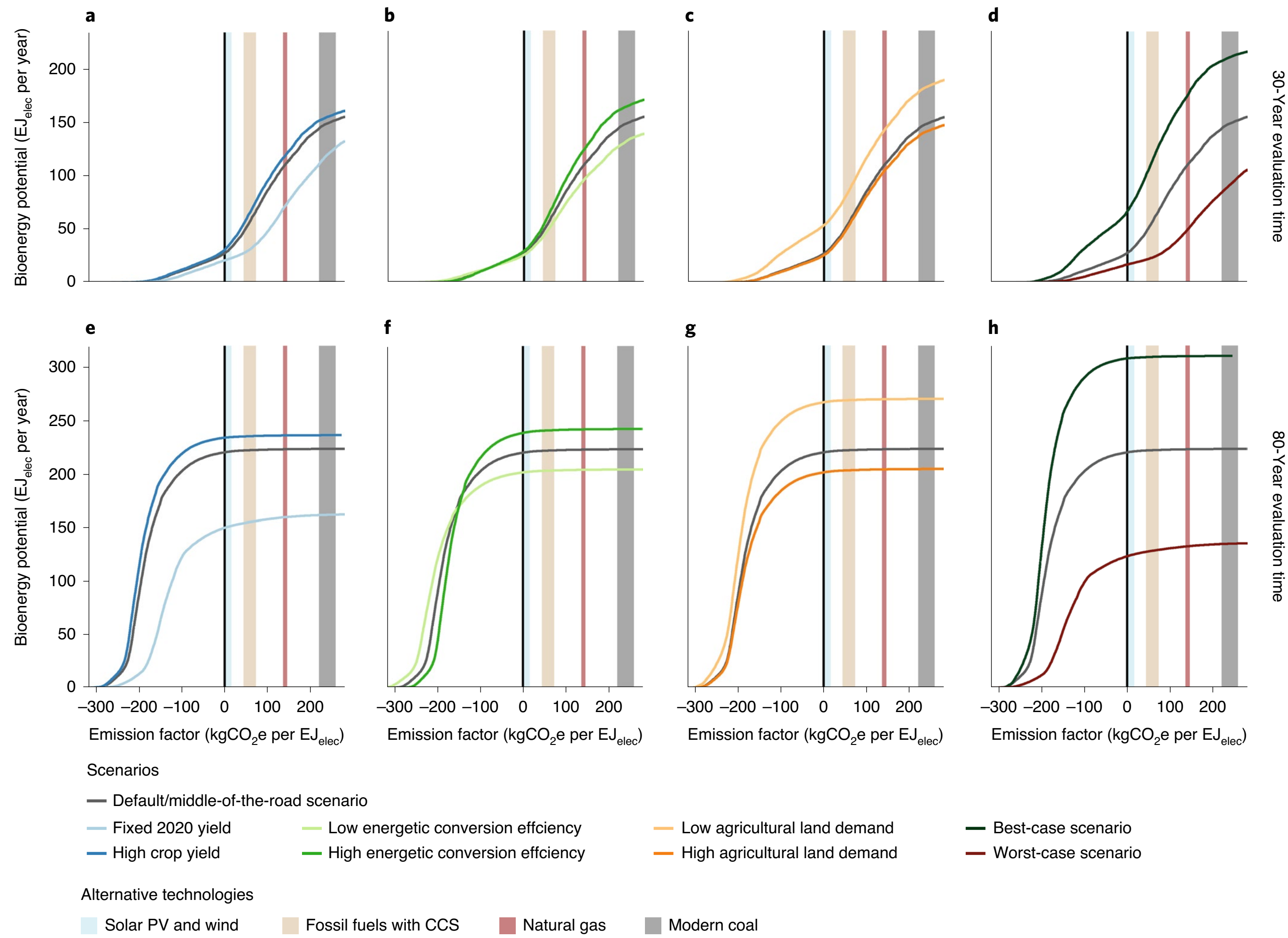

Fig. 5 | Sensitivity of BECCS electricity emission–supply curves to parameterization. The default emission–supply curve is plotted in grey in all panels. **a**, Emission–supply curves at constant 2020 crop yields (light blue) and high SSP1 crop yields (dark blue). **b**, Emission–supply curves for low (light green) and high (dark green) biomass to energy carrier conversion efficiencies (based on literature, Supplementary Table 1). **c**, Emission–supply curves for scenarios with low (yellow) and high (orange) agricultural land requirements (based on SSP1 and SSP3 in IMAGE; default is SSP2). **d**, Emission–supply curves for a best-case (green) and worst-case (red) scenario. **e**–**h**, These same emission–supply curves for an evaluation period of 80 years rather than 30 years. Shaded columns indicate EF ranges for alternative electricity generation technologies[55,56].

achieved by sourcing biomass from sustainably managed forests, if their carbon stocks are maintained[37,38]. Under such boreal continuous cover forestry, we find that electricity supply potential with negative emissions increases by 2.5 EJ per year over a 30-year evaluation period, but decreases over longer evaluation periods, as yields are lower than for lignocellulosic crops (Supplementary Figs. 16 and 17). Continuous cover forestry would, on the other hand, have key benefits in terms of biodiversity conservation and ecosystem services[37–39]. Second, we excluded projected agricultural areas (cropland and pastures) to avoid iLUC effects, but conversion of managed forests could also lead to iLUC emissions, as forestry products like timber and paper are partly sourced from such forests. Third, biomass yields in the LPJml model are not explicitly influenced by soil quality parameters. However, yields are calibrated (see Methods) and we found that over 99% of the BECCS electricity potential with negative emissions is derived from areas with soils that are classified as moderately or highly suitable for rainfed crop cultivation over the continuous period 2011–2100[40]. Finally, albedo reduction could lower mitigation, which is not accounted for in our calculations. Changes in albedo are typically limited though for grasses and coppiced trees (approximately 5% maximum reduction)[5].

Implications

We conclude that the climate change mitigation potential of lignocellulosic crop-based BECCS is largest when producing electricity at locations with high biomass yields and relatively low carbon stocks (that is, abandoned lands and typically warmer temperate and subtropical areas) while utilizing the original vegetation for bioenergy or materials. We found that the EFs derived for BECCS are crucially dependent on the evaluation period considered, as they account for LUC emissions and foregone sequestration. Our global emission–supply curves and EF maps show that, biophysically, many cultivation locations could supply electricity with negative EFs, leading to a large global electricity supply and carbon sequestration potential of 28 EJ_{elec} and 2.5 Gt per year over 30 years, 220 EJ_{elec} and 40 $GtCO_2e$ per year over 80 years, and 129 EJ_{elec} and 11 $GtCO_2e$ per year over 30 years when utilizing initial biomass. The sequestration potential of liquid biofuels with CCS is limited, although BECCS FT-diesel can lead to negative emissions over an 80-year evaluation period and replacing GHG-intensive fossil transport fuels greatly reduces emissions.

Using our global emission–supply curves, we showed that the projected trajectory of BECCS-based sequestration in mitigation pathways S2 and S5[7] can biophysically be approached (88–94%) but not fully achieved as residues and arable land with negative emissions become depleted. Part of the reason for this is that S2 in particular deploys BECCS later in the century and that biomass residues are used first, which leads to shorter evaluation periods up to 2100 for crop-based BECCS and therefore larger land requirements. This highlights that crop-based BECCS should be deployed early on to most effectively contribute to climate change mitigation; still, the land requirements for BECCS to achieve the cumulative amount of carbon sequestration projected in these pathways would probably be large to the point of being unfeasible, as also suggested in bottom-up assessments of BECCS's sequestration potential[41].

Depending on the exact scenario, around 50–90% of the land area required, carbon sequestered and energy supplied would come from natural forests and grasslands. As land conversion to BECCS strongly reduces biodiversity[42], trade-offs clearly exist between BECCS's climate change mitigating effect and biodiversity conservation[13,14,43]. The mitigation potential of BECCS is further reduced by other environmental[5,10–12] and socio-political[17–20] constraints, limitations to the amount of developed geologic storage sites[44–47], and the challenge of upscaling BECCS by orders of magnitude from its current demonstration phase[46,48–50].

Yet, BECCS may play an important role in mitigating climate change and the energy transition, alongside renewables, other negative emission technologies[16] and deep-emission reduction[6,51]. Residues[52] and waste flows[53] form low-impact feedstocks for BECCS with little effect on land-use. Lignocellulosic crop-based BECCS could also be deployed on abandoned agricultural lands[47]. Biodiversity and other environmental impacts of BECCS could be reduced using locally optimal crops[54] and supply chain configurations[12]. In all cases, our results indicate that earlier deployment of BECCS greatly increases its climate change mitigation potential, and suggest that policymakers ought to complement BECCS with other options for GHG emission reduction and carbon dioxide removal.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, Supplementary Information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-020-0885-y.

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Methods

Calculations. The GHG EFs for feedstock i (fast-growing grasses/short-rotation coppicing/sugarcane), carrier j (electricity/FT-diesel/ethanol), evaluation period t (20–80 years) and location x (66,663 land cells; 30×30 arcminute raster) were calculated as the sum of GHG emissions minus sequestration per unit energy carrier produced (in tCO_2e per $GJ_{carrier}$; equation (1)).

$$EF_{i,j,t,x} = Em_{LUC,i,j,t,x} + Em_{Fertilizer,i,j,x} + Em_{Supply\ chain,i,j} - Seq_{CCS,i,j} \quad (1)$$

Land-use change emissions (Em_{LUC}) were calculated as the difference in carbon stocks between the bioenergy plantation and a natural vegetation regrowth benchmark at the end of the considered evaluation period (that is, including foregone sequestration) divided by energy carrier production over the evaluation period (equation (2)). Fertilizer N_2O emissions ($Em_{Fertilizer}$) were obtained by converting crop-specific fertilizer emissions to emissions per carrier produced (equation (3)). Life-cycle supply chain emissions for the production of the energy carrier, including CH_4 ($Em_{Supply\ chain}$) were based on the literature (Supplementary Table 1). Net CO_2 sequestration from CCS (Seq_{CCS}) was calculated as the captured amount of carbon per carrier produced minus additional supply chain emissions of CCS per carrier produced (equation (4)).

$$Em_{LUC,i,j,t,x} = \frac{\Delta C_{i,t,x} \times r}{Y_{i,t,x} \times t \times f_{loss} \times \left(\eta_{i,j} - \pi_{i,j}\right)} \quad (2)$$

$$Em_{Fertilizer,i,j,x} = \frac{Em_{Fertilizer,x}}{\left(\eta_{i,j} - \pi_{i,j}\right)} \quad (3)$$

$$Seq_{CCS,i,j} = \frac{f_{loss} \times cc_i \times r \times \kappa_{i,j}}{\left(\eta_{i,j} - \pi_{i,j}\right)} - Em_{Supply\ chain\ CCS,j} \quad (4)$$

Where ΔC is the difference in above- and below-ground carbon stocks (tonne C per hectare) between the bioenergy plantation and a natural regrowth benchmark at the end of the considered evaluation period; r is the molar ratio between CO_2 and C (that is, 3.66); Y is the annual bioenergy crop yield over the considered evaluation period (tonne dry biomass/(hectares × year)); t is the evaluation period (in years); f_{loss} is the biomass loss correction factor; η is the biomass to final carrier conversion efficiency ($GJ_{carrier}$ per tonne dry biomass); π the penalty in conversion efficiency due to CCS ($GJ_{carrier}$ per tonne dry biomass); Em represents GHG emissions per biomass produced ($kgCO_2e$ per tonne dry biomass); cc is the carbon content of the feedstock (tonne C per tonne dry biomass); κ is the carbon capture efficiency of CCS (tonne CO_2 captured per tonne CO_2 emitted) at the power plant or fuel production facility. $Em_{Supply\ chain\ CCS}$ represents the (additional) life-cycle supply chain emissions from using CCS (tonne CO_2e per $GJ_{carrier}$). Note that EFs are expressed in $kgCO_2e$ per $GJ_{carrier}$ throughout the main text.

Energy potentials (EP; in $GJ_{carrier}$ per year) per grid cell were calculated as production area times net bioenergy yields (equation (5))

$$EP_{i,j,t,x} = A_{x,t} \times Y_{i,t,x} \times f_{loss} \times \left(\eta_{i,j} - \pi_{i,j}\right) \quad (5)$$

Where A is the land area of each grid cell (in hectares).

Global emission–supply curves were determined by sorting all grid cells available for BECCS by ascending emission factor and summing energy potential across these cells. Lignocellulosic bioenergy crop results in the main text were combined from the results for grasses and short-rotation coppicing, by selecting the crop type for each grid cell that results in the lowest EF (details and alternative selection methods are provided in Supplementary Figs. 3 and 4). Carbon stocks and bioenergy crop yields were modelled in the (IMAGE-)LPJml global vegetation model and land availability was determined using the IMAGE integrated assessment model, as detailed below. All other parameter values and their ranges are based on literature (Supplementary Tables 1 and 2). Of these parameters, κ stands out as its value differs strongly among the different energy carriers: 90% for lignocellulosic electricity, 52% for lignocellulosic FT-diesel, 12% for lignocellulosic ethanol and 24% for sugarcane ethanol, with the reason for these differences being the assumption that CO_2 emissions from liquid fuel combustion are not captured and stored, as these fuels are almost entirely used in transport and other decentralized applications without feasible CCS capability. Furthermore, we assume that only CO_2 from the FT-process or fermentation step itself is captured in the FT-plant or biorefinery. The more disparate flows of CO_2 that, for instance, arise from the combustion of biomass or fossil fuels for process heat or auxiliary power (modelled as part of supply chain emissions) are relatively small in volume and low in CO_2 concentration and are assumed not be captured, in line with previous work, as explained in detail in Supplementary Section 14. Emission factors of alternative energy technologies were derived from literature (Supplementary Table 3). Non-CO_2 GHGs were accounted for using global warming potentials over a 100-year time period based on the IPPC fifth assessment report[58].

Carbon stocks and bioenergy crop yields in IMAGE-LPJml. We used the IMAGE integrated assessment model[59] coupled to the LPJml global vegetation and hydrological model[60,61] to determine carbon stocks and yields per location over time. By default, we used a forced climate scenario via a representative concentration pathway leading to 2.6 W m^{-2} radiative forcing by 2100[62], reflecting substantial climate change mitigation. A warmer climate scenario is explored in the Supplementary Fig. 14.

Carbon dynamics modelled in LPJml cover above-ground biomass, below-ground biomass and soil carbon. We determined carbon stock changes by comparing the difference in carbon stocks at the end of the evaluation period between two scenarios: (1) the bioenergy scenario, where land in each available cell is used to grow a bioenergy crop (excluding above-ground biomass, which is harvested), and (2) the natural vegetation 'benchmark' scenario, where vegetation grows naturally without management. By looking at this difference in carbon stocks, we thus explicitly account for the lost sequestration capacity of natural vegetation that is foregone by using the land for bioenergy crop plantations instead. Three bioenergy crop types were considered: (1) grassy bioenergy crops, that is, fast-growing grasses parameterized based on both *Miscanthus* and switchgrass cultivars, (2) woody bioenergy crops, that is, short-rotation coppiced trees parameterized based on *Eucalyptus* spp. in the tropics and both willow and poplar in colder areas, and (3) sugarcane. Non-CO_2 GHG emissions of land conversion were not explicitly included here but, based on Whitaker and co-workers[63], would typically be below 2% of total GHG emissions per energy carrier in this study.

Yield is determined as the crop-specific rainfed potential biophysical yield in the LPJml model multiplied by a calibration factor that expresses how much of that potential yield is realized. Globally, the average yield potential in LPJml increases by approximately 25–30% from 2020 towards 2100, due to climate feedbacks. The calibration factors were determined[24,64] based on empirical data of historic, current and best-practice yields[65,66] and are projected into the future as part of the IMAGE model. They represent agricultural management, including fertilization, improved crop strains and pest control[24]. In line with historic trends, the calibration factors result in a global average increase in yields of 0.72–1.0% per year for grasses and woody bioenergy crops, and 0.76% per year for sugarcane, from 2020 towards 2100. Energy potentials and EFs were always determined using yields and carbon stock changes from 2020 onwards (for example, 2020–2060 for a 40-year evaluation period).

Land availability. The availability of locations for bioenergy production was determined using the IMAGE model. It was assumed that areas used for agriculture (cropland and pastures) over the considered evaluation period, are not available for bioenergy production. Default results were based on a median land-use scenario following shared SSP2[67]. Scenarios with lower and higher agricultural land demand in the sensitivity analysis were based on SSP1 and 3, respectively. SSP1 includes assumptions on a shift towards less meat-intensive diets and a low population size. SSP3 on the other hand, is characterized by high population growth and low technological development and therefore higher agricultural land requirements. Beside agricultural land, built-up areas were also excluded. The amount of land available for bioenergy was further constrained by a minimum yield threshold; that is, lands yielding less than 2.5 tonne wet biomass per hectare per year (or 10 t for sugarcane) as determined in LPJml, were excluded in our analysis. For all crop types these thresholds are about 5% of the global maximum yields per hectare per year.

Land cover types. The original land cover types presented in this analysis were based on IMAGE classification[59] (Supplementary Fig. 2). Specifically, abandoned lands are based on which agricultural lands are abandoned towards 2100, depending on the projected supply and demand of agricultural products as determined in IMAGE. The managed and degraded forests land cover type is defined here as forestland that is in a regrowing state after recent human interventions. It encompasses: (1) managed forests for wood production, which predominantly occur in temperate and boreal zones, and (2) regrowing degraded forests that remain after logging for the most valuable trees or slash-and-burn practices, predominantly in tropical areas. For degraded forests specifically, default LPJml carbon dynamics were recalibrated on the basis of the literature[68–71]. We estimated that above-ground carbon stocks in forests that have been degraded within the last 20 years are approximately two-thirds of unharvested carbon stocks, as detailed in Supplementary Section 3. In the natural vegetation benchmark scenario, we therefore modelled carbon stocks of degraded forests following the default growth curves for natural forests in LPJml, but starting where above-ground carbon stocks are at two-thirds of their maximum.

Alternative uses initial biomass. When initial biomass from the original vegetation is utilized in other sectors, EFs and EPs were calculated by subtracting 80% (ref. [34]) of the carbon present in initial stem biomass from the original (preconversion) carbon stocks. When initial biomass is used to produce bioenergy, 80% of initial stem biomass is instead added to the overall yield over the evaluation period. It is assumed that initial biomass is used to produce the same energy carrier, including CCS.

BECCS in mitigation pathways. As a starting point of this analysis we took two illustrative climate change mitigation pathways from the IPCC special report on 1.5 °C (ref. [7]): the S2 middle-of-the-road pathway (MESSAGE-GLOBIOM 1.0 SSP2) and the S5 fossil fuel and BECCS-intensive pathway (REMIND-MagPIE 1.5 SSP5). The IPCC SR1.5 °C online database[35] provides total global carbon sequestered by BECCS electricity (Carbon Sequestration|CCS|Biomass) and primary energy used in BECCS electricity (Primary Energy|Biomass|Modern|w/CCS). We converted global primary energy used to global electricity produced with BECCS, assuming an energetic conversion efficiency of 0.31 $GJ_{electric}$ per $GJ_{biomass}$, following the IPCC Fifth Assessment Report median dedicated biomass electricity plant efficiency[72]. We used ten year intervals in our calculations, as provided in the IPCC database, with linear interpolation. In the analysis, we deploy land starting with best locations (that is, with the lowest EFs) and follow the global energy and sequestration-based BECCS deployment rates. We use an evaluation period up until 2100 (for example, 50 years for capacity installed in 2050, 40 years for 2060 and so on). From 2070 onwards we use the default evaluation period of 30 years to avoid underestimating BECCS potential.

When including biomass residues, we deployed all residues available for bioenergy to BECCS, before allocating any land to bioenergy crop production for BECCS. In all cases, residue availability for bioenergy was based on the IMAGE SSP2 baseline scenario and included both agricultural and forestry residues (Supplementary Table 4). The GHG balance of residues-based BECCS included CO_2 sequestered via CCS (assuming a 50% carbon content; Supplementary Table 1) and supply chain emissions (based on parameterization for grassy lignocellulosic biomass, excluding fertilizer emissions; Supplementary Table 1). Residues were assumed not to cause land-use change emissions or result in foregone sequestration of a natural vegetation reference scenario.

Data availability

Data supporting the findings of this study are available within the paper and its Supplementary Information. All source data for figures and datasets generated during the current study are available online at https://doi.org/10.17026/dans-x73-tqeg. Source data for figures in the Supplementary Information are available from the corresponding author on reasonable request.

Code availability

The code used in the analyses of the current study is available from the corresponding author on reasonable request.

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Author contributions

S.V.H., V.D., D.P.v.V. and M.A.J.H. designed the study. J.C.D. and V.D. performed the LPJml and IMAGE runs. S.V.H. collected literature data. S.V.H. performed the EF, emission–supply curve and mitigation pathway analyses, with help from V.D., Z.J.N.S. and M.A.J.H. The manuscript was written by S.V.H., with revisions from all authors.

Competing interests

The authors declare no competing interests.

Additional information

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