Burning Biomass to Limit Global Warming

on the potential and trade-offs of second-generation bioenergy

APPENDIX II

SUPPLEMENTARY INFORMATION

Supplementary information to the PhD thesis

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on the potential and trade-offs of second-generation bioenergy

by

Steef Hanssen

This research was financed by the European Research Council Consolidator Grant ‘SIZE’ (no. 647224)

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Supplementary Information

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Steef V. Hanssen, Anna S. Duden, Martin Junginger, Virginia H. Dale, Floor van der Hilst

SUPPORTING INFORMATION

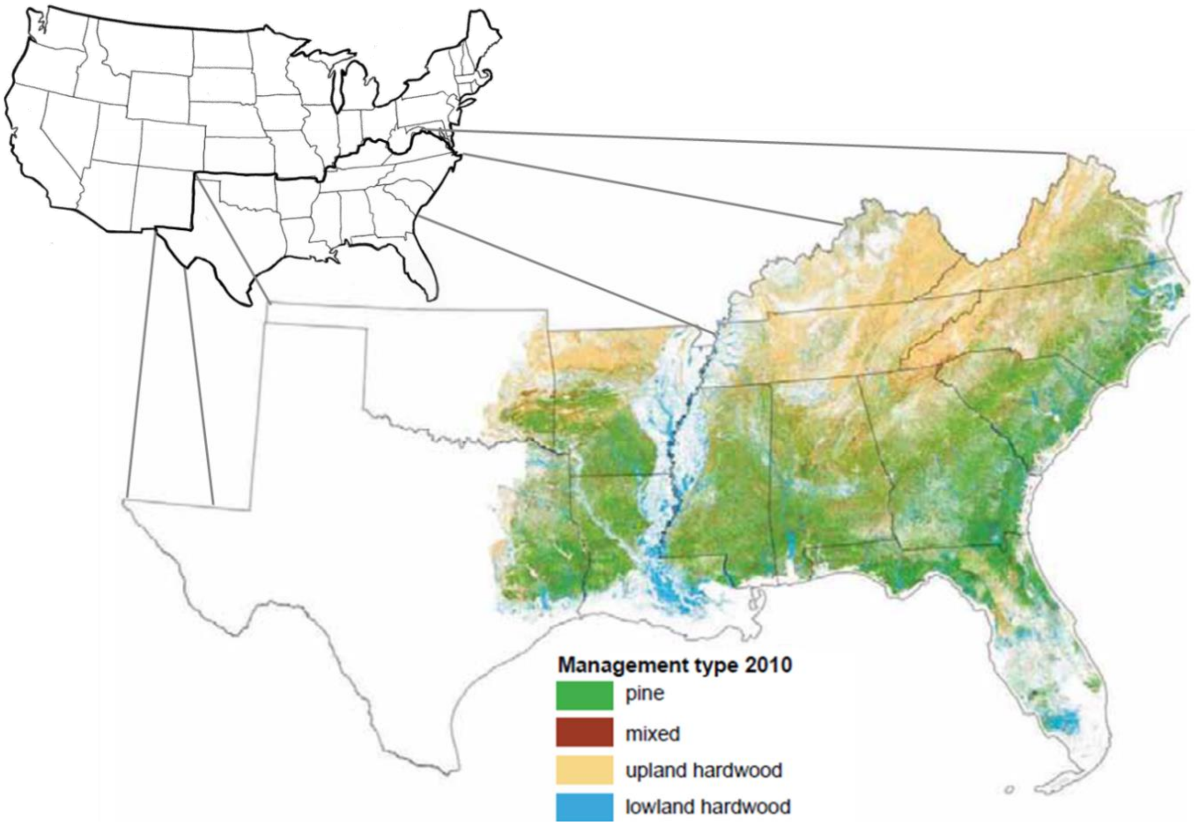

Fig. S1. *Forests in the United States Southeast (US SE; based on Wear & Greis, 2012). Throughout this study the US SE includes the south-eastern states up until Arkansas, Kentucky and Virginia in the North, and the forested, eastern areas of Texas and Oklahoma in the West (based on Wear & Greis, 2012).*

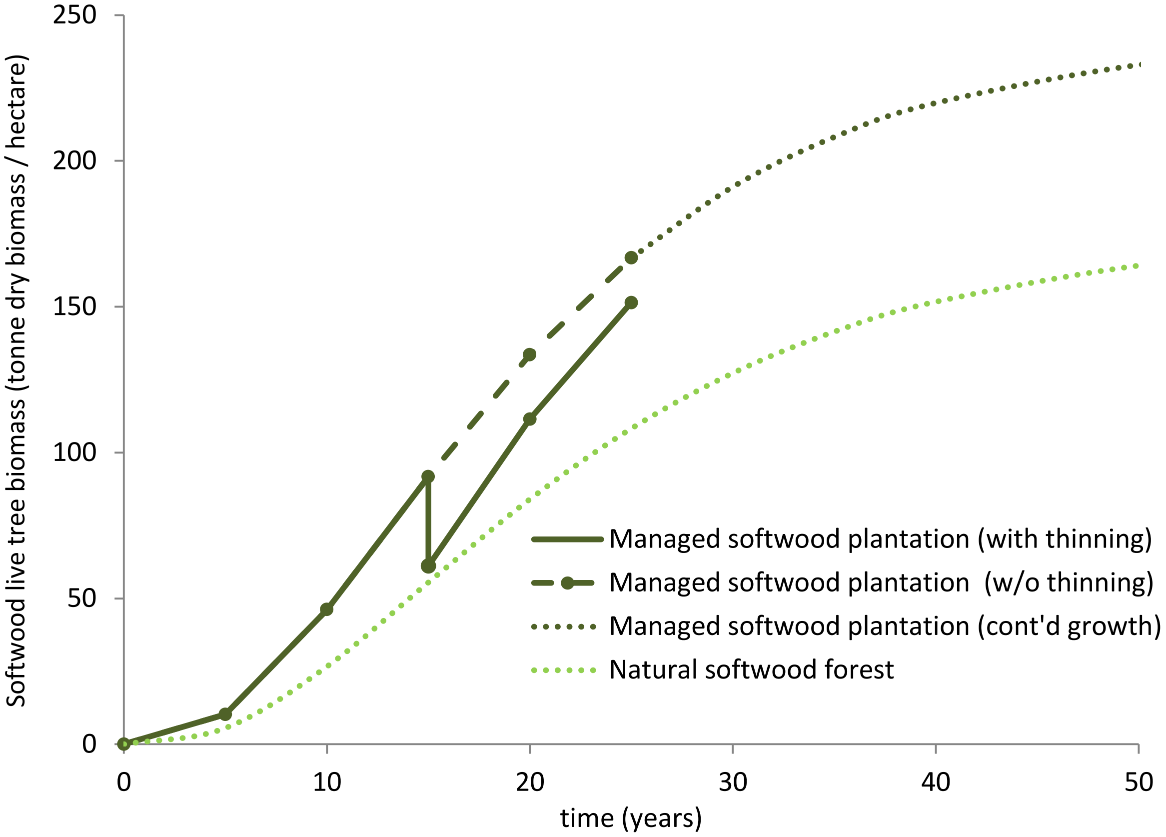

Fig. S2. *Assumed growth curve of a managed softwood plantation in the US SE based on COLE data (Carbon OnLine Estimator; NCASI, 2016) both with and without plantation thinning. As a reference a COLE-based natural growth curve without thinning for softwood in the US SE is presented.*

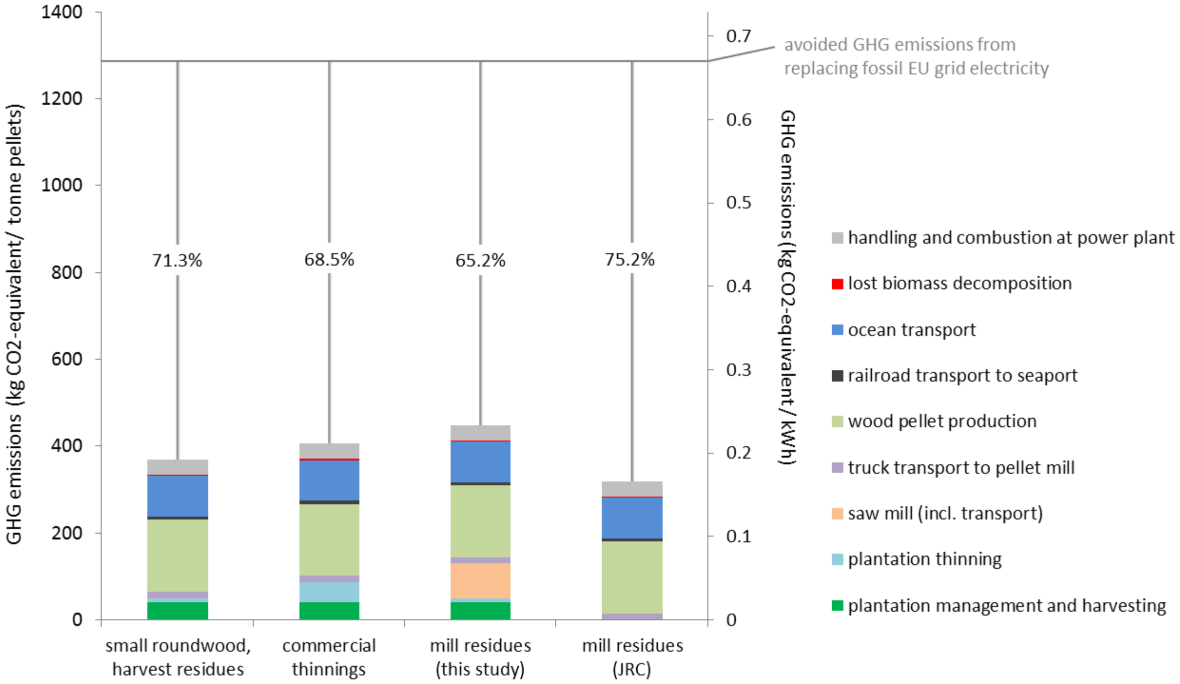

Fig. S3. *Results of GHG footptinting (considering biogenic CO_2 emissions GHG neutral and not including alternative scenarios): GHG emissions of wood-pellet electricity from different feedstocks are compared to the emissions avoided through replacing EU fossil grid electricity (1288 kg CO_2-eq./tonne pellets or 0.67 kg CO_2-eq./kWh). GHG emissions are expressed per tonne wood pellets and per kWh wood-pellet electricity (assuming a conversion of 1920 kWh/tonne pellets, see note x in table S1). The GHG emission reduction percentages, as compared to fossil EU electricity are indicated. Results for mill residues are presented both according to the GHG accounting of this study (including upstream GHG emissions of mill residues like plantation management) and for comparison according to GHG accounting rules for mill residues by the EU Joint Research Centre (JRC, 2014), which excludes upstream GHG emissions. Note that carbon sequestration and immediate biogenic CO_2 emission cancel eachother out on landscape scale; these two flows are excluded from this figure for clarity and to enable comparison with GHG footprinting studies that use LCA methodology.*

Table S1. *Input parameters of this study.*

parameter	unit	value	notes
softwood plantation			
rotation period	year	25	a
compensation of thinned biomass through enhanced growth	%	50	b
forest management (excl. thinning) and harvesting GHG em. ($\mathbf{e_{MH}}$)	kg CO_2-eq. · t pellets^{-1}	40.8	c
thinning GHG emissions ($\mathbf{e_{TH}}$) *commercial thinnings*	kg CO_2-eq. · t pellets^{-1}	46.3	d
other feedstocks	kg CO_2-eq. · t pellets^{-1}	9.35	d
carbon sequestration (**SQ**)	kg CO_2-eq. · t pellets^{-1}	2341	e
sawmill			
saw wood transport (50 km) GHG em. allocated to pellets	kg CO_2-eq. · t saw wood^{-1}	5.9	f, g
sawmill operation electricity use (debarking, sawing)	kWh · t saw wood^{-1}	48.5	h
electricity GHG emission factor US	kg CO_2-eq. · kWh^{-1}	0.518	i
total sawmill GHG emissions incl. transport ($\mathbf{e_{SM}}$) *mill residues*	kg CO_2-eq. · t pellets^{-1}	79.2	j
other feedstocks	kg CO_2-eq. · t pellets^{-1}	0	
wood pellet mill			
pellet feedstock transport (50 km) GHG em.	kg CO_2-eq. · t pellets^{-1}	15	f, g
moisture content of (all) feedstock materials (**mc**)	kg H_2O · kg wet feedstock^{-1}	0.50	k
moisture content wood pellets	kg H_2O · kg pellets^{-1}	0.07	k
carbon content dry feedstock (**cc**)	kg C · kg dry feedstock^{-1}	0.50	k
heat requirement of drying biomass in pellet mill	GJ · t H_2O evaporated^{-1}	3.96	l
heat delivered by wet biomass (50% m.c.)	GJ_{LHV} · wet t biomass^{-1}	7.74	m
wood pellet conversion efficiency (incl. drying requirements)	t wet biomass · t pellets^{-1}	2.3	j
incoming biomass required for drying	mass %	19	j
bark content small roundwood and commercial thinnings	mass%	18	n
biogenic CO_2 em. from burning bark / feedstock for drying	kg CO_2-eq. · t pellets^{-1}	424	o
CH_4 and N_2O em. from burning bark / feedstock for drying	kg CO_2-eq. · t pellets^{-1}	6.7	p
GHG emissions from (mechanical) pelletising steps (excl. drying)	kg CO_2-eq. · t pellets^{-1}	158	q
total GHG emissions from pelletising incl. transport and drying ($\mathbf{e_{PM}}$)	kg CO_2-eq. · t pellets^{-1}	604	j
wood pellet transport to- and combustion at power plant			
transport to seaport distance	km	300	r
transport to seaport (railroads) GHG em.	kg CO_2-eq. · t pellets^{-1}	7.6	g
ocean shipping distance	km	7127	s
ocean shipping (7127 km) GHG em.	kg CO_2-eq. · t pellets^{-1}	93	g
transport distance EU seaport to power plant	km	100	t
transport EU seaport to power plant GHG em. (barge/train)	kg CO_2-eq. · t pellets^{-1}	3.0	g
GHG em. of handling pellets at seaport and power plant	kg CO_2-eq. · t pellets^{-1}	7.9	t
CO_2 em. from burning wood pellets	kg CO_2-eq. · t pellets^{-1}	1704	o
CH_4 and N_2O em. from burning wood pellets	kg CO_2-eq. · t pellets^{-1}	26.8	p, u
total GHG em. from pellet mill up to and including power plant ($\mathbf{e_{PP}}$)	kg CO_2-eq. · t pellets^{-1}	1842	j
wood pellet supply chain losses and overall efficiency			
Total losses along supply chain	mass %	10	v
feedstock losses (to pellet plant)	mass % of feedstock	5.26	w
wood pellet losses	mass % of pellets	5	r, t
biogenic CO_2 em. from lost biomass decomposition ($\mathbf{e_{LO}}$)	kg CO_2-eq. · t pellets^{-1}	216	j, o
overall feedstock to wood pellet efficiency, including losses ($\mathbf{H_{WP}}$)	t wet feedstock · t pellets^{-1}	2.56	j
avoided GHG emissions wood-pellet electricity			
wood pellet to electricity conversion efficiency, through co-firing ($\boldsymbol{\eta}$)	MWh · t pellets^{-1}	1.92	x
European fossil grid electricity GHG emission factor (**EF**)	kg CO_2-eq. · MWh^{-1}	671	y
alternative scenarios			
GHG emissions of alternative product production ($\boldsymbol{\varepsilon_{APp}}$)	kg CO_2-eq. · t feedstock^{-1}	794	z,aa
avoided emissions of alternative product ($\boldsymbol{\alpha\varepsilon}$)	kg CO_2-eq. · t feedstock^{-1}	313	ab, aa
GHG emissions of not thinning ($\boldsymbol{\varepsilon_{NT}}$)	kg CO_2-eq. · t feedstock^{-1}	0	ac
half-life of carbon during in-forest decomposition assuming exponential decay ($\mathbf{T_{1/2DC}}$) *harvest residues*	year	4.65	ad
small roundwood and commercial thinnings	year	18.4	ae
fraction of decomposed C that is emitted as CO_2 ($\mathbf{f_{DC\,CO2}}$)	*dimensionless*	0.65	j
fraction of decomposed C that is emitted as CH_4 ($\mathbf{f_{DC\,CH4}}$)	*dimensionless*	0.02	af

fraction of decomposed C that is stored belowground ($\mathbf{f_{DC\,soil}}$)	*dimensionless*	0.33	ag
feedstock to alternative product efficiency, including losses ($\mathbf{H_{AP}}$)	t wet fdstock · t alt. product^{-1}	2.41	ah, aa
GHG em. of incinerating disposed alt. products as waste ($\mathbf{\bar{e}_{IW}}$)	kg CO_2-eq. · t alt.product^{-1}	1712	p
GHG em. of incinerating disposed alt. products for electricity ($\mathbf{\bar{e}_{IE}}$)	kg CO_2-eq. · t alt.product^{-1}	1250	ai
half-life of carbon in landfill assuming exponential decay ($\mathbf{t_{1/2LF}}$)	year	14.4	aj
overall lifetime landfill CH_4 production (**MP**)	kg CO_2-eq. · t alt. product^{-1}	2221	aj, aa
overall lifetime landfill CO_2 production (**CP**)	kg CO_2-eq. · t alt. product^{-1}	179	ak
fraction of landfill-produced CH_4 that is flared ($\mathbf{f_{LFflared}}$)	*dimensionless*	0.246	aj, al
fraction of landfill-produced CH_4 that is emitted directly ($\mathbf{f_{LF\,CH4}}$)	*dimensionless*	0.469	aj, al
fraction of landfill-produced CH_4 used for electricity gen. ($\mathbf{f_{LFel}}$)	*dimensionless*	0.285	aj, al, am
fraction of landfill-produced CO_2 that is emitted ($\mathbf{f_{LF\,CO2}}$)	*dimensionless*	0.352	aj, al
Global warming potential over 100 years (CH_4, N_2O resp.)	kg CO_2-equivalent	34;298	an

Abbreviations: t=metric tonne; em.=emissions; alt.=alternative; exp.=exponential. **Notes: a:** Previous studies in the US Southeast assumed 20-35 year rotation periods for planted softwood (Marland & Schlamadinger, 1997; Markewitz, 2006; Colnes et al., 2012; Jonker et al., 2013). We chose a 25 year rotation period, as it maximises average annual growth (and hence plantation efficiency) on our growth curve and lies within the theoretical economically optimal rotation period of softwood plantations in the US Southeast, which was estimated to be 21-27 years depending on management intensity (Dwivedi et al., 2014bc, 2015). **b.** Thinning enhances growth of the remaining trees (beside improving wood quality and reducing risks of wildfire and pest damage). The *additional* growth can compensate around 100% of the biomass taken out during thinning, as shown by finding that final biomass stocks of a thinned US SE softwood plantation are similar to an unthinned plantation (Gonzalez-Benecke et al., 2010, 2011; Jonker et al., 2013; also reported for other regions: Mund et al., 2002; Garcia-Gonzalo 2007a,b; Pohjola & Valsta, 2007; Jiménez et al., 2011; Powers et al., 2012; Saunders et al., 2012; Lindgren & Sullivan, 2013). Here, we (conservatively) estimate that *enhanced* growth after thinning compensates only 50% of the biomass taken out during thinning (see fig. S2) and vary this percentage from 0 to 100% in our sensitivity analysis (table 1). **c:** 5600 kg CO_2-eq. · ha^{-1} · rotation period^{-1} (based on on a review by Jonker et al., 2013; Markewitz, 2006; Dwivedi et al., 2011, 2014a,c, 2015) that is mass-allocated over different forest products (incl. pellet feedstocks, saw wood, etc., and excl. non-collectible residues). **d:** 1600 CO_2-eq. · ha^{-1} · rotation period^{-1} (based on: Dwivedi et al., 2011; Jonker et al., 2013) mass-allocated over biomass from thinnings and from additional growth resulting from thinning (assuming that all forest products increase the same relative amount). **e:** 1 tonne feedstock · feedstock to pellet efficiency [main table] · 0.25 carbon content of wet feedstock · 1000 kg/tonne · 44.01/12.01 kg CO_2/kg C. **f:** The transport distance of saw wood (saw logs and chip-n-saw wood) to a sawmill, and of wood-pellet feedstock to a pellet mill was assumed to be 50 km, based on the average distance to the centre of a 75 km wide woodshed around a mill. Sawmill residues were assumed to also travel 50 km from a sawmill to the pellet mill. **g:** Based on: Magelli et al., 2009; Sikkema et al., 2010; Jonker et al., 2013; Dwivedi et al., 2011, 2014a; Jonker et al., 2013. For trucking 60% reduced GHG emissions were assumed on the return journey (Jonker et al., 2013), other transport was one way (return journey allocated to other transported goods). **h:** Based on Röder et al., 2015, who used EcoInvent. **i:** EPA, 2015a. **j:** calculated from table values. **k:** based on: Ragland & Aerds, 1991; Sikkema et al., 2010; Magelli et al., 2009; Uasuf, 2010; Jonker et al., 2013; Greene et al., 2014; Sosa et al., 2015; ECN, 2015; NCASI, 2016. Moisture content of mill residues vary between 0.39 and 0.56 (based on: FAO, 1990; Briggs, 1994; Reeb et al., 1999; Stahl et al., 2004; Alakangas, 2005; BERC, 2011; Gjerdrum, 2013; Aebiom, 2013, 201). Varying mill residue moisture content over this range does not alter the GHG parity times. **l:** Uasuf, 2010. **m:** Uasuf, 2010, who considered wet saw dust and bark (53% moisture content) for drying. **n:** Based on Jenkins et al. (2003), using the 15-25 cm diameter at breast height of pulpwood (SC Forestry Commission, 2015). **o:** Calculated as [44.01/12.01] kg CO_2 released per kg C contained in burnt/decomposed material (feedstock or pellet). **p:** Combustion of wood and wood products (including bark, wood-pellet feedstock, wood pellets, alternative wood products) results in CH_4 and N_2O emissions, which form approximately 1.55% of total GWP-100 weighted GHG emissions of this combustion (WDNR, 2010; EPA, 2014; IPCC, 2013). CH_4 and N_2O emissions can be calculated from the remaining 98.45% GHG emissions that are formed by CO_2 and hence can be calculated from the carbon content of the material burned (25% for wet feedstock; see main table). **q:** Based on: Dwivedi et al. (2011, 2014a) and Jonker et al. (2013); GHG emissions arise from the use of electricity, diesel (non-drying) and propane (non- drying) for debarking and pelletising. **r:** Jonker et al., 2013. **s:** Wood pellets are shipped from the main pellet exporting seaports in the US Southeast - Charleston, Chesapeake (Norfolk), Jacksonville, Mobile and Savannah (T. Young, personal communication, April 10, 2015) - to the main seaports of wood pellet-for-power importing countries in Europe - Antwerp (Belgium), Liverpool (UK) and Rotterdam (the Netherlands) - over an average shipping distance of 7127 km (searates.com, 2015). **t:** Sikkema et al., 2010. **u:** in line with Dwivedi et al., 2014a. **v:** Röder et al., 2015. **w:** Derived from total- and wood pellet losses. **x:** Reported wood pellet energy densities are 16.5-19 GJ (LHV) per tonne, and power plant thermal conversion efficiencies are in the order of 35 to 40% (Zhang et al., 2010; Jonker et al, 2013; Sikkema et al., 2010; Stephenson & Mackay, 2014; Röder et al., 2015). **y:** This is a standardised GHG emission factor for fossil EU grid electricity that includes supply chain GHG emissions of the electricity generation system, following JRC methodology (JRC, 2014). **z:** GHG emissions of the production of pulp and paper, OSB and other wood panels (MDF and panelboard) were obtained from Matthews et al. (2015), average values for the US in 2010 were used (incl. transport), , yielding 861, 488 and 1150 kg CO2-equivalent per (wet) tonne feedstock used (assuming 50% moisture content). **aa:** Alternative products consisted of: 80% pulp and paper (of various types), 19% oriented strand board (OSB) and 1% other wood panels, based on softwood pulpwood usage in the US Southeast in 2005 (Smith et al., 2006). **ab:** Based on the counterfactual equivalence values (including efficiency of production) and emissions factors of counterfactual products for paper & pulp, OSB and other panels: recycled paper & card, blockwork external cladding, and plasterboard partition wall respectively, as reported by Matthews et al. (2015) for the US in 2010. **ac:** See the counterfactual and alternative scenarios section. **ad:** Half-life based on: Palviainen et al. (2004), Zanchi et al. (2012), Naesset (1999), Russell et al. (2014), Palosuo et al. (2001), Liski et al. (2002); half-life = ln(0.5)/-decay rate; HR were assumed to be 75% branches, 25% coarse woody debris (Gustavsson et al., 2015). **ae:** Half-life based on: Naesset (1999), Palosuo et al. (2001), Liski et al. (2002), Dunn & Bailey (2012); Russell et al. (2014, 2015); half-life = ln(0.5)/-decay rate; SR and CT were assumed to be 100% roundwood/stemwood. **af:** Based on 700 kg CO_2-eq. of CH_4 and N_2O emissions over entire decomposition of one tonne (piled) wood, based on Wihersaari (2005) and BTG (2002). **ag:** Mattson et al. (1987); in line with Huang et al. (2011) applied to the present study's calculations. **ah:** Based on Holmberg & Gustavsson (2007) and UNECE & FAO (2010): 1.45 t wet feedstock per t OSB or other panel and 2.5 t wet feedstock per t paper; assuming 5% losses during feedstock transport. **ai:** Avoided emissions through electricity production are 462 kg CO_2-eq. · tonne alternative product incinerated^{-1}, based on 518 kg CO_2-eq. · MWh^{-1} (EPA, 2015a) and 0.892 MWH· tonne wet paper^{-1} (Merrild et al., 2008). **aj:** half-life based on EPA (2015b); half-life = ln(0.5)/-decay rate. **ak:** 44.01/(16.04*34) · overall lifetime landfill CH_4 production. **al:** Landfill-produced gas (CO_2 and CH_4) collection efficiency was assumed to be 64.8% based on EPA (2015b). **am:** Note that avoided emissions from burning landfill-CH_4 were assumed to be equal to the replaced emissions of burning natural gas for electricity. **an:** IPCC, 2013; EPA, 2016.

Table S2. *Mass fractions, relative prices, and mass-based and economic allocation factors of different forest products that were used to allocate GHG emissions of plantation management & harvesting, and saw milling (for definitions of the forest products see the feedstock definition section in the the main text). The forest products' mass fractions were determined assuming medium to highly intensively managed softwood plantations with a rotation period of 25 years. Economic allocation factors were based on each product's mass fraction multiplied by its value, which was based on its relative price. Note that the results presented in the main text are based on mass-allocation, as economic allocation did not change GHG parity times compared to mass-allocation.*

					GHG emission allocation factor	
product	mass fraction	sources & notes	relative price	sources & notes	mass-based	economic
softwood plantation						
saw logs	0.211	a	3.72	f	*included via: mill residues, dried lumber and bark*	
chip 'n saw wood	0.254	a	2.02	f		
commercial thinnings	0.155	b	1.51	f, g	1	0.78
small roundwood	0.254	a	**1.00**	f, h	1	0.52
collectible harvest residues	0.089	a	0.77	f	1	0.40
non-collectible harv. resid.	0.0374	a	0		0	0
mill residues	-	-	-	-	1	0.70
dried lumber & excess bark	-	-	-	-	1	1.95
sawmill						
lumber	0.45	c	4.25	f	1	1.69
mill residues	0.40	d	1.40	f	1	0.55
bark used for drying lumber	0.10	e	0.20	f	1	0.08
leftover bark	0.05	e	0.20	f	1	0.08

Abbreviation: DBH = diameter at breast height. **Sources & notes: a:** Based on Dwivedi et al. (2011, 2014abc, 2015), Straka (2014) and M. Jostrom (personal communication, December 2, 2015): 25% saw logs, 30% chip 'n saw, 30% small roundwood, 15% harvest residues at the *final harvest* at 25 years of medium to high intensity softwood plantations. Saw logs and chip 'n saw wood were assumed to both produce lumber. Practically and economically feasible harvest residue collection efficiency was 70% (Dwivedi et al., 2014a). **b:** Commercial thinnings are made before the final harvest and form 15.5% of the total biomass extracted during one rotation period (based on assumptions on thinnings in the main text). **c:** Based on: FAO, 1990; Steele et al., 1991; Alderman, 1998; Renström, 2006; Aebiom, 2013; Dwivedi et al., 2016. **d:** Based on: Renström, 2006; Aebiom, 2013; sawmill residues consist of sawdust, shavings and wood chips. **e:** Bark forms 15% of saw wood (Jenkins et al., 2004; Aebiom, 2013), approximately 10% of biomass received at the saw mill is required for drying lumber (based on Renström, 2006), leaving 5% unused bark. **f:** Based on: Munsell & Fox (2010); Wear & Greis (2013); Forest2market (2014, 2015); Madisonsreport.com (2015); Timbermart-south.com (2015); Timberupdate.com (2015). **g:** Assumed to be 50% small roundwood and 50% chip 'n saw wood quality. **h:** The relative price of pulpwood was set at 1, its absolute price was about $11.5 US\$_{2015} \cdot \text{tonne}^{-1}$.

Table S3. *Fractions (f) of alternative product that is disposed after k years since production via: landfilling (LF), incineration with electricity production (IE) and incineration as waste (IW). Disposal patterns were based on Smith et al. (2006) and were specific for US SE forest products (pulp and paper, OSB and other wood panels) from softwood pulpwood, i.e. the alternative products in this study. The fraction of material incinerated at year 0 in the study by Smith et al. (2006; with or without energy capture) was excluded as this material was never part of the current study's alternative products.*

k	f_{LF}	f_{IE}	f_{IW}	k	f_{LF}	f_{IE}	f_{IW}	k	f_{LF}	f_{IE}	f_{IW}	k	f_{LF}	f_{IE}	f_{IW}
1	0.0438	0.0434	0.0398	***26***	0	0.0007	0.0029	***51***	0	0	0.0014	***76***	0	0	0.0007
2	0.0370	0.0416	0.0325	***27***	0	0.0007	0.0029	***52***	0	0	0.0014	***77***	0	0	0.0007
3	0.0318	0.0344	0.0289	***28***	0	0.0007	0.0029	***53***	0	0	0.0014	***78***	0	0	0.0007
4	0.0248	0.0307	0.0253	***29***	0	0.0007	0.0029	***54***	0	0	0.0014	***79***	0	0	0.0007
5	0.0213	0.0253	0.0199	***30***	0	0.0007	0.0029	***55***	0	0	0.0014	***80***	0	0	0.0007
6	0.0178	0.0217	0.0199	***31***	0	0.0004	0.0022	***56***	0	0	0.0011	***81***	0	0	0.0004
7	0.0161	0.0199	0.0181	***32***	0	0.0004	0.0022	***57***	0	0	0.0011	***82***	0	0	0.0004
8	0.0143	0.0199	0.0163	***33***	0	0.0004	0.0022	***58***	0	0	0.0011	***83***	0	0	0.0004
9	0.0126	0.0163	0.0163	***34***	0	0.0004	0.0022	***59***	0	0	0.0011	***84***	0	0	0.0004
10	0.0090	0.0163	0.0127	***35***	0	0.0004	0.0022	***60***	0	0	0.0011	***85***	0	0	0.0004
11	0.0046	0.0083	0.0090	***36***	0	0	0.0022	***61***	0	0	0.0007	***86***	0	0	0.0004
12	0.0046	0.0083	0.0090	***37***	0	0	0.0022	***62***	0	0	0.0007	***87***	0	0	0.0004
13	0.0045	0.0083	0.0090	***38***	0	0	0.0022	***63***	0	0	0.0007	***88***	0	0	0.0004
14	0.0045	0.0083	0.0090	***39***	0	0	0.0022	***64***	0	0	0.0007	***89***	0	0	0.0004
15	0.0045	0.0083	0.0090	***40***	0	0	0.0022	***65***	0	0	0.0007	***90***	0	0	0.0004
16	0.0001	0.0029	0.0051	***41***	0	0	0.0018	***66***	0	0	0.0007	***91***	0	0	0.0007
17	0	0.0029	0.0051	***42***	0	0	0.0018	***67***	0	0	0.0007	***92***	0	0	0.0007
18	0	0.0029	0.0051	***43***	0	0	0.0018	***68***	0	0	0.0007	***93***	0	0	0.0007
19	0	0.0029	0.0051	***44***	0	0	0.0018	***69***	0	0	0.0007	***94***	0	0	0.0007
20	0	0.0029	0.0051	***45***	0	0	0.0018	***70***	0	0	0.0007	***95***	0	0	0.0007
21	0	0.0014	0.0036	***46***	0	0	0.0014	***71***	0	0	0.0007	***96***	0	0	0.0004
22	0	0.0014	0.0036	***47***	0	0	0.0014	***72***	0	0	0.0007	***97***	0	0	0.0004
23	0	0.0014	0.0036	***48***	0	0	0.0014	***73***	0	0	0.0007	***98***	0	0	0.0004
24	0	0.0014	0.0036	***49***	0	0	0.0014	***74***	0	0	0.0007	***99***	0	0	0.0004
25	0	0.0014	0.0036	***50***	0	0	0.0014	***75***	0	0	0.0007	***100***	0	0	0.0004

Table S4. *GHG parity times of wood-pellet electricity from different feedstocks, as compared to this study's three individual feedstock-fate based counterfactuals.*

	feedstock used to produce alternative products	feedstock left to decompose	no commercial thinning (feedstock never produced)
small roundwood	1	30	-
commercial thinnings	1	30	0
harvest residues	1	6	-
mill residues	1	-	-

Table S5. *GHG parity times of wood-pellet electricity from different feedstocks, as compared to each feedstock's alternative scenario at three levels of feedstock demand for alternative products.*

	low feedstock demand for alternative products	average feedstock demand for alternative products	high feedstock demand for alternative products
small roundwood	21	6	3
commercial thinnings	0	0	1
harvest residues	6	6	5
mill residues	1	1	1

Table S6. *GHG parity times of wood-pellet electricity from different feedstocks, as compared to each feedstock's alternative scenarios, while assuming that disposal of half of the alternative product is delayed by 50 years.*

	low feedstock demand for alternative products	average feedstock demand for alternative products	high feedstock demand for alternative products
small roundwood	26	12	8
commercial thinnings	0	0	3
harvest residues	6	6	6
mill residues	4	4	4

ADDITIONAL REFERENCES *(SI only)*

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3

Life cycle greenhouse gas benefits or burdens of residual biomass from landscape management

Supplementary Information

Life cycle greenhouse gas benefits or burdens of residual biomass from landscape management

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Supplementary Information

S1: Description of applications and counterfactuals

Supplementary to Table 1.

S1.1 Biomass left on site and ploughed on site

Woody and grassy biomass are sometimes left at the location where vegetation management takes place (woody biomass left on site, *WLS*, and grassy biomass left on site, *GLS*). This is not allowed in all locations, since biomass may obstruct the water flow. But it does occur, especially when volumes are small. Biomass is usually not stacked up and decomposes naturally under aerobic conditions. These applications do not provide any products and have no counterfactual. Recently, water management organisations entered collaborations with local farmers that plough grassy biomass on fields adjacent to vegetation management sites (grassy biomass ploughed on site, *GPoS*). The aim of GPoS is to increase the organic matter content of the soil, but experience is limited. Fresh biomass generally features lower effective organic matter in comparison to composted biomass, which is frequently used to improve soil organic matter (Veeken et al., 2016). GPoS may have an effect on soil quality, but this is not reliably quantified and in current practice does not result in a reduced use of fertilisers or other soil improving materials. Dutch regulation allows for application of a specified amount of fertiliser per area. The use of fresh biomass is not considered in the sum. Contrastingly, application of compost is considered and reduces the amount of artificial fertiliser that can be applied. It is assumed that GPoS does not have a counterfactual, while compost does (see S1.4). If GPoS is proven to replace some fertilisers in the future, a counterfactual for this application should be considered. Data on emissions of GPoS are lacking, and it is assumed that emissions are the same as for GLS.

S1.2 Grazing

Several protected nature areas feature vegetation management by year-round free roaming of large grazing animals; a mix consisting mainly of cattle (70%) and horses (grassy biomass grazing large grazers, *GLG*). Other areas are managed by herds of sheep, spending about nine months in the field and three months in a shed (grassy biomass grazing sheep, *GGS*). In both cases, the main function of the animals is vegetation management, but they also produce small amounts of organic meat replacing conventionally farmed animals as counterfactual.

S1.3 Energy production

Bioenergy production from woody biomass includes burning of wood chips in incineration installations to produce either heat (woody biomass heat, *WH*) or heat and electricity in combined heat and power (CHP) plants (woody biomass CHP, *WCHP*). Conventionally produced heat and grid-electricity were assumed as counterfactuals. Grassy biomass can be co-digested together with manure and other co-products to produce biogas. The biogas can then be applied in CHP installations to produce heat and electricity (grassy biomass CHP, *GCHP*), or can be upgraded to green gas (grassy biomass green gas, *GGG*), which can be fed into the gas grid. GCHP counterfactuals are conventionally produced heat and grid-electricity, while natural gas was assumed as counterfactual for GGG. Emissions from green gas and natural gas were compared directly to avoid uncertainties relating to assumptions about applications of gas.

S1.4 Material production

Grassy biomass can be turned into compost, which is mainly applied on agricultural fields to improve soil quality (grassy biomass composting for agriculture, *GCA*), replacing artificial fertilisers. It can also be used to replace peat in the production of growth media (grassy biomass composting for growth media, *GCG*). Grassy biomass from vegetation management is sometimes ensilaged and used as livestock fodder (grassy biomass fodder, *GFo*), replacing organic production grass used in organic farming. A relatively new application of grassy biomass is the production of grass fibres (grassy biomass fibres, *GFi*). Grass is treated in a biological process to extract fibres, which are then mixed with pulp from recycled paper to produce cardboard. The grass fibres replace a part of the recycled paper pulp, and the counterfactual is pre-treated waste paper. Pre-treatment of waste paper was assumed to include collection, sorting and re-pulping of the paper (Gaudreault and Vice, 2011).

S2: Formulas GHG emission calculations.

Supplementary to Eq. 1-8. All parameters used are presented in Table S1 and Table S2.

S2.1 Emission vegetation management activities woody biomass ($\varepsilon_{VM\,(W)}$)

$$\varepsilon_{VM\ (W)} = \mathrm{FQVM}_W \times (\varepsilon_{chainsaw} + \varepsilon_{tractor\ with\ chipper} + \varepsilon_{agricultural\ machine\ with\ chipper})$$

$$\varepsilon_{chainsaw} = \mathrm{HP}_W \times \mathrm{MU}_{CS} \times \mathrm{E}_{PS}$$

$$\varepsilon_{tractor\ with\ chipper} = MU_{TC} \times [HP_W \times W_{TC} \div LTM \times \mathrm{E}_{TP} + FU_{TC} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH}) + FU_{TC(\frac{L}{hr})} \div 2 \times DT \div BMH_W \times \frac{1\ kg\ diesel}{1.135\ L\ diesel} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH})]$$

$$\varepsilon_{agricultural\ machine\ with\ chipper} = MU_{AM} \times [HP_W \times W_{AM} \div LTM \times \mathrm{E}_{TP} + FU_{AM} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH}) + FU_{AM(\frac{L}{hr})} \div 2 \times DT \div BMH_W \times \frac{1\ kg\ diesel}{1.135\ L\ diesel} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH})]$$

Data to calculate GHG emissions from vegetation management were based on reports of contractors conducting vegetation management in the Netherlands. Reports were chosen based on relevance from https://www.skao.nl/ketenanalyses. For chainsaw use (including production, fuel use and transport of machinery) a representative ecoinvent record was used. For other machinery, no representative record was available. Instead, we calculated the emission based on the emissions of machinery production, fuel production, fuel consumption and fuel production and consumption for transport of machinery to the maintenance site. Emissions of machinery production were based on Nemecek and Kagi (2007): kg / FU = Weight machine (kg) * operation time (h/FU) /lifetime (h). Fuel consumption during transport is assumed to be 50% of fuel use during full machinery use on vegetation management site, based on Muilwijk and Houben (2017).

S2.2 Emission vegetation management activities grassy biomass ($\varepsilon_{VM\,(G)}$)

$$\varepsilon_{VM\ (G)} = \mathrm{FQVM}_G \times (\varepsilon_{mowing\ motor\ mower} + \varepsilon_{mowing\ small\ tractor} + \varepsilon_{mowing\ large\ tractor})$$

$$\varepsilon_{mowing\ motor\ mower} = \mathrm{MU}_{MM} \times \mathrm{BMP}_G \times \mathrm{E}_{MM}$$

$$\varepsilon_{mowing\ small\ tractor} = MU_{ST} \times [HP_G \times W_{ST} \div LTM \times \mathrm{E}_{TP} + FU_{ST} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH}) + FU_{ST(\frac{L}{hr})} \div 2 \times DT \div BMH_G \times \frac{1\ kg\ diesel}{1.135\ L\ diesel} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH})]$$

$$\varepsilon_{mowing\ large\ tractor} = MU_{LT} \times [HP_G \times W_{LT} \div LTM \times \mathrm{E}_{TP} + FU_{LT} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH}) + FU_{LT(\frac{L}{hr})} \div 2 \times DT \div BMH_G \times \frac{1\ kg\ diesel}{1.135\ L\ diesel} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH})]$$

Data to calculate GHG emissions from vegetation management were based on reports of contractors conducting vegetation management in the Netherlands. Reports were chosen based on relevance from https://www.skao.nl/ketenanalyses. For motor mower use (including production, fuel use and transport of machinery) a representative ecoinvent record was used. For other machinery, no representative record was available. Instead, we calculated the emission based on the emissions of machinery production, fuel production, fuel consumption and fuel production and consumption for transport of machinery to the maintenance site. Emissions of machinery production were based on Nemecek and Kagi (2007): kg / FU = Weight machine (kg) * operation time (h/FU) /lifetime (h). Fuel consumption during transport is assumed to be 50% of fuel use during full machinery use on vegetation management site, based on Muilwijk and Houben (2017).

S2.3 Biogenic CO$_2$ emission woody biomass ($\varepsilon_{B\,(WLS,\,WH,\,WCHP)}$)

$$\varepsilon_{B\,(WLS,WH,WCHP)} = 1000 \times DM_W \times C_W \times \frac{44}{12} \times E_{CinCO2\,(WLS,WH,WCHP)} \times (fBMP_{WHigh} \times GWPbio_{5yr} + fBMP_{WLow} \times GWPbio_{20yr})$$

S2.4 Emission of biomass transport to processing location ($\varepsilon_{T\,(WH,\,WCHP,\,GGG,\,GCHP,\,GCA,\,GCG,\,GFi)}$)

$$\varepsilon_{T\,(WH,WCHP,GGG,GCHP,GCA,GCG,GFi)} = 2 \times TD_{(WH,WCHP,GGG,GCHP,GCA,GCG,GFi)} \times \mathrm{E}_T$$

S2.5 Emission woody biomass left on site (ε_{WLS})

$$\varepsilon_{WLS} = \varepsilon_{VM\,(W)} + \varepsilon_{B\,(WLS)} + \varepsilon_{D\,(WLS)}$$

$$\varepsilon_{D\,(WLS)} = 1000 \times DM_W \times C_W \times fE_{CinCH4} \times \frac{16}{12} \times \mathrm{GWP}_{CH4} + 1000 \times DM_W \times N_W \times fE_{NinN2O} \times \frac{44}{28} \times \mathrm{GWP}_{N2O}$$

S2.6 Emission woody biomass heat (ε_{WH})

$$\varepsilon_{WH} = \varepsilon_{VM\,(W)} + \varepsilon_{T\,(WH)} + \varepsilon_{P\,(WH)} + \varepsilon_{B\,(WH)} - \varepsilon_{C\,(WH)}$$

$$\varepsilon_{P\,(WH)} = CV_{W50\%} \times EF_{H>500kW} \times fI_{5MW} \times \mathrm{E}_{H5MW} + CV_{W50\%} \times EF_{H>500kW} \times fI_{1MW} \times \mathrm{E}_{H1MW} + CV_{W40\%} \times EF_{H<500kW} \times fI_{0.3MW} \times \mathrm{E}_{H0.3MW}$$

$$\varepsilon_{C\,(WH)} = (CV_{W50\%} \times EF_{H>500kW} \times fI_{5MW} + CV_{W50\%} \times EF_{H>500kW} \times fI_{1MW} + CV_{W40\%} \times EF_{H<500kW} \times fI_{0.3MW}) \times \mathrm{E}_{HNG}$$

Processing emissions are the sum of the emissions of heat production in different installation sizes. The emissions retrieved from ecoinvent records include the infrastructure and energy consumption or processing installations.

S2.7 Emission woody biomass CHP (ε_{WCHP})

$$\varepsilon_{WCHP} = \varepsilon_{VM\,(W)} + \varepsilon_{B\,(WCHP)} + \varepsilon_{T\,(WCHP)} + \varepsilon_{P\,(WCHP)} - \varepsilon_{C\,(WCHP)}$$

$$\varepsilon_{P\,(WCHP)} = (EF_{WCHPel} \times f_{WCHPel} + EF_{WCHPth} \times f_{WCHPth}) \times CV_{W50\%} \times \mathrm{E}_{CHPWood}$$

$$\varepsilon_{C\,(WCHP)} = EF_{WCHPel} \times f_{WCHPel} \times CV_{W50\%} \times \mathrm{E}_{El} + EF_{WCHPth} \times f_{WCHPth} \times CV_{W50\%} \times \mathrm{E}_{HNG}$$

The ecoinvent record $\mathrm{E}_{CHPWood}$ includes the infrastructure, energy and material consumption of the processing installation.

S2.8 Emission grassy biomass left on site (ε_{GLS})

$$\varepsilon_{GLS} = \varepsilon_{VM\,(G)} + \varepsilon_{D\,(GLS)}$$

$$\varepsilon_{D\,(GLS)} = E_{N2OGLS} \times \mathrm{GWP}_{N2O}$$

We assume that CH$_4$ emissions do not occur due to aerated decay.

S2.9 Emission grassy biomass ploughed on site (ε_{GPoS})

$$\varepsilon_{GPoS} = \varepsilon_{VM\,(G)} + \varepsilon_{P\,(GPoS)} + \varepsilon_{D\,(GPoS)}$$

$$\varepsilon_{P\,(GPoS)} = AP \times \mathrm{E}_{Til}$$

$$\varepsilon_{D\,(GPoS)} = E_{N2OGPoS} \times \mathrm{GWP}_{N2O}$$

Processing emissions are the emissions of the ploughing activities, ecoinvent record $\mathrm{E}_{\mathrm{Til}}$ includes the construction of machinery and energy consumption.

S2.10 Emission grassy biomass green gas (ε_{GGG})

$$\varepsilon_{GGG} = \varepsilon_{VM\,(G)} + \varepsilon_{T\,(GGG)} + \varepsilon_{P\,(GGG)} - \varepsilon_{C\,(GGG)}$$

$$\varepsilon_{P\,(GGG)} = BGY \times E_{biogas} + BGY \times EF_{BGtoGG} \times \mathrm{E}_{biogastoCH4}$$

$$\varepsilon_{C\,(GGG)} = BGY \times EF_{BGtoGG} \times R_{NGbyGG} \times (E_{NG} + \mathrm{E}_{MC})$$

Combustion of green gas can replace combustion of natural gas in all energy applications, so we compare green gas combusted with natural gas combusted and thus include the difference in biogenic vs. fossil carbon emissions.

S2.11 Emission grassy biomass biogas CHP (ε_{GCHP})

$$\varepsilon_{GCHP} = \varepsilon_{VM\,(G)} + \varepsilon_{T\,(GCHP)} + \varepsilon_{P\,(GCHP)} - \varepsilon_{C\,(GCHP)}$$

$$\varepsilon_{P\,(GCHP)} = BGY \times E_{biogas} + BGY \times EY_{BGCHP} \times \mathrm{EF}_{GCHP} \times E_{biogasCHP}$$

$$\varepsilon_{C\,(GCHP)} = BGY \times EY_{BGCHP} \times \mathrm{EF}_{GCHP} \times f_{GCHPth} \times E_{HNG} + BGY \times EY_{BGCHP} \times \mathrm{EF}_{GCHP} \times f_{GCHPel} \times E_{El}$$

Processing emissions include biogas production and biogas conversion to heat and power. Ecoinvent record $\mathrm{E}_{\mathrm{biogasCHP}}$ includes infrastructure and material consumption.

S2.12 Emission grassy biomass compost for agriculture (ε_{GCA})

$$\varepsilon_{GCA} = \varepsilon_{VM\,(G)} + \varepsilon_{T\,(GCA)} + \varepsilon_{P\,(GCA)} - \varepsilon_{C\,(GCA)}$$

$$\begin{aligned}\varepsilon_{P\,(GCA)} = {} & \frac{1}{250{,}000} \times E_{CF} + DC_{GC} \times (E_{DP} + E_{DCI}) + \mathrm{ElC}_{GC} \times E_{El} + E_{N2OGC} \times E_{N2O} + E_{CH4GC} \times E_{CH4} \\ & + DC_{GCA} \times (E_{DP} + E_{DCI}) + E_{CH4GCA} \times E_{CH4} + FR_{NGCA} \times \frac{44}{28} \times Fert_{N2O} \times E_{N2O}\end{aligned}$$

$$\varepsilon_{C\,(GCA)} = FR_{P2O5GCA} \times E_{Pfert} + FR_{K2OGCA} \times E_{Kfert} + FR_{NGCA} \times E_{Nfert} + FR_{NGCA} \times \frac{44}{28} \times Fert_{N2O} \times E_{N2O}$$

Processing emissions are the sum of the emissions of composting installation production, emissions of diesel and electricity consumption of composting installation, emissions from the composting process, diesel consumption during compost application on agricultural grounds, and emissions of compost application on agricultural grounds. According to ecoinvent record E_{CF} 250,000 tonnes of biomass are treated during the lifetime of an installation, so 1/250000 p / t_{wb} are applied. Counterfactual emissions are the emissions of artificial fertilizer production and application of N fertilizer in N_2O.

S2.13 Emission grassy biomass compost for growth media (ε_{GCG})

$$\varepsilon_{GCG} = \varepsilon_{VM\,(G)} + \varepsilon_{T\,(GCG)} + \varepsilon_{P\,(GCG)} - \varepsilon_{C\,(GCG)}$$

$$\varepsilon_{P\,(GCG)} = \frac{1}{250{,}000} \times E_{CF} + DC_{GC} \times (E_{DP} + E_{DCI}) + \mathrm{ElC}_{GC} \times E_{El} + E_{N2OGC} \times E_{N2O} + E_{CH4GC} \times E_{CH4}$$

$$\varepsilon_{C\,(GCG)} = PR_{GCG} \times (E_{PeatP} + E_{GCPA})$$

Processing emissions are the sum of the emissions of composting installation production, emissions of diesel and electricity consumption of composting installation and emissions from the composting process. According to ecoinvent record E_{CF} 250,000 tonnes of biomass are treated during the lifetime of an installation, so 1/250000 p / t_{wb} are applied. Counterfactual emissions are the emissions of peat harvesting and carbon emissions during application of peat in growth media.

S2.14 Emission grassy biomass fibre (ε_{GFi})

$$\varepsilon_{GFi} = \varepsilon_{VM\,(G)} + \varepsilon_{T\,(GFi)} + \varepsilon_{P\,(GFi)} - \varepsilon_{C\,(GFi)}$$

$$\varepsilon_{P\,(GFi)} = FC_{GFi} \times E_{fac} + SGP \times E_{SGP} + TSR_{GFi} \times E_{Tr} + ElC_{GFi} \times E_{El}$$

$$\varepsilon_{C\,(GFi)} = PR_{GFi} \times P_{GFi} \div BM_{GFi} \times E_{RPP}$$

Processing emissions are the sum of the emissions of factory construction, emission of grass silage, emission of transport of sand removed from the grass, and emission of electricity consumption during processing. Counterfactual emissions are emissions of paperpulp production from waste paper. For the future scenario, construction of a biogas installation and a net electricity production, with excess electricity feeding into the net, are calculated.

S2.15 Emission grassy biomass fodder (ε_{GFo})

$$\varepsilon_{GFo} = \varepsilon_{VM\,(G)} + \varepsilon_{P\,(GFo)} - \varepsilon_{C\,(GFo)}$$

$$\varepsilon_{P\,(GFo)} = FL_{GFo} \times E_{FL} + SGP \times E_{SGP}$$

$$\varepsilon_{C\,(GFo)} = 1 \times E_{GPO} + SGP \times E_{SGP}$$

Silage grass production is included in both our considered process and the counterfactual. Silage grass production is not represented in the ecoinvent record of the counterfactual, however, based on current practice it is realistic to assume silage for both fodder production from grassland and residual grass. Fodder loading is included in $\varepsilon_{P\,(GFo)}$, and is part of the counterfactual ecoinvent record E_{GPO}.

S2.16 Emission grassy biomass grazing sheep (ε_{GGS})

$$\varepsilon_{GGS} = \varepsilon_{P\,(GGS)} + \varepsilon_{R\,(GGS)} - \varepsilon_{C\,(GGS)}$$

$$\varepsilon_{P\,(GGS)} = Feed_{GGS} \times E_{GPO}$$

$$\varepsilon_{R\,(GGS)} = E_{RGGS} \times AR_{GGS} \div BMP_G \times 365\ days \times GWP_{CH4}$$

$$\varepsilon_{C\,(GGS)} = MP_{GGS} \times E_{SS}$$

Processing emissions are the feed required during the period in which sheep are held in a shed. This is assumed to be supplied from the same landscape in which grazing occurs, and thus considered extensive production.

S2.17 Emission grassy biomass grazing large grazers (ε_{GLG})

$$\varepsilon_{GLG} = \varepsilon_{RGLG} - \varepsilon_{C\,(GLG)}$$

$$\varepsilon_{R\,(GLG)} = E_{RGLG} \times AR_{GLG} \div BMP_G \times 365\ days \times GWP_{CH4}$$

$$\varepsilon_{C\,(GLG)} = MP_{GLG} \times E_{CS}$$

Table S1: Parameters used in GHG emission calculations. All parameters based on literature, personal communication and own calculations are presented, including the abbreviation used in the formulas in S1., units, values (exception: confidential data), references and comments. Emission data shown in this table are based on literature, emission data from ecoinvent are shown in Table S2.

Parameter	Abbreviation	Unit	Default value	References and comments
Multiple applications				
Total woody biomass production public areas	$TBMP_{WP}$	t_{wb}	48896	Calculated as described in methods Section 2.3
Total woody biomass production all floodplains	$TBMP_{WA}$	t_{wb}	92774	Calculated as described in methods Section 2.3
Total grassy biomass production public areas	$TBMP_{GP}$	t_{wb}	322057	Calculated as described in methods Section 2.3
Total grassy biomass production all floodplains	$TBMP_{GA}$	t_{wb}	582993	Calculated as described in methods Section 2.3
Grassy biomass production per ha	BMP_G	t_{wb} / ha	30.4	Amounts of woody and grassy biomass production per hectare were calculated by dividing the woody and grassy biomass produced in each section, as described in methods Section 2.3, by the surface areas of the same section for both biomass types. Subsequently, the average for all sections was calculated for both biomass types.
Woody biomass production per ha	BMP_W	t_{wb} / ha	11.64	Amounts of woody and grassy biomass production per hectare were calculated by dividing the woody and grassy biomass produced in each section, as described in methods Section 2.3, by the surface areas of the same section for both biomass types. Subsequently, the average for all sections was calculated for both biomass types.
Fraction of trees in high flow zones (5 y rotation time)	$fBMP_{WHigh}$	*dimensionless*	0.47	Calculated as described in methods Section 2.3. Rotation time based on personal communication Rijkswaterstaat.
Fraction of trees in low flow zones (20 y rotation time)	$fBMP_{WLow}$	*dimensionless*	0.53	Calculated as described in methods Section 2.3. Rotation time based on personal communication Rijkswaterstaat.
GWPbio 1y rotation time	$GWPbio_{1y}$	*dimensionless*	0	Cherubini et al. (2011); GWPbio TH100 FIRF. Consequently, ε_{bio} of grassy biomass is 0 and thus not considered in formulas.
GWPbio 5y rotation time	$GWPbio_{5y}$	*dimensionless*	0.02	Cherubini et al. (2011); GWPbio TH100 FIRF
GWPbio 20y rotation time	$GWPbio_{20y}$	*dimensionless*	0.08	Cherubini et al. (2011); GWPbio TH100 FIRF

Parameter	Abbreviation	Unit	Default value	References and comments
Fraction of C emissions in CO_2	$fE_{CinCO2\ (WLS)}$ $fE_{CinCO2\ (WH)}$ $fE_{CinCO2\ (WCHP)}$	*dimensionless*	0.99 1 1	WLS: Based on Wihersaari (2005). Assuming all C not emitted as CH_4 emitted as CO_2 and accordingly calculated as $E_{CinCO2\ (WLS)} = 1\text{-}E_{CinCH4}$. WH and WCHP: $E_{CinCO2\ (WH,WCHP)} = 1$; assuming all C is emitted as CO_2
Fraction dry matter woody biomass	DM_W	*dimensionless*	0.5	Best estimate based on literature (IVAM, 2013; Schulze et al., 2017; Spijker and Elbersen, 2013; Tolkamp et al., 2006)
Fraction dry matter of grassy biomass	DM_G	*dimensionless*	0.3	Best estimate based on literature (Bokhorst, 2007; Brinkmann, 2014; Eurofins Agro Wiki, 2018; IVAM, 2013; Ortner et al., 2013; Schulze et al., 2017; van Doorn et al., 2001)
Caloric value residual wood 50% wet	$CV_{W50\%}$	MJ / t_{wb}	8030	Based on Francescato et al. (2008). Caloric value differs between types of wood and with different moisture contents. Differences between types of wood are negligible, but moisture content is very influential. Since no data was available considering both factors, we chose data considering moisture content. To account for potential differences, we included this parameter in the sensitivity analysis.
Caloric value residual wood 40% wet (air dried)	$CV_{W40\%}$	MJ / t_{wb}	10120	Based on Francescato et al. (2008). Caloric value differs between types of wood and with different moisture contents. Differences between types of wood are negligible, but moisture content is very influential. Since no data was available considering both factors, we chose data considering moisture content. To account for potential differences, we included this parameter in the sensitivity analysis.
C content wood dry	C_W	*dimensionless*	0.5	ECN (2018)
N content wood dry	N_W	*dimensionless*	0.004	ECN (2018)
Woodchips m^3 to t	Wm^3t	*dimensionless*	0.3	Based on ecoinvent record heat from woodchips and Dones et al. (2007)
Grass m^3 to t	Gm^3t	*dimensionless*	0.17	Van Doorn et al. (2001)
Emission diesel combustion in harvesting machinery	E_{DCH}	kg CO_2-eq. / kg diesel	3.09	Calculated based on EPA (2014) Table 2 and Table 5, Agricultural Equipment
Emission diesel combustion in industrial installations	E_{DCI}	kg CO_2-eq. / kg diesel	3.3	Calculated based on EPA (2014) Table 1
Energy yield of Dutch natural gas	CV_{NG}	MJ / m^3	35.08	Based on online resources (Biogas-E, 2018; Wikipedia, 2018)
N_2O emission factor of nitrogen fertilizer	$Fert_{N2O}$	*dimensionless*	0.01	Based on De Klein et al. (2006); Tier 1 methodology

Parameter	Abbreviation	Unit	Default value	References and comments
Silage grass produced per tonne biomass	SGP	tonne silage grass / t_{wb}	0.7	Based on Jungbluth and Chudacoff (2007)
Vegetation management woody biomass (VM_W) and grassy biomass (VM_G)				
Frequency vegetation management grassy biomass	$FQVM_G$	times / y	2	Based on Muilwijk and Houben (2017) and personal communication with Rijkswaterstaat and Water boards
Frequency vegetation management woody biomass	$FQVM_W$	times / y	1	personal communication with Rijkswaterstaat and Water boards
Harvesting pace grassy biomass	HP_G	h / t_{wb}	0.23	Based on Muilwijk and Houben (2017) and Velghe et al. (2014). We chose the high end of the range as default value, because the sources refer to maintenance of roadside vegetation. The duration of maintenance execution is assumed to be higher in floodplain areas than along roadsides, because the landscape is more versatile and more difficult to access.
Harvesting pace woody biomass	HP_W	h / t_{wb}	0.91	Based on Cusveller (2015) and Weening (2014)
Fraction of machine use during vegetation management grassy biomass: large tractor	MU_{LT}	*dimensionless*	0.13	Calculated based on data of contractors (Bokhorst, 2007; Brinkmann, 2014; Brouwers Groenaannemers, 2015; Droog, 2015; Muilwijk and Houben, 2017; van Doorn, 2015; Vos and van Eijk, 2016)
Fraction of machine use during vegetation management grassy biomass: small tractor	MU_{ST}	*dimensionless*	0.45	Calculated based on data of contractors (Bokhorst, 2007; Brinkmann, 2014; Brouwers Groenaannemers, 2015; Droog, 2015; Muilwijk and Houben, 2017; van Doorn, 2015; Vos and van Eijk, 2016)
Fraction of machine use during vegetation management grassy biomass: motor mower	MU_{MM}	*dimensionless*	0.41	Calculated based on data of contractors (Bokhorst, 2007; Brinkmann, 2014; Brouwers Groenaannemers, 2015; Droog, 2015; Muilwijk and Houben, 2017; van Doorn, 2015; Vos and van Eijk, 2016)
Fraction of machine use during vegetation management woody biomass: chainsaw	MU_{CS}	*dimensionless*	0.1	Cusveller (2015)
Fraction of machine use during vegetation management woody biomass: tractor with mobile chipper	MU_{TC}	*dimensionless*	0.4	Cusveller (2015)
Fraction of machine use during vegetation	MU_{AM}	*dimensionless*	0.5	Based on Cusveller (2015) and Weening (2014)

Parameter	Abbreviation	Unit	Default value	References and comments
management woody biomass: agricultural machine with chipper				
Fuel use large tractor	FU_{LT}	L / h kg / t_{wb}	18 8.98	Calculated based on data of contractors (Bokhorst, 2007; Brinkmann, 2014; Brouwers Groenaannemers, 2015; Droog, 2015; Muilwijk and Houben, 2017; van Doorn, 2015; Vos and van Eijk, 2016)
Fuel use small tractor	FU_{ST}	L / h kg / t_{wb}	12.82 6.4	Calculated based on data of contractors (Bokhorst, 2007; Brinkmann, 2014; Brouwers Groenaannemers, 2015; Droog, 2015; Muilwijk and Houben, 2017; van Doorn, 2015; Vos and van Eijk, 2016)
Fuel use agricultural machine with chipper	FU_{AM}	L / h kg / t_{wb}	2.3 1.84	Weening (2014)
Fuel use tractor with mobile chipper	FU_{TC}	L / h kg / t_{wb}	10 8.01	Cusveller (2015)
Weight large tractor	W_{LT}	kg	4000	Based on ecoinvent record tractor production, 4-wheel, agricultural and internet search
Weight large mower	W_{LM}	kg	3000	Based on ecoinvent record tractor production, 4-wheel, agricultural and internet search
Weight tractor with mobile chipper	W_{TC}	kg	3000	Based on ecoinvent record tractor production, 4-wheel, agricultural and internet search
Weight agricultural machine with chipper	W_{AM}	kg	7000	Based on Weening (2014) and internet search
Lifetime machinery	LTM	h	7000	Based on ecoinvent record tractor production, 4-wheel, agricultural
Driving time to and from vegetation management location	DT	h	1	Based on Muilwijk and Houben (2017), estimating the total driving time to and from location
Amount of grassy biomass harvested per assignment	BMH_G	t_{wb}	2439.65	Based on Droog (2015) and van Doorn (2015)
Amount of woody biomass harvested per assignment	BMH_W	t_{wb}	647.05	Proportional to amount of grassy biomass harvested per assignment, assuming that maintenance is executed in a certain area, maintaining all vegetation in one assignment. Calculated based on the proportion between total biomass production woody and grassy.
Woody biomass left on site (WLS)				
Fraction of C emissions in CH_4	fE_{CinCH4}	*dimensionless*	0.01	Based on Wihersaari (2005). We choose the lowest value of the range, because the assumption in this study is wet wood that is piled up, which

Parameter	**Abbreviation**	**Unit**	**Default value**	**References and comments**
				would result in higher emissions than wood that is spread out, which is the more realistic scenario in our case study. We use the geometric average of the range for piled wood as approximation for the maximum emissions of non-piled wood in the sensitivity analysis.
Fraction of N emissions in N_2O	fE_{NinN2O}	*dimensionless*	0.01	Based on Wihersaari (2005). We choose the lowest value of the range, because the assumption in this study is wet wood that is piled up, which would result in higher emissions than wood that is spread out, which is the more realistic scenario in our case study. We use the geometric average of the range for piled wood as approximation for the maximum emissions of non-piled wood in the sensitivity analysis.
Woody biomass heat (WH)				
Transport distance	TD_{WH}	km	26.29	Calculated as described in methods section.
Efficiency heat production of installations >500kW	$EF_{H>500kW}$	*dimensionless*	0.9	ECN (2017)
Efficiency heat production of installations <500kW	$EF_{H<500kW}$	*dimensionless*	0.89	RVO (2018a)
Fraction of installations ~5MWth	fI_{5MW}	*dimensionless*	0.82	Calculated based on the thermic power output of the installations in all identified processing locations, as provided by RVO (2018b). Distinction in installations was chosen based on the nominal capacity described in ecoinvent records $E_{H0.3MW}$, E_{H1MW}, E_{H5MW}
Fraction of installations ~1MWth	fI_{1MW}	*dimensionless*	0.16	Calculated based on the thermic power output of the installations in all identified processing locations, as provided by RVO (2018b). Distinction in installations was chosen based on the nominal capacity described in ecoinvent records $E_{H0.3MW}$, E_{H1MW}, E_{H5MW}
Fraction of installations ~0.3MWth	$fI_{0.3MW}$	*dimensionless*	0.02	Calculated based on the thermic power output of the installations in all identified processing locations, as provided by RVO (2018b). Distinction in installations was chosen based on the nominal capacity described in ecoinvent records $E_{H0.3MW}$, E_{H1MW}, E_{H5MW}
Woody biomass CHP (WCHP)				
Transport distance	TD_{WCHP}	km	73.19	Calculated as described in methods section.

Parameter	Abbreviation	Unit	Default value	References and comments
Efficiency of CHP unit electric	EF_{WCHPel}	*dimensionless*	0.16	ECN (2017). For the sensitivity analysis, a higher electric conversion efficiency was assumed. Based on IEA (2007), stating an efficiency of 32% and an assumed efficiency loss of 2 percent point, due to drying (based on calorific value of wood and heat of evaporation of water) an efficiency of 30% can be assumed.
Efficiency of CHP unit thermic	EF_{WCHPth}	*dimensionless*	0.8	ECN (2017)
Fraction of CHP in electricity	f_{WCHPel}	*dimensionless*	0.34	calculated based on ecoinvent record Heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014
Fraction of CHP in heat	f_{WCHPth}	*dimensionless*	0.66	calculated based on ecoinvent record Heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014
Grassy biomass left on site (GLS)				
N_2O emissions during natural decomposition	E_{N2OGLS}	kg N_2O / t_{wb}	0.07	Calculated based on Velghe et al. (2014).
Grassy biomass ploughed on site (GPoS)				
N_2O emissions during natural decomposition in soil	$E_{N2OGPoS}$	kgN_2O / t_{wb}	0.07	Velghe et al. (2014). Assuming that emissions are similar to left on site on the long term. Little is known about the effect of ploughing on emissions in N2O. N2O is formed in different conditions, which makes reasonable estimates difficult. This parameter is therefore included in the sensitivity analysis.
Area ploughed to apply biomass	AP	ha / t_{wb}	0.2	Calculated based on Biomassa Alliantie (2017)
Grassy biomass green gas (GGG) and biogas CHP (GCHP)				
Transport distance	TD_{GGG}	km	40.19	Calculated as described in methods section.
Transport distance	TD_{GCHP}	km	59.05	Calculated as described in methods section.
Biogas yield per tonne grass	BGY	m^3 / t_{wb}	70.23	Based on Jungbluth and Chudacoff (2007) and IVAM (2013)
Efficiency of biogas to green gas conversion	EF_{BGtoGG}	*dimensionless*	0.67	Based on ecoinvent record biogas purification to methane 96 vol-%
Replacement of natural gas by green gas	R_{NGbyGG}	*dimensionless*	0.96	Based on ecoinvent record biogas purification to methane 96 vol-%. Describing a green gas methane content of 96% and CO_2 content of 4%, which does not replace natural gas

Parameter	Abbreviation	Unit	Default value	References and comments
Energy yield from biogas CHP	EY_{BGCHP}	MJ / m^3 biogas	22.69	Based on IVAM (2013) and Biogas-E (2018)
Fraction of CHP in heat	f_{GCHPth}	*dimensionless*	0.59	calculated based on ecoinvent record heat and power co-generation, biogas, gas engine
Fraction of CHP in electricity	f_{GCHPel}	*dimensionless*	0.41	calculated based on ecoinvent record heat and power co-generation, biogas, gas engine
Efficiency CHP unit	EF_{GCHP}	*dimensionless*	0.9	calculated based on ecoinvent record heat and power co-generation, biogas, gas engine
Density natural gas	DNG	kg / m^3	0.66	Based on Air Liquide (2018), assuming 1atm pressure and T of 25C
CO_2 production during methane combustion	E_{MC}	kg CO_2 / m^3 natural gas	1.80	Calculated as E_{MC} = DNG*44,01/16,04. Assuming stoichiometry of methane combustion for small ethane and propane content of natural gas (±1% each).

Grassy biomass compost for agriculture (GCA) and compost for growth media (GCG)

Parameter	Abbreviation	Unit	Default value	References and comments
Transport distance	TD_{GCA}	km	36.62	Calculated as described in methods section.
Transport distance	TD_{GCG}	km	26.97	Calculated as described in methods section.
Electricity consumption composting process	ElC_{GC}	MJ / t_{wb}	39.59	Based on Boldrin et al. (2009) and IVAM (2013)
Diesel consumption composting process	DC_{GC}	kg diesel / t_{wb}	1.81	Based on Boldrin et al. (2009) and IVAM (2013)
N_2O Emission composting process	E_{N2OGC}	kg N_2O / t_{wb}	0.06	Based on Boldrin et al. (2009), IVAM (2013) and Velghe et al. (2014)
CH_4 Emission composting process	E_{CH4GC}	kg CH_4 / t_{wb}	0.82	Based on Boldrin et al. (2009), IPCC (2006), IVAM (2013) and Velghe et al. (2014)
Efficiency composting process	EF_{GC}	tonne compost / t_{wb}	0.56	Based on Boldrin et al. (2009) and IVAM (2013)
Inorganic fertilizer replacement by compost for agriculture: N	FR_{NGCA}	kg N / t_{wb}	0.89	Based on Boldrin et al. (2009), Velghe et al. (2014) and BGK (2013)
Inorganic fertilizer replacement by compost for agriculture: P_2O_5	$FR_{P2O5GCA}$	kg P_2O_5 / t_{wb}	1.29	Based on Boldrin et al. (2009), Velghe et al. (2014) and BGK (2013)
Inorganic fertilizer replacement by compost for agriculture: K_2O	FR_{K2OGCA}	kg K_2O / t_{wb}	4.42	Based on Boldrin et al. (2009), Velghe et al. (2014) and BGK (2013)
Diesel consumption application of compost	DC_{GCA}	kg diesel / t_{wb}	0.31	Based on Boldrin et al. (2009)

Parameter	**Abbreviation**	**Unit**	**Default value**	**References and comments**
on agricultural land				
Emissions of compost application on agricultural land: CH_4	E_{CH4GCA}	kg CH_4 / t_{wb}	0.0004	Based on IVAM (2013)
Emissions of peat application in growth media	E_{GCPA}	kg CO_2-eq. / t_peat	811.39	Based on Boldrin et al. (2009)
Efficiency of peat replacement of compost application in growth media	EF_{GCG}	tonne peat / tonne compost	0.67	Based on Boldrin et al. (2009) and personal communication composting companies Attero and Bruins & Kwast, 2017
Efficiency of peat replacement	PR_{GCG}	tonne peat / t_{wb}	0.374	Calculated as $PR_{GCG} = EF_{GC} * EF_{GCG}$
Grassy biomass fibre (GFi)				
Transport distance	TD_{GF}	km	74.71	Calculated as described in methods section.
Amount of paper replaced by grass fibers	PR_{GFi}	*dimensionless*	*confidential*	Personal communication NewFoss 2017-2018
Wet biomass input total	BM_{GFi}	t_{wb} / y	*confidential*	Based on silage grass input (Personal communication NewFoss 2017-2018) and SGP
NewFoss Fibre end product	P_{GFi}	t / y	*confidential*	Personal communication NewFoss 2017-2018
Sand removal from grass	SR_{GFi}	t / t_{wb}	*confidential*	Personal communication NewFoss 2017-2018
Transport distance sand disposal	$TDSR_{GFi}$	km	*confidential*	Personal communication NewFoss 2017-2018
Transport for and disposal	TSR_{GFi}	tkm / t_{wb}	*confidential*	Calculated as $TSR_{GFi} = TDSR_{GFi} * SR_{GFi}$
Plant operation time	POT_{GFi}	h / y	*confidential*	Personal communication NewFoss 2017-2018
Factory construction required per processed biomass	FC_{GFi}	m^2 / t_{wb}	*confidential*	Personal communication NewFoss 2017-2018. Based on annual processing of biomass and lifetime of 50 years, stated in ecoinvent record Building, hall, steel construction
Electricity consumption	ElC_{GFi}	MJ / t_{wb}	*confidential*	Personal communication NewFoss 2017-2018
Emission recycled paper production	E_{RP}	kg CO_2-eq. / t_paper	743.86	Based on Hillman et al. (2015) and Laurijssen et al. (2010) and ecoinvent record Paper production, newsprint, recycled
Emission of energy use paper recycling	E_{RPEU}	kg CO_2-eq. / t_paper	532.64	Calculated from Laurijssen et al. (2010) and Wang et al. (2012)

Parameter	Abbreviation	Unit	Default value	References and comments
Emission factor paperpulp, pre-processed from waste paper, before upcycling into new paper	E_{RPP}	kg CO_2-eq. / tonne paperpulp	211.23	Calculated as $E_{RPP} = E_{RP}-E_{RPEU}$. Merrild et al. (2009) established that during the recycling of paper, the upcycling of sorted paper into recycled paper has the highest impact, while upstream processing contributes only marginally to GHG emissions. Energy use for upcycling is identified as one of the most important factors for emissions during paper recycling (Gaudreault and Vice, 2011; Merrild et al., 2009, 2008).
Grassy biomass livestock fodder (GFo)				
Fodder loading	FL_{GFo}	m^3 / t_{wb}	56	Based on ecoinvent record Grass production, permanent grassland, extensive, organic. Included in both our considered process and the counterfactual.
Grassy biomass grazing sheep (GGS) and grazing large grazers (GLG)				
Ruminant CH_4 emissions sheep	E_{RGGS}	kg CH_4 / head /d	0.02	Based on Crutzen et al. (1986), Judd et al. (1999), Lassey (2007), Lassey et al. (1997) and Yusuf et al. (2012).
Animals required to maintain 1ha for a year	AR_{GGS}	head / ha	5.24	Based on data from a pilot along the Twentekanalen in the Netherlands (including data on grazing rounds per year, number of animals in the herd and grazing speed) presented in Boon (2016). Additionally, we made an estimation of sheep required for year-round management, based on a comparison between food uptake of large grazers (cattle and horses) and sheep. We think that this gives a better picture, since the number of animals required with large grazers is based on real-life experience with year-round grazing, while the numbers for grazing with sheep are only based on a short-term pilot. We then aggregated our estimate with the result of the pilot.
Feed for grazers during period in shed	$Feed_{GGS}$	tonne hay / t_{wb}	0.11	Calculated from feed requirement in kgDM (Personal communication shepherder involved in the pilot along the Twentekanalen in the Netherlands) as $Feed_{GGS} = kgDM*DM_G/1000*AR_{GGS}/BMP_G$
Meat production mutton and lamb	MP_{GGS}	kg / t_{wb}	2.1	Calculated from meat production in kg/hd/y (Personal communication shepherder involved in the pilot along the Twentekanalen in the Netherlands) as $MP_{GGS} = kg/hd/y*AR_{GGS}/BMP_G$
Ruminant CH_4 emissions large grazers	E_{RGLG}	kg CH_4 / head	0.15	Based on ruminant emission of cattle of 0.19 kgCH_4/hd/d (Crutzen et al.,

Parameter	Abbreviation	Unit	Default value	References and comments
		/ d		1986; Lassey, 2007; Lassey et al., 1997; Yusuf et al., 2012) and horses of 0.05 kgCH$_4$/hd/d (Crutzen et al., 1986; Yusuf et al., 2012) and the fraction of animals that are cattle of 0.7 (FREE Nature, 2016)
Animals required to maintain 1ha for a year	AR_{GLG}	head / ha	1.41	Based on personal communication with Staatsbosbeheer, 2017, and FREE Nature, 2017
Meat production beef	MP_{GLG}	kg / t_{wb}	*confidential*	Calculated from meat production in kg/hd/y (Personal communication FREE Nature, 2018, confidential) as MP_{GLG} = kg/hd/y*AR_{GLG}/BMP_G

Table S2: Ecoinvent records used for GHG emission calculations (Wernet et al., 2016). Wherever different geographical representations were available we chose according to the following order of preference: NL, RER, Europe without Switzerland, CH, GLO, RoW

Name ecoinvent record	Abbreviation	Geographical representation	Unit	Value	Comments
Multiple applications					
Transport, freight, lorry 16-32 metric ton, EURO5	E_T	RER	kg CO_2-eq. / tkm	0.17	Choice based on (Bruins en Kwast, 2018; Cusveller, 2015; Muilwijk and Houben, 2017; Weening, 2014)
Tractor production, 4-wheel, agricultural	E_{TP}	CH	kg CO_2-eq. / kg machine	5.73	
Diesel, low-sulfur, market group for	E_{DP}	RER	kg CO_2-eq. / kg diesel	0.6	
Mowing, by motor mower	E_{MM}	CH	kg CO_2-eq. / ha	17.8	
Power sawing, without catalytic converter	E_{PS}	RER	kg CO_2-eq. / h	7.22	
Market for electricity, high voltage	E_{El}	NL	kg CO_2-eq. / MJ	0.15	
Market for heat, district or industrial, natural gas	E_{HNG}	Europe without Switzerland	kg CO_2-eq. / MJ	0.03	
Grass silage, organic, production	E_{SGP}	CH	kg CO_2-eq. / tonne silage grass	0.1	
Emissions to air; dinitrogen monoxide	GWP_{N2O}	General	kg CO_2-eq. / kg	265	
Emissions to air; methane	GWP_{CH4}	General	kg CO_2-eq. / kg	30.5	
Tillage, ploughing	E_{Til}	CH	kg CO_2-eq. / ha	120	
Grass production, permanent grassland, extensive, organic	E_{GPO}	CH	kg CO_2-eq. / tonne	54.8	
Woody biomass heat (WH)					
Heat production, softwood chips from forest, at furnace 300kW	$E_{H0.3MW}$	CH	kg CO_2-eq. / MJ	0.002	Input of wood chips excluded for calculation of emission
Heat production, softwood chips from forest, at furnace 1000kW	E_{H1MW}	CH	kg CO_2-eq. / MJ	0.002	Input of wood chips excluded for calculation of emission
Heat production, softwood chips from	E_{H5MW}	RoW	kg CO_2-eq. / MJ	0.0054	Input of wood chips excluded for calculation of

Name ecoinvent record	Abbreviation	Geographical representation	Unit	Value	Comments
forest, at furnace 5000kW, state of the art					emission
Woody biomass CHP (WCHP)					
Heat and power co-generation, wood chips, 6667kW state of the art 2014	$E_{CHPwood}$	RoW	kg CO_2-eq. / MJ	0.00078	Input of wood chips excluded for calculation of emission
Electricity production hard coal, high voltage	E_{EP}	NL	kg CO_2-eq. / MJ	0.29	Used for alternative scenario sensitivity analysis
Grassy biomass green gas (GGG) and biogas CHP (GCHP)					
Heat and power co-generation, biogas, gas engine	$E_{biogasCHP}$	NL	kg CO_2-eq. / MJ	0.00078	Input of biogas excluded for calculation of emission
Market for natural gas, high pressure	E_{NG}	NL	kg CO_2-eq. / m^3	0.14	
Biogas production from grass	E_{biogas}	CH	kg CO_2-eq. / m^3	0.36	Input of grass excluded for calculation of emission
Biogas purification to methane 96 vol-%	$E_{biogastoCH4}$	CH	kg CO_2-eq. / m^3	0.73	Input of biogas excluded for calculation of emission
Grassy biomass compost for agriculture (GCA) and compost for growth media (GCG)					
Nitrogen fertilizer, as N, market for	E_{Nfert}	GLO	kg CO_2-eq. / kg	11.4	
Phosphate fertilizer, as P2O5, market for	E_{Pfert}	GLO	kg CO_2-eq. / kg	2.16	
Potassium fertilizer, as K2O, market for	E_{Kfert}	GLO	kg CO_2-eq. / kg	2.01	
Composting facility, open, construction	E_{CF}	CH	kg CO_2-eq. / p	765,000	Record describes that 250,000 tonnes of biomass are treated during the lifetime of an installation
Peat, production	E_{PeatP}	RoW	kg CO_2-eq. / tonne	10.8	
Grassy biomass fibre (GFi)					
Building, hall, steel construction	E_{Fac}	CH	kg CO_2-eq. / m^2	399	Record assumes a factory life time of 50 years
Anaerobic digestion plant construction, for biowaste	E_{ADP}	CH	kg CO_2-eq. / p	1,020,000	Record assumes a installation lifetime of 25 years. Used for alternative scenario.
Paper production, newsprint, recycled	E_{PaperP}	CH	kg CO_2-eq. /	735	

Name ecoinvent record	Abbreviation	Geographical representation	Unit	Value	Comments
			tonne		
Grassy biomass livestock fodder (GFo)					
Fodder loading, by self-loading trailer	E_{FL}	CH	kg CO_2-eq. / m^3	0.69	
Grassy biomass grazing sheep (GGS) and grazing large grazers (GLG)					
Sheep for slaughtering	E_{SS}	RoW	kg CO_2-eq. / kg	13	
Cattle for slaughtering	E_{CS}	RoW	kg CO_2-eq. / kg	14.2	

Table S3: Identification of processing locations.

Application	Number of processing locations identified	References
Woody biomass heat	28	Bio-energie cluster Oost-Nederland 2018; RVO 2018b; personal communication Staatsbosbeheer
Woody biomass CHP	3	Bio-energie cluster Oost-Nederland 2018; RVO 2018b; personal communication Staatsbosbeheer
Grassy biomass green gas	4	Brinkmann 2014; personal communication Bio-energie cluster Oost-Nederland, Bruins & Kwast and Staatsbosbeheer; online search. Specific selection of installations capable of co-digesting grass
Grassy biomass biogas CHP	8	Brinkmann 2014; personal communication Bio-energie cluster Oost-Nederland, Bruins & Kwast, Staatsbosbeheer; online search. Specific selection of installations capable of co-digesting grass
Grassy biomass fibre	1	NewFoss 2018
Grassy biomass compost for agriculture	13	BVOR 2018
Grassy biomass compost for growth media	38	BVOR 2018

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5

Biomass residues as twenty-first century bioenergy feedstock — a comparison of eight integrated assessment models

Supplementary Information

Biomass residues as 21st century bioenergy feedstock

a comparison of eight integrated assessment models

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Supporting information

Table S1 References for the Integrated Assessment Models used in this study

Integrated Assessment Model	reference(s) with detailed model description
AIM	Fujimori et al. 2012; Hasegawa et al., 2017
BET	Yamamoto et al., 2014
DNE21+	Akimoto et al., 2008, 2010
GCAM	Edmonds & Reilly, 1985; Kim et al., 2006
GLOBIOM[a]	Havlik et al., 2014; Lauri et al., 2014
GRAPE	Kurosawa, 1999; Kurosawa et al., 2006
IMAGE	Stehfest et al., 2014
NLU[a]	Souty et al. 2012

Notes: [a] The NLU and GLOBIOM models are not IAMs *sensu stricto*, but rather land use competition models and IAM components that focus on agriculture and forestry, respectively.

Table S2 Subset of EMF-33 scenarios used in this study

Scenario name	Exogenous 2nd gen. bioenergy demand	Exogenous biomass price	Additional scenario components
B100 B200 B300 B400	model baseline demand in 2010 linearly increases to 100, 200, 300 or 400 EJ/yr by 2100	*n/a*	*n/a*
B100C B200C B300C B400C	as above	*n/a*	*GHG price*: 20 US\$$_{2005}$/tonne CO_2eq. in 2020, with a 3% annual increase[a]
B100LP B200LP B300LP B400LP	as above	*n/a*	*Land protection*: default land protection settings per model[b]
B100CLP B200CLP B300CLP B400CLP	as above	*n/a*	*GHG price* and *Land protection* (as above)
PB3 PB5 PB9 PB15	*n/a*	price fixed at 3/5/9/15 US\$$_{2005}$ /GJ at farm gate	*n/a*
PB3C PB5C, PB9C PB15C	*n/a*	as above	*GHG price*: 20 US\$$_{2005}$/tonne CO_2eq. in 2020, with a 3% annual increase[a]

Notes: [a] this GHG price is applied to all major GHGs (CO_2, CH_4 and N_2O) and affects all modelled GHG emission mitigation technologies; [b] Land protection means that on top of the current natural protected areas, certain areas are to remain or transform in(to) a natural state and are not available for human land uses such as agriculture, model default land protection settings determine what areas (Rose et al., *this issue*).

Table S3 Aggregation at five region level (IIASA, 2017)

Region	Countries
OECD90 = OECD member countries in 1990.	Australia, Austria, Belgium, Canada, Denmark, Fiji, Finland, France, French Polynesia, Germany, Greece, Guam, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Caledonia, New Zealand, Norway, Portugal, Samoa, Solomon Islands, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States of America, Vanuatu
REF = Countries from the Reforming Economies of Eastern Europe and the Former Soviet Union.	Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Malta, Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, Slovenia, Tajikistan, TFYR Macedonia, Turkmenistan, Ukraine, Uzbekistan, Yugoslavia
ASIA = The region includes most Asian countries with the exception of the Middle East, Japan and Former Soviet Union states.	Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China, China Hong Kong SAR, China Macao SAR, Democratic People's Republic of Korea, East Timor, India, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Singapore, Sri Lanka, Taiwan, Thailand, Viet Nam
MAF = This region includes the countries of the Middle East and Africa.	Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Cote d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Oman, Qatar, Reunion, Rwanda, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Syrian Arab Republic, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Yemen, Zambia, Zimbabwe
LAM = This region includes the countries of Latin America and the Caribbean.	Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela

Table S4 ANOVA-based variance decomposition analysis results indicating how exogenous bioenergy demand, GHG pricing and inter-model differences contribute to differences in the quantity of residues supplied across all studied models and exogenous demand/GHG pricing scenarios, the interaction effect of bioenergy demand and GHG pricing was negligible (<0.7% attributed variance)

Dependent variable *(models included)*	Factor *Year:*	Variance explained 2050	 2100
Quantity of residues supplied - log transformed *(all models)*	exogenous bioenergy demand	8.6%	5.0%
	presence of GHG pricing	0.5%	2.3%
	inter-model differences (residual)	90.9%	92.8%
Residues as share of bioenergy supply - logit transformed *(all models)*	exogenous bioenergy demand	10.9%	14.8%
	presence of GHG pricing	0.1%	3.2%
	inter-model differences (residual)	89.0%	81.8%
Quantity of residues supplied - log transformed *(excl. DNE21+ and NLU)*	exogenous bioenergy demand	15.6%	25.1%
	presence of GHG pricing	0.9%	11.5%
	inter-model differences (residual)	83.4%	63.4%
Residues as share of bioenergy supply - logit transformed *(excl. DNE21+ and NLU)*	exogenous bioenergy demand	11.7%	23.9%
	presence of GHG pricing	0.1%	10.6%
	IAM differences (residual)	88.2%	64.8%

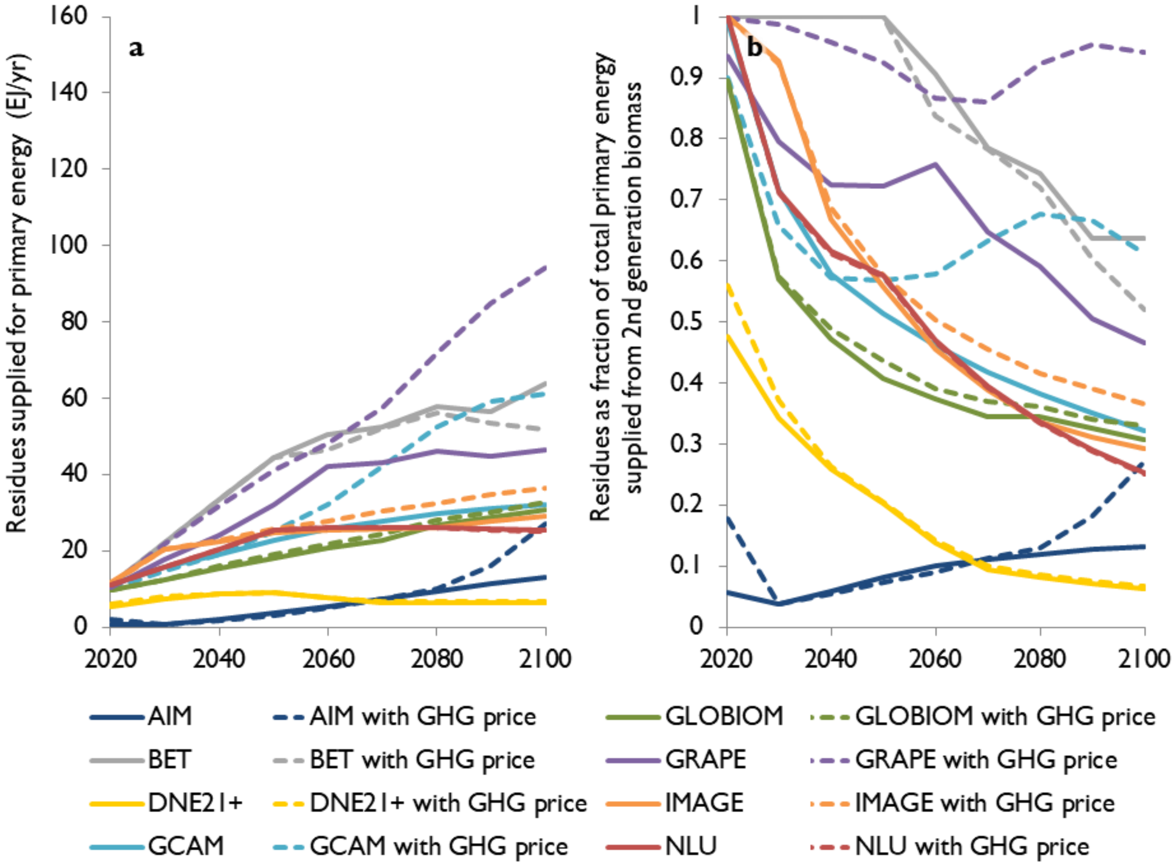

Figure S1 Quantity of residue supplied for primary energy (EJ/year) at an exogenous demand for 2nd generation bioenergy that increases linearly from 2010 levels to 100 EJ/yr by 2100, with and without GHG pricing (scenarios B100 and B100C respectively; see Table S2) (**a**), residues as share of total second-generation biomass use for primary energy under the same scenarios (**b**), for NLU and DNE21+ dashed lines may underlie their respective solid line

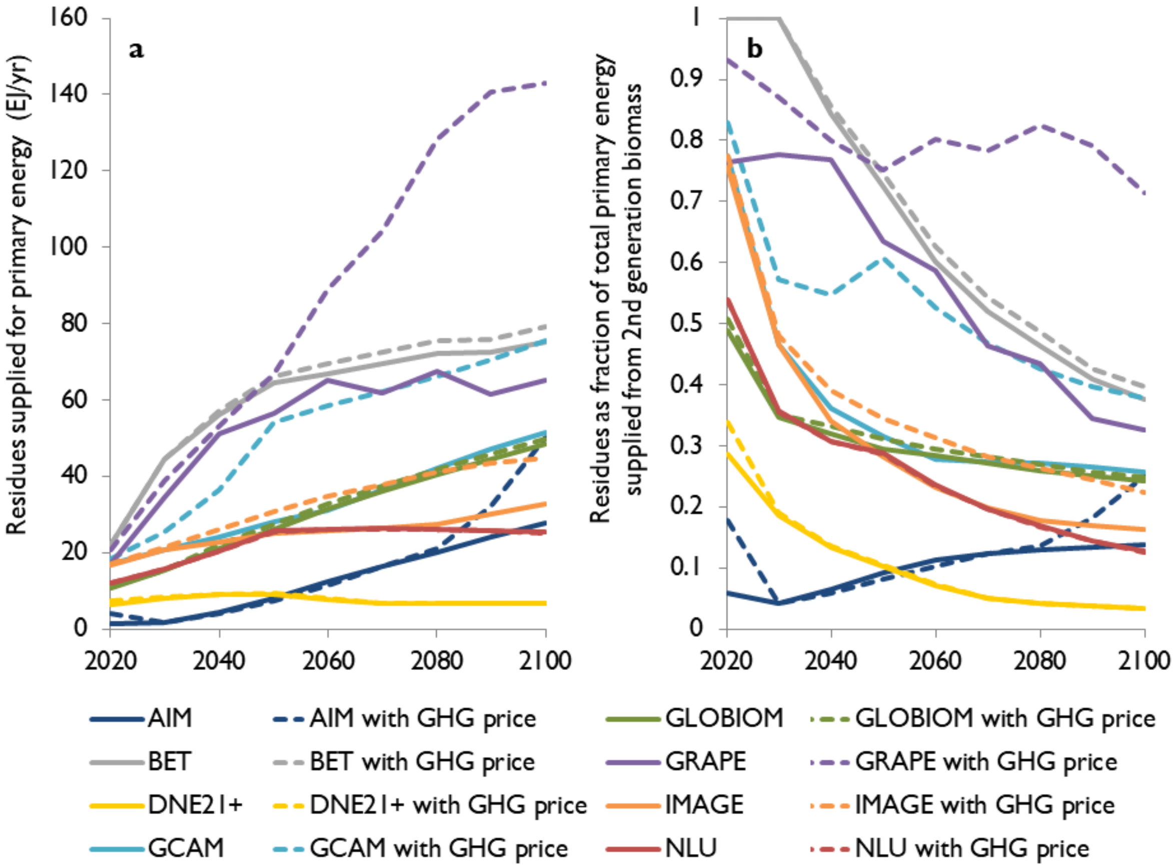

Figure S2 Quantity of residue supplied for primary energy (EJ/year) at an exogenous demand for 2nd generation bioenergy that increases linearly from 2010 levels to 200 EJ/yr by 2100, with and without GHG pricing (scenarios B200 and B200C respectively; see Table S2) (**a**), residues as share of total second-generation biomass use for primary energy under the same scenarios (**b**), for NLU and DNE21+ dashed lines may underlie their respective solid line

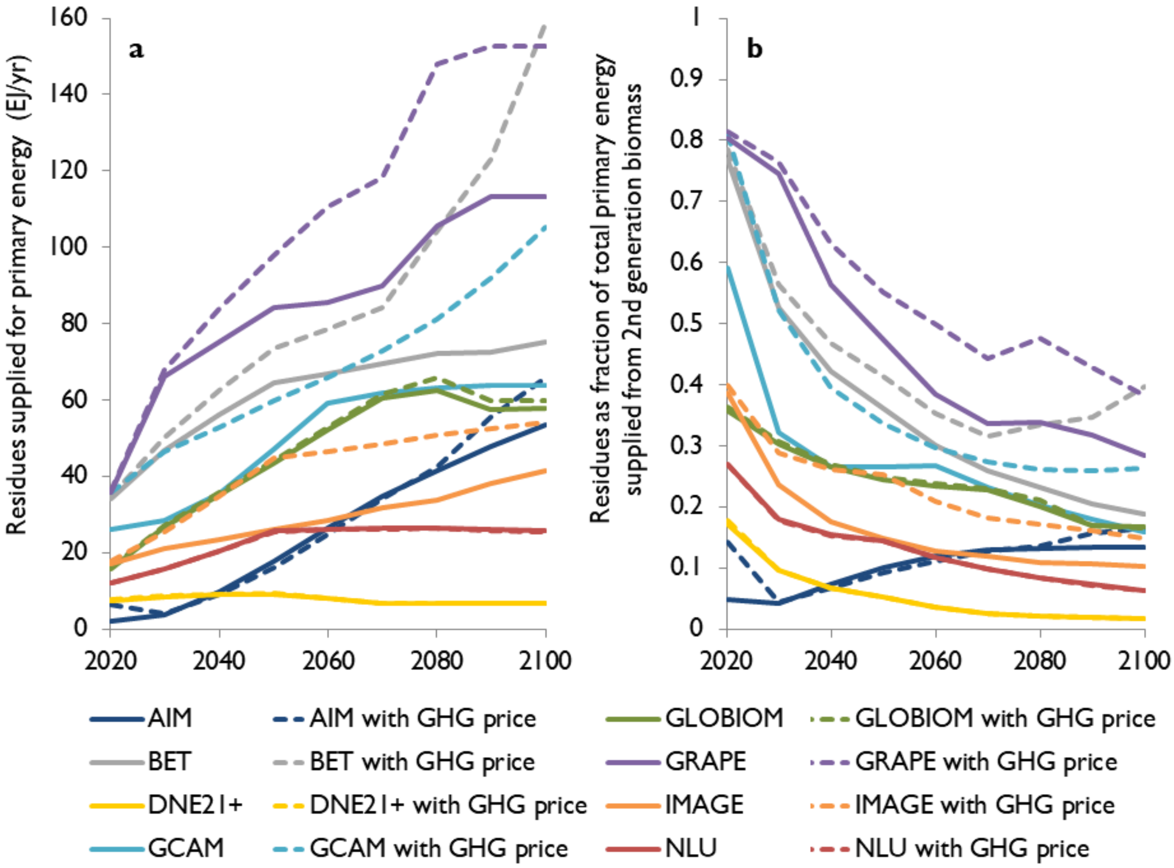

Figure S3 Quantity of residue supplied for primary energy (EJ/year) at an exogenous demand for 2nd generation bioenergy that increases linearly from 2010 levels to 400 EJ/yr by 2100, with and without GHG pricing (scenarios B400 and B400C respectively; see Table S2) (**a**), residues as share of total second-generation biomass use for primary energy under the same scenarios (**b**), for NLU and DNE21+ dashed lines may underlie their respective solid line

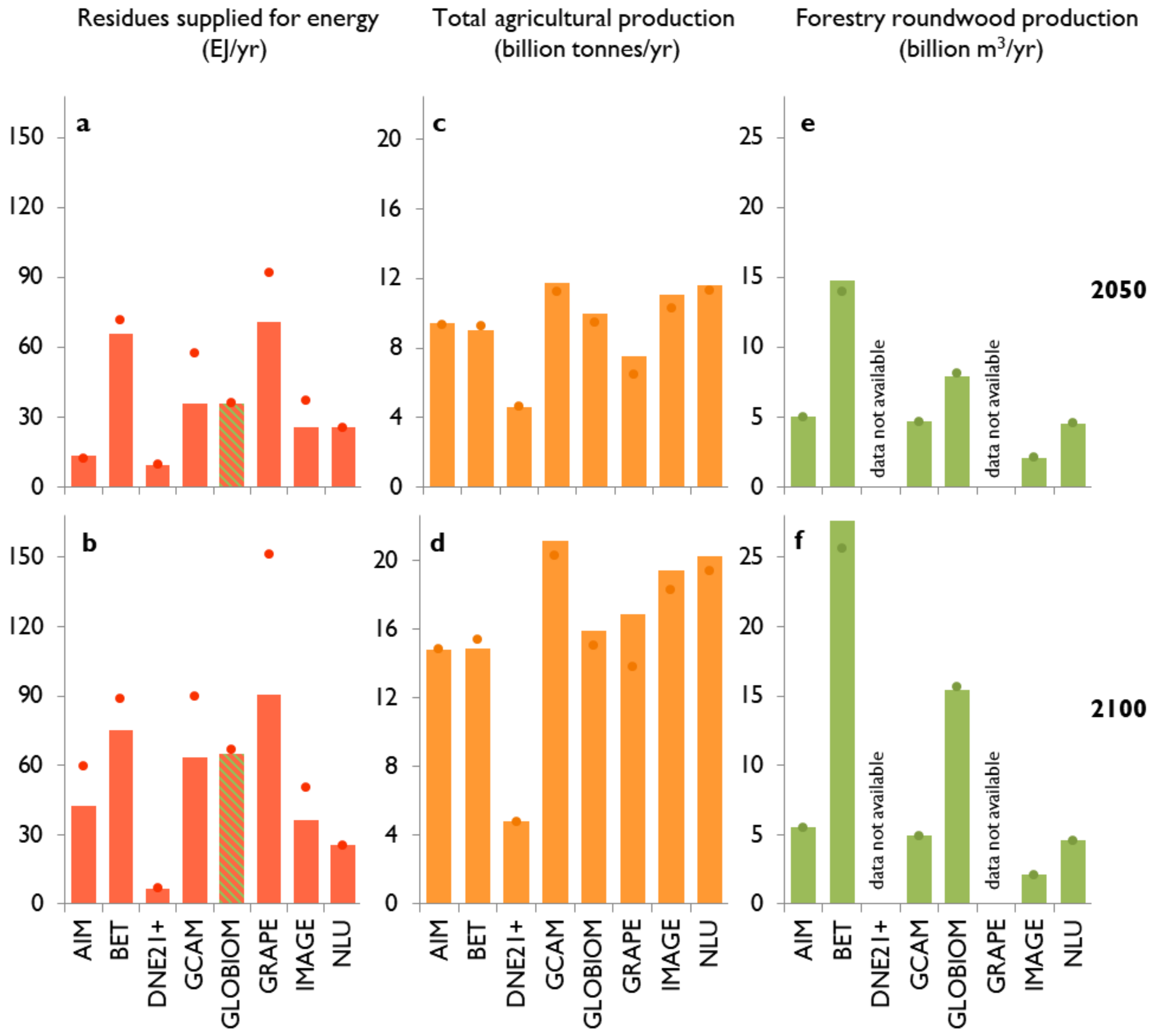

Figure S4 Quantity of residue supplied for primary energy (EJ/year) in 2050 (**a**) and 2100 (**b**), agricultural production (billion tonnes) in 2050 (**c**) and 2100 (**d**), and roundwood production (billion m^3) in 2050 (**e**) and 2100 (**f**) in a scenario with an exogenous demand for 2nd generation bioenergy that increases linearly from 2010 levels to 300 EJ/yr by 2100, dots indicate the level of supplied energy, agricultural production and roundwood production when GHG pricing is included in the scenario, note that GLOBIOM only includes forestry residues

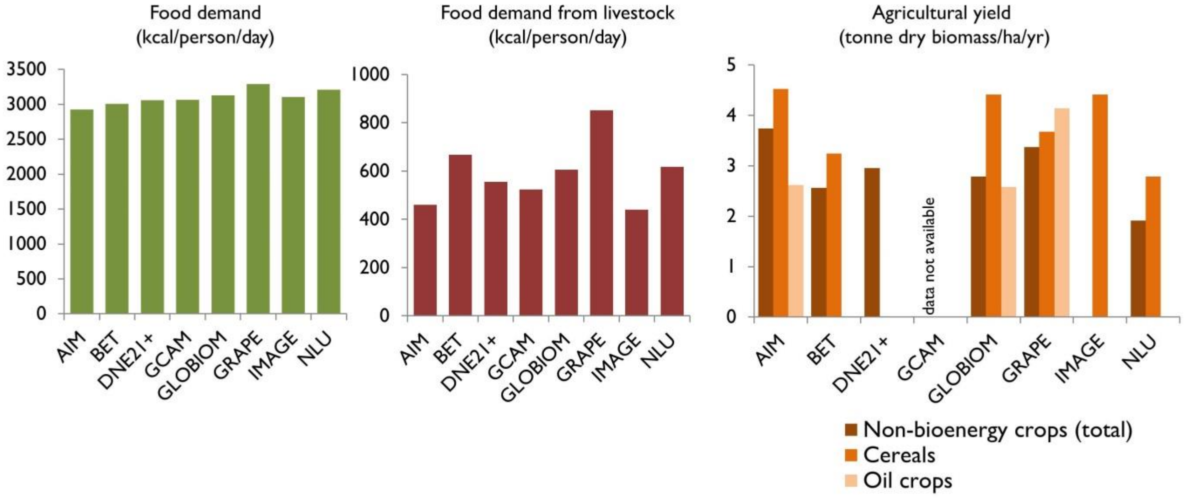

Figure S5 Model outcomes for 2050 in a scenario with an exogenous demand for 2nd generation bioenergy that increases linearly from 2010 levels to 300 EJ/yr by 2100: per capita food demand (**a**), diet, i.e., per capita food demand from livestock (meat, dairy) (**b**), and agricultural yields for total non-bioenergy crops, as well as for cereals and oil crops, separately (**c**).

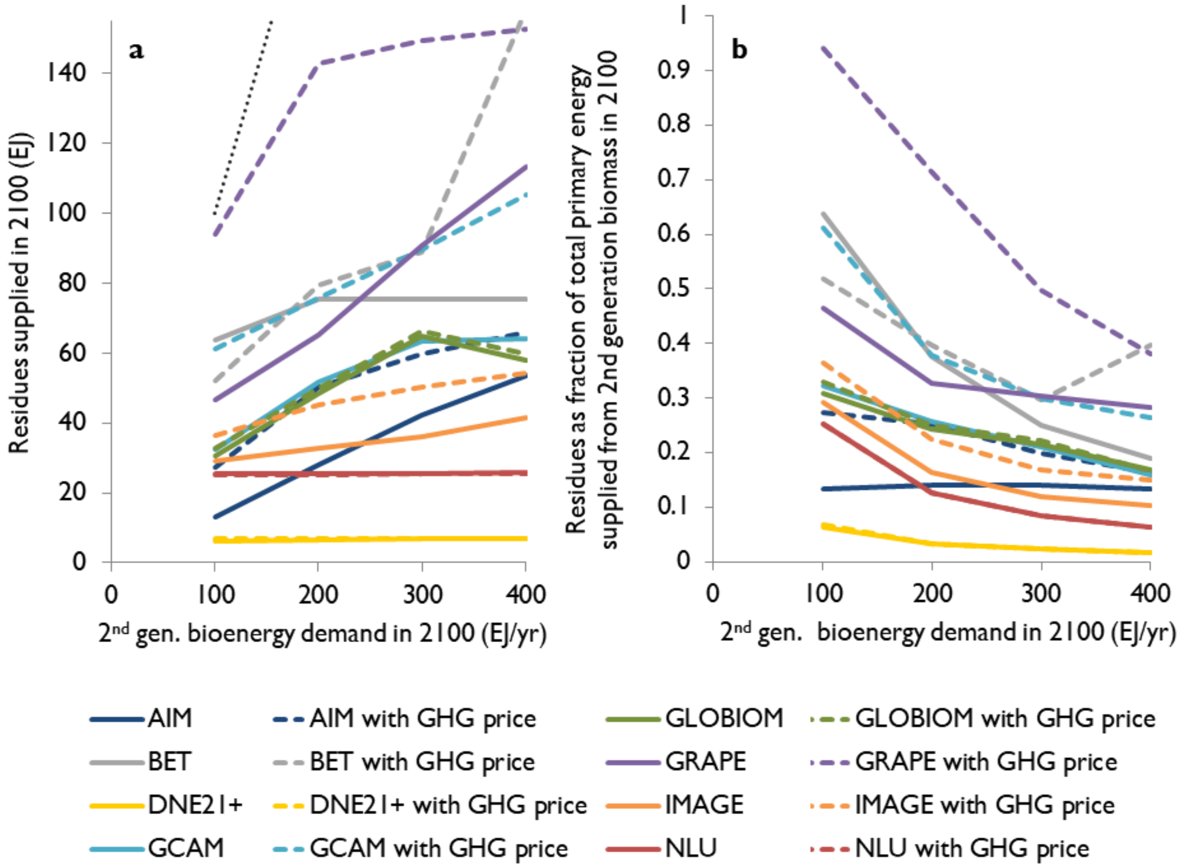

Figure S6 Quantity of residues supplied in the studied IAMs for the year 2100, across four scenarios with increasing exogenous bioenergy demand (to 100, 200, 300 and 400 EJ/yr by 2100; see Table S2), with and without GHG pricing (**a**), residues as share of total second-generation biomass use for primary energy across the same scenarios in 2100 (**b**), the black dotted line indicates residues meeting 100% of exogenous bioenergy demand

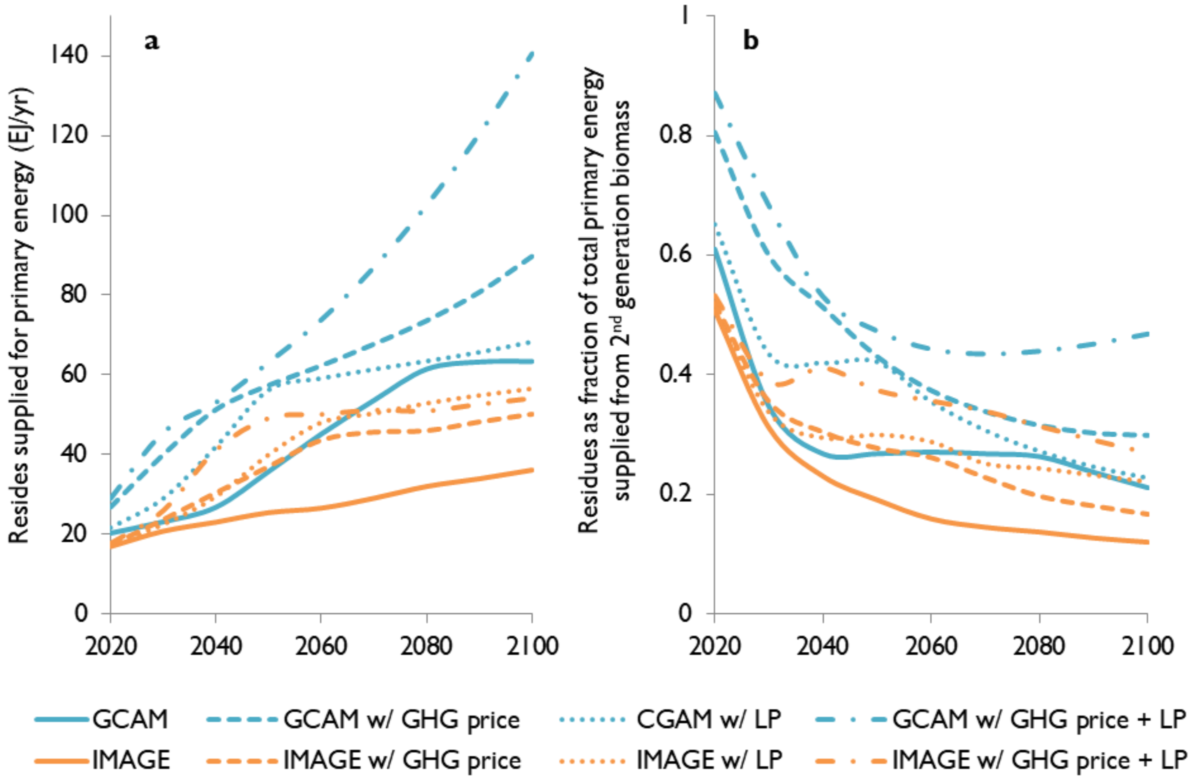

Figure S7 Quantity of Residues supplied for primary energy (EJ/year), with and without land protection (LP), and with and without GHG emissions pricing, at an exogenous demand for 2nd generation bioenergy that increases linearly from 2010 levels to 300 EJ/yr by 2100 (**a**), residues as share of total second-generation biomass use for primary energy under the same scenarios (**b**)

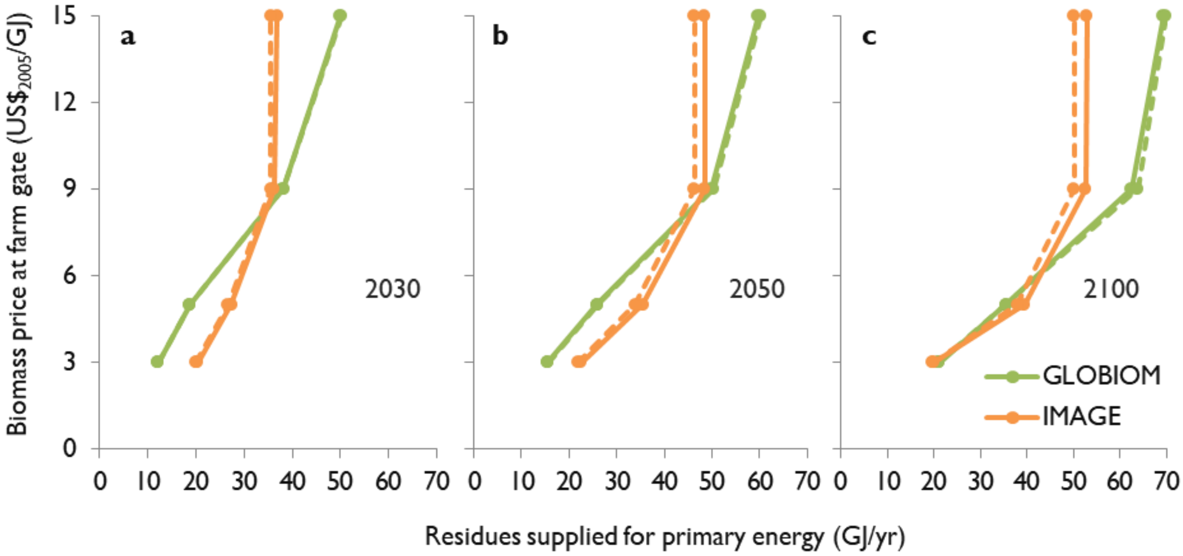

Figure S8 Quantity of residues supplied for primary energy in 2030 (**a**), 2050 (**b**), and 2100 (**c**), at fixed exogenous biomass prices of 3, 5, 9 and 15 US$$_{2005}$/GJ second-generation biomass (specifically used for energy) at farm gate, with (dashed) and without (no dash) GHG pricing

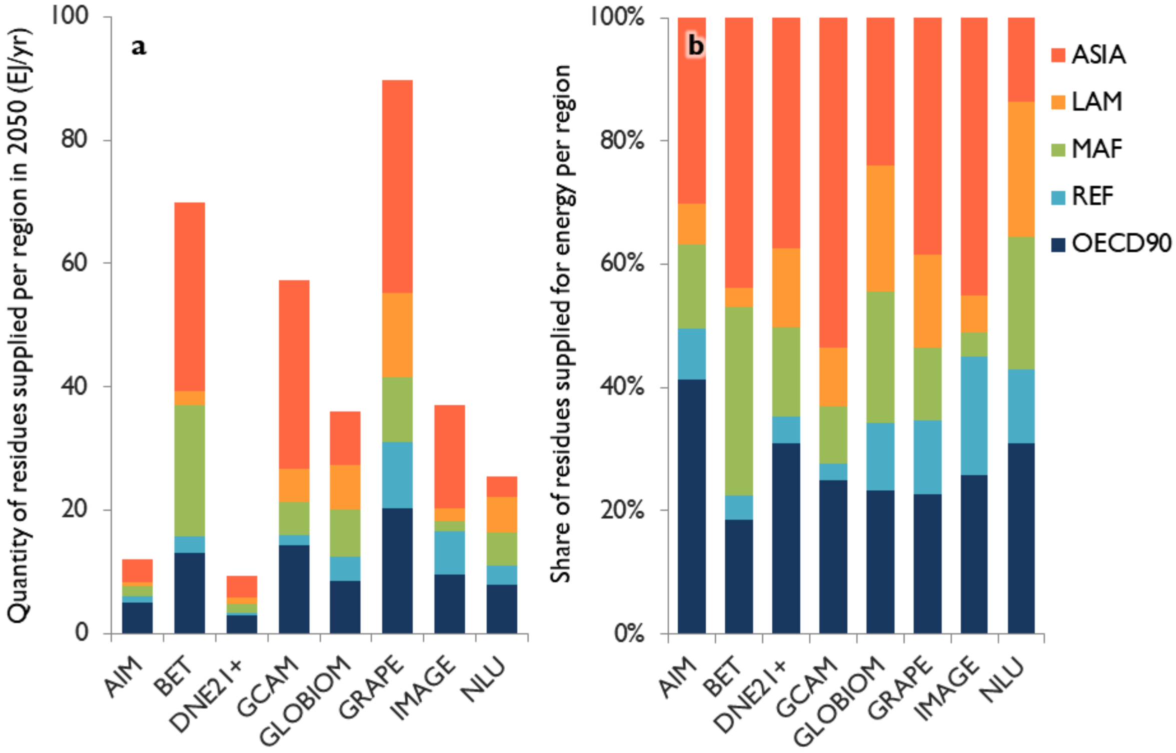

Figure S9 Quantity of biomass residues supplied for energy per region in 2050 in a scenario with an exogenous bioenergy demand of 300 EJ/yr by 2100 and GHG pricing (**a**), share of residues supplied for energy per region in 2050 (**b**), abbreviations: LAM= Latin America, MAF= Middle East and Africa; REF = reforming economies (former Soviet Union and Eastern Europe); OECD90 = OECD member countries in 1990, for regional definitions see Table S3

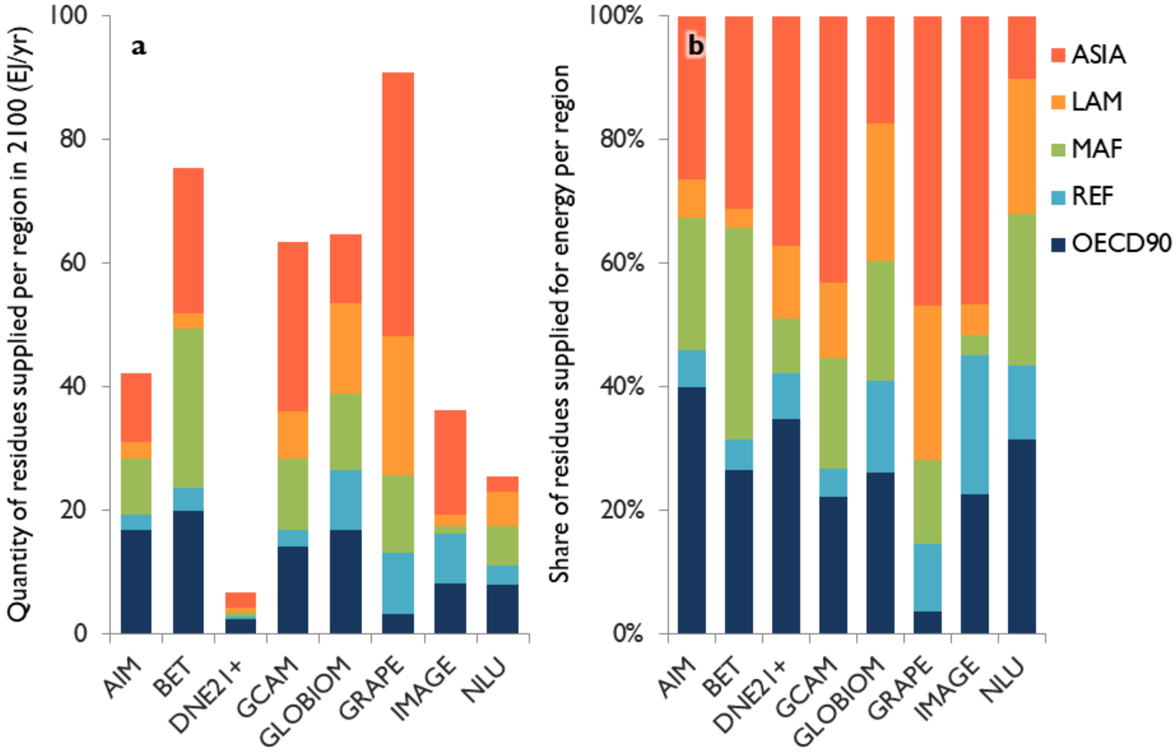

Figure S10 Quantity of biomass residues supplied for energy per region in 2100 in a scenario with an exogenous bioenergy demand of 300 EJ/yr by 2100 (**a**), share of residues supplied for energy per region in 2100 (**b**), abbreviations: LAM= Latin America, MAF= Middle East and Africa; REF = reforming economies (former Soviet Union and Eastern Europe); OECD90 = OECD member countries in 1990, for regional definitions see Table S3

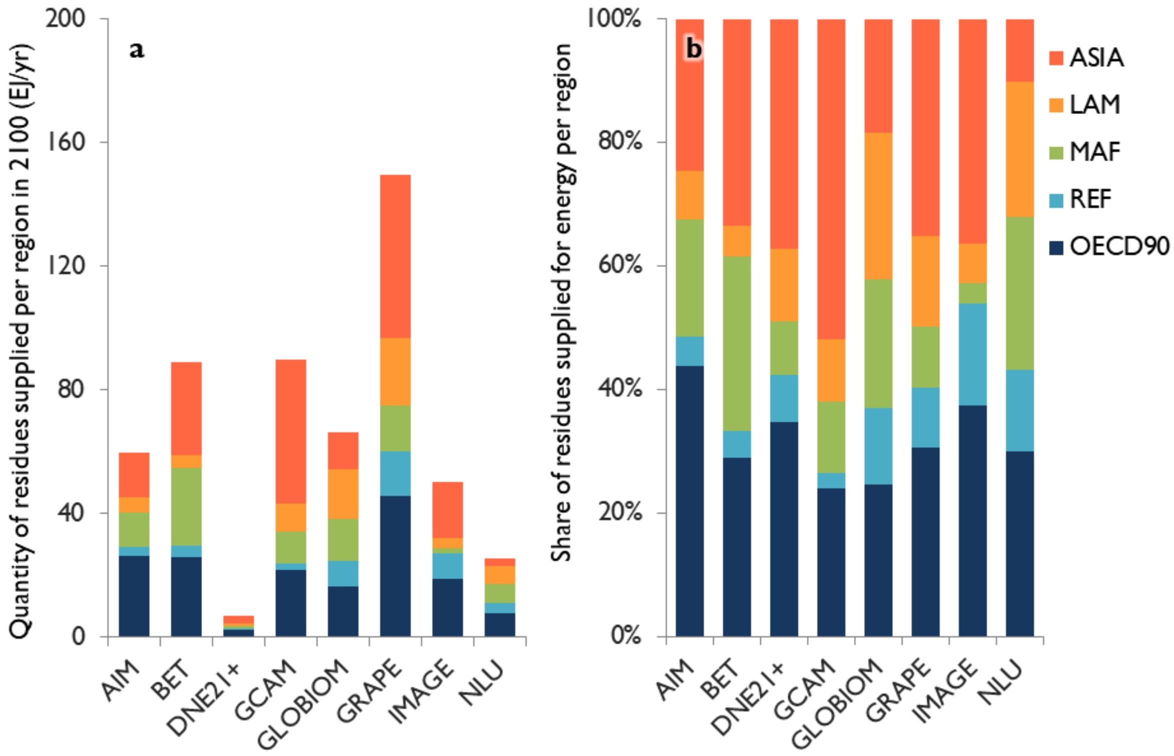

Figure S11 Quantity of biomass residues supplied for energy per region in 2100 in a scenario with an exogenous bioenergy demand of 300 EJ/yr by 2100 and GHG pricing (**a**), share of residues supplied for energy per region in 2100 (**b**), abbreviations: LAM= Latin America, MAF= Middle East and Africa; REF = reforming economies (former Soviet Union and Eastern Europe); OECD90 = OECD member countries in 1990, for regional definitions see Table S3

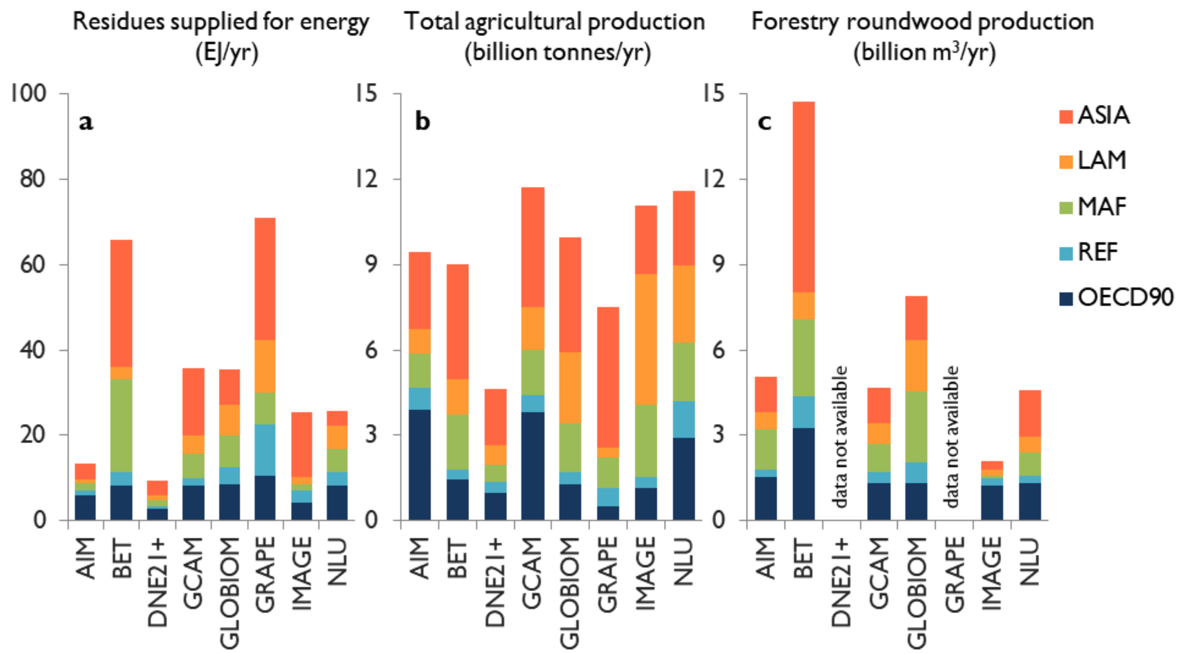

Figure S12 Quantity of residue supplied for primary energy per region (EJ/year) (**a**), agricultural production per region (billion tonnes) (**b**), and roundwood production per region (billion m^3) (**c**) in a scenario with an exogenous demand for 2nd generation bioenergy that increases linearly from 2010 levels to 300 EJ/yr by 2100, note that GLOBIOM only includes forestry residues, abbreviations: LAM= Latin America, MAF= Middle East and Africa; REF = reforming economies (former Soviet Union and Eastern Europe); OECD90 = OECD member countries in 1990, for regional definitions see Table S3

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6

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

Supplementary Information

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

Supplementary information

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1. Parameterisation

Table S1 | Parameter values. Default values are means across literature. Minimum and maximum values are detailed in notes b and e below. *References per parameter are listed in Table S2.*

Parameter	Abbreviation	Specification	Value (min-max)	Unit
Biomass to energy carrier conversion efficiency[a]	η	electricity from woody biomass	5.8 (5.4 - 6.1)[b]	GJ_{elec}/t dbm
		electricity from grassy biomass	5.7 (5.4 - 6.0)[b]	
		FT-diesel from woody biomass	8.1 (7.6 - 8.6)[b]	GJ_{fuel}/t dbm
		FT-diesel from grassy biomass	8.0 (7.5 - 8.5)[b]	
		ethanol from woody biomass	7.1 (6.5 - 7.6)[b]	
		ethanol from grassy biomass	7.0 (6.4 - 7.5)[b]	
		ethanol from sugar cane	7.2 (7.0 - 7.4)[b]	
Conversion efficiency penalty due to CCS	π	lignocellulosic electricity	1.8	GJ_{elec}/t dbm
		lignocellulosic FT-diesel	0[c]	GJ_{fuel}/t dbm
		lignocellulosic ethanol	1.9	
		sugarcane ethanol	0.3	
Fertiliser emissions	$em_{Fertiliser}$	woody biomass	55	
		grassy biomass	54	kg CO_2-eq. /t dbm
		sugarcane (South America)	73	
		sugarcane (rest of World)	151	
Supply chain emissions[d]	$Em_{Supply\ Chain}$	electricity from woody biomass	13 (7 - 27)[e]	kg CO_2-eq./GJ_{elec}
		electricity from grassy biomass	16 (8 - 31)[e]	
		FT-diesel from woody biomass	19 (9 - 37)[e]	kg CO_2-eq./GJ_{fuel}
		FT-diesel from grassy biomass	18 (9 - 36)[e]	
		ethanol from woody biomass	14 (7 - 28)[e]	
		ethanol from grassy biomass	20 (10 - 39)[e]	
		ethanol from sugar cane	16 (8 - 33)[e]	
Additional supply chain emissions CCS	$Em_{Supply\ Chain\ CCS}$	electricity	11	kg CO_2-eq./GJ_{elec}
		liquid fuels	3.0	kg CO_2-eq./GJ_{fuel}
Biomass carbon content	cc	lignocellulosic biomass	0.50	t C / t dbm
		sugarcane	0.45[f]	
Carbon capture efficiency	κ	electricity	0.90	t biogenic CO_2 captured / t CO_2 produced[h]
		FT-diesel	0.52[g]	
		lignocellulosic ethanol	0.12	
		sugarcane ethanol	0.24	
Loss factor[i]	f_{loss}	all	0.92	*dimensionless*

Abbreviations | t = metric tonne, dbm= dry biomass, FT = Fischer-Tropsch. **Notes | a,** The calculation of the literature-derived biomass to final energy carrier conversion efficiency ('conversion efficiency') is explained detail below. **b,** Minimum and maximum values for biomass to energy carrier conversion efficiency represent the range of variation of the mean value, and were based on the 2.5 and 97.5 percentiles of the uncertainty of the mean. This range was estimated by multiplying the inverse of the T distribution for these percentiles by the standard error of the mean across the mean or default values reported in literature. **c,** The conversion efficiency of lignocellulosic biomass to FT-diesel is not or hardly reduced by adding CCS (Van Vliet et al., 2009; Xie et al., 2011; Meerman et al., 2011; Koorneef et al., 2012), as a relatively pure stream of CO_2 is already produced in the FT-process. The CCS conversion efficiency penalty was therefore set to zero. **d,** Supply chain GHG emissions represent a well-to-tank perspective for fuels and a cradle-to-factory-gate perspective for electricity, but exclude N_2O emissions from fertilisers which are separately reported. **e,** Supply chain GHG emissions have large technological and geographical variability and future estimates of these emissions are uncertain. Minimum and maximum values are a therefore set at a factor two lower or higher than the literature average, as explained in the sensitivity analysis on page 28 of this SI. **f,** The carbon content of dry sugarcane biomass was determined as the weighted average of the carbon contents of sucrose and bagasse (Table S2). **g,** Nearly all CO_2 released during FT-diesel production can be captured and only CO_2 released during combustion is emitted, explaining the relatively high carbon capture rate of FT-diesel with CCS. **h**, CO_2 produced refers to the CO_2 produced in the power plant or refinery, and during liquid fuel use. **i,** The loss fraction refers to the fraction of biomass that remains after losses along the supply chain.

Conversion efficiency calculations

The conversion efficiency (η) parameter (Table 1) gives the amount of final energy produced per amount of biomass used, expressed in $GJ_{carrier}$ / tonne dry biomass. For lignocellulosic feedstocks, this parameter was calculated by multiplying the *energetic* conversion efficiency ($GJ_{carrier}/GJ_{biomass}$) with the energy content (enthalpy) of the lignocellulosic biomass feedstock ($GJ_{biomass}$/tonne dry biomass). Default values for these parameters were determined as the means across literature values reported in Table S2. For sugarcane, conversion efficiency (η) was determined as the mean of literature-based conversion efficiencies, which were in turn calculated per study assuming a typical moisture content of 75%, an ethanol energy density of 27 GJ/kg and an ethanol density of 0.789 kg/L. Throughout this study, all presented conversion efficiencies are lower heating value (LHV)-based.

Table S2 | Literature data used for this study's parameterisation. The values presented below are the reported or derived means per study or the median per study (where only the median was reported).

Parameter	Specification	Value	Unit	Reference
Energy content of biomass feedstock	Grasses (Miscanthus/switchgr.)	18.4	$GJ_{biomass}$ / t dbm	Phyllis2, 2019
	Woody (SRC / forestry)	18.6	$GJ_{biomass}$ / t dbm	Phyllis2, 2019
Energetic conversion efficiency w/o CCS	Lignocellulosic electricity	0.30	$MJ_{elec}/MJ_{biomass}$	NTL, 2012
		0.32	$MJ_{elec}/MJ_{biomass}$	Al Qayim 2015
		0.40	$MJ_{elec}/MJ_{biomass}$	IEA, 2007
		0.25	$MJ_{elec}/MJ_{biomass}$	Cherubini 2009
		0.32	$MJ_{elec}/MJ_{biomass}$	Hanssen et al. 2017
		0.29	$MJ_{elec}/MJ_{biomass}$	Hetland et al., 2016
		0.25	$MJ_{elec}/MJ_{biomass}$	IEA GHG, 2009
		0.34	$MJ_{elec}/MJ_{biomass}$	Edwards et al., 2013
		0.35	$MJ_{elec}/MJ_{biomass}$	Dwivedi et al., 2011
		0.34	$MJ_{elec}/MJ_{biomass}$	Guest et al., 2011
		0.27	$MJ_{elec}/MJ_{biomass}$	Thornley et al., 2008
		0.28	$MJ_{elec}/MJ_{biomass}$	Oreggioni et al., 2017
		0.33	$MJ_{elec}/MJ_{biomass}$	Thakur et al., 2014
		0.27	$MJ_{elec}/MJ_{biomass}$	Evans et al. ,2010
		0.32	$MJ_{elec}/MJ_{biomass}$	Steubing et al., 2011

Energetic conversion efficiency w/o CCS	Lignocellulosic electricity	0.27	$MJ_{elec}/MJ_{biomass}$	Van de Walle et al., 2007
		0.26	$MJ_{elec}/MJ_{biomass}$	Farine et al., 2012
		0.33	$MJ_{elec}/MJ_{biomass}$	IEA, 2007
		0.32	$MJ_{elec}/MJ_{biomass}$	Meerman et al., 2011
		0.30	$MJ_{elec}/MJ_{biomass}$	Heller et al. 2003
		0.33	$MJ_{elec}/MJ_{biomass}$	Hansen et al., 2013
		0.25	$MJ_{elec}/MJ_{biomass}$	Hennig & Gawor, 2012
		0.38	$MJ_{elec}/MJ_{biomass}$	Styles & Jones, 2007
		0.31	$MJ_{elec}/MJ_{biomass}$	Schlömer et al., 2014
	Lignocellulosic FT-diesel	0.25	$MJ_{fuel}/MJ_{biomass}$	Cruz et al., 2017
		0.45	$MJ_{fuel}/MJ_{biomass}$	Bright et al., 2010
		0.48	$MJ_{fuel}/MJ_{biomass}$	Van Vliet et al.,2009
		0.52	$MJ_{fuel}/MJ_{biomass}$	Xie et al., 2011
		0.45	$MJ_{fuel}/MJ_{biomass}$	Woods et al., 2003
		0.47	$MJ_{fuel}/MJ_{biomass}$	Meerman et al., 2011
		0.45	$MJ_{fuel}/MJ_{biomass}$	Bright & Strømman, 2010
		0.40	$MJ_{fuel}/MJ_{biomass}$	Jungbluth et al., 2007
		0.45	$MJ_{fuel}/MJ_{biomass}$	Edwards et al., 2013
		0.35	$MJ_{fuel}/MJ_{biomass}$	Ail & Dasappa 2016
		0.41	$MJ_{fuel}/MJ_{biomass}$	Wu et al., 2006
		0.46	$MJ_{fuel}/MJ_{biomass}$	Larson & Jin, 1999
		0.46	$MJ_{fuel}/MJ_{biomass}$	Larson et al., 2006
		0.36	$MJ_{fuel}/MJ_{biomass}$	Prins et al., 2004
		0.43	$MJ_{fuel}/MJ_{biomass}$	Tijmensen et al., 2002
		0.44	$MJ_{fuel}/MJ_{biomass}$	Liu et al., 2010
		0.41	$MJ_{fuel}/MJ_{biomass}$	Hamelinck et al., 2004
		0.49	$MJ_{fuel}/MJ_{biomass}$	Reichling et al., 2011
	Lignocellulosic ethanol[a]	0.34	$MJ_{fuel}/MJ_{biomass}$	Gonzalez-Garcia et al., 2010
		0.50	$MJ_{fuel}/MJ_{biomass}$	Laser et al., 2009
		0.50	$MJ_{fuel}/MJ_{biomass}$	Wu et al., 2005
		0.42	$MJ_{fuel}/MJ_{biomass}$	Bright et al., 2010
		0.33	$MJ_{fuel}/MJ_{biomass}$	Edwards et al., 2013
		0.46	$MJ_{fuel}/MJ_{biomass}$	Bright & Strømman, 2010
		0.43	$MJ_{fuel}/MJ_{biomass}$	Mu et al., 2010
		0.42	$MJ_{fuel}/MJ_{biomass}$	Mullins et al., 2011
		0.34	$MJ_{fuel}/MJ_{biomass}$	Woods & Bauen, 2003
		0.37	$MJ_{fuel}/MJ_{biomass}$	McKechnie et al., 2011b
		0.42	$MJ_{fuel}/MJ_{biomass}$	Spatari et al., 2005
		0.29	$MJ_{fuel}/MJ_{biomass}$	Spatari et al., 2010
		0.33	$MJ_{fuel}/MJ_{biomass}$	Daystar et al., 2015
		0.42	$MJ_{fuel}/MJ_{biomass}$	Daystar et al., 2012
		0.33	$MJ_{fuel}/MJ_{biomass}$	Farine et al., 2012
		0.32	$MJ_{fuel}/MJ_{biomass}$	Zhuang et al., 2013
		0.33	$MJ_{fuel}/MJ_{biomass}$	Girard & Fallot, 2006

Energetic conversion efficiency w/o CCS	Lignocellulosic ethanol[a]	0.44	$MJ_{fuel}/MJ_{biomass}$	Schmer et al., 2008
		0.36	$MJ_{fuel}/MJ_{biomass}$	Budsberg et al., 2012
		0.43	$MJ_{fuel}/MJ_{biomass}$	Wang et al., 2012
		0.38	$MJ_{fuel}/MJ_{biomass}$	Jonker et al., 2015
		0.28	$MJ_{fuel}/MJ_{biomass}$	Murphy et al., 2015
		0.27	$MJ_{fuel}/MJ_{biomass}$	Cadoux et al., 2014
Conversion efficiency w/o CCS	Sugarcane ethanol[b]	1.89	GJ_{fuel}/ t wbm	Macedo et al., 2004
		1.71	GJ_{fuel}/ t wbm	Jonker et al., 2015
		1.77	GJ_{fuel}/ t wbm	Jonker et al., 2016
		1.84	GJ_{fuel}/ t wbm	Macedo et al., 2008
		1.81	GJ_{fuel}/ t wbm	Dias de Oliveira et al., 2005
		1.77	GJ_{fuel}/ t wbm	de Vries et al., 2010
		1.92	GJ_{fuel}/ t wbm	Macedo et al., 2004
		1.85	GJ_{fuel}/ t wbm	Egeskog et al., 2014
		1.70	GJ_{fuel}/ t wbm	Manochio et al., 2017
		1.73	GJ_{fuel}/ t wbm	Seabra et al., 2011
		1.80	GJ_{fuel}/ t wbm	Tsiropoulos et al., 2014
Energetic conversion efficiency penalty due to CCS	Lignocellulosic electricity (pre-combustion BECCS)	0.08	$MJ_{elec}/MJ_{biomass}$	Erlach et al., 2012
		0.1	$MJ_{elec}/MJ_{biomass}$	Hetland et al. 2016
		0.07	$MJ_{elec}/MJ_{biomass}$	Meerman et al., 2011, 2013
		0.12	$MJ_{elec}/MJ_{biomass}$	Markewitz et al., 2012
		0.1	$MJ_{elec}/MJ_{biomass}$	Damen et al., 2006
	Lignocellulosic electricity (post-combustion BECCS)	0.12	$MJ_{elec}/MJ_{biomass}$	NTL, 2012
		0.09	$MJ_{elec}/MJ_{biomass}$	Al Qayim et al., 2015
		0.1	$MJ_{elec}/MJ_{biomass}$	Schakel et al., 2014
		0.1	$MJ_{elec}/MJ_{biomass}$	Damen et al., 2006
		0.11	$MJ_{elec}/MJ_{biomass}$	Markewitz et al., 2012
	Lignocellulosic electricity (oxyfuel BECCS)	0.06	$MJ_{elec}/MJ_{biomass}$	Al Qayim et al., 2015
		0.07	$MJ_{elec}/MJ_{biomass}$	NTL, 2012
		0.1	$MJ_{elec}/MJ_{biomass}$	Markewitz et al., 2012
		0.11	$MJ_{elec}/MJ_{biomass}$	Damen et al., 2006
	Lignocellulosic electricity ([BE]CCS in general)	0.1	$MJ_{elec}/MJ_{biomass}$	Hetland et al., 2016
		0.1	$MJ_{elec}/MJ_{biomass}$	Spath & Mann, 2004
	Lignocellulosic FT-diesel[c]	0.00	$MJ_{fuel}/MJ_{biomass}$	*note **c***
Conversion efficiency penalty due to CCS	Sugarcane ethanol	0.33	GJ_{fuel}/ t wbm	Moreira et al., 2016
Energetic conversion efficiency with CCS	Lignocellulosic FT-diesel[c]	0.42	$MJ_{fuel}/MJ_{biomass}$	Koorneef et al., 2012
		0.45	$MJ_{fuel}/MJ_{biomass}$	Meerman et al. 2011, 2013
		0.47	$MJ_{fuel}/MJ_{biomass}$	Van vliet et al., 2009
		0.50	$MJ_{fuel}/MJ_{biomass}$	Xie et al., 2011
	Lignocellulosic ethanol[d]	0.29	$MJ_{fuel}/MJ_{biomass}$	Koorneef et al., 2012
		0.26	$MJ_{fuel}/MJ_{biomass}$	Wetterlund et al., 2010

Fertiliser GHG emissions	Woody biomass (SRC)	55	kg CO_2-eq. / t dbm	Hamelinck & Hoogwijk, 2007
	Grasses (Miscanthus)	54	kg CO_2-eq. / t dbm	Hamelinck & Hoogwijk, 2007
	Sugarcane(South America)	73	kg CO_2-eq. / t dbm	Smeets et al., 2009
	Sugarcane (rest of world)	151	kg CO_2-eq. / t dbm	Smeets et al., 2009
Fraction N2O in total lifecycle supply chain GHG emissions (GWP-100 based)[e]	Various supply chains	0.18	dimensionless	Elsayed et al., 2003
		0.37	dimensionless	Boschiero et al., 2016
		0.07	dimensionless	Dwivedi et al., 2011
		0.15	dimensionless	Jonker et al., 2013
		0.11	dimensionless	Oreggioni et al., 2017
		0.01	dimensionless	Whittaker et al., 2011
		0.21	dimensionless	Elsayed et al., 2003
		0.58	dimensionless	Djomo et al., 2015
		0.49	dimensionless	Whittaker et al., 2016
		0.52	dimensionless	Hansen et al., 2013
		0.21	dimensionless	Elsayed et al., 2003
		0.25	dimensionless	Fazio & Monti, 2011
		0.53	dimensionless	Djomo et al., 2015
		0.01	dimensionless	Hoefnagels et al., 2010
		0.21	dimensionless	Brinkman et al., 2005
		0.31	dimensionless	Stephenson et al., 2010
		0.11	dimensionless	Edwards et al., 2014
		0.31	dimensionless	Hoefnagels et al., 2010
		0.18	dimensionless	Hoefnagels et al., 2010
		0.17	dimensionless	Wang et al., 2012
		0.22	dimensionless	Fazio & Monti, 2011
		0.11	dimensionless	Gonzalez-Garcia et al., 2010
		0.16	dimensionless	Murphy et al., 2015
		0.08	dimensionless	Hsu et al., 2010
		0.29	dimensionless	Groode & Heywood, 2007
		0.37	dimensionless	Wu et al., 2005
		0.22	dimensionless	Mullins et al., 2011
		0.44	dimensionless	Spatari et al., 2005
		0.27	dimensionless	Spatari et al., 2010
		0.11	dimensionless	Bai et al., 2010
		0.00	dimensionless	Van Vliet et al., 2009
		0.00	dimensionless	Van Vliet et al., 2009
		0.02	dimensionless	Hoefnagels et al., 2010
		0.23	dimensionless	Jungbluth et al., 2007
		0.32	dimensionless	Hoefnagels et al., 2010
		0.22	dimensionless	Hoefnagels et al., 2010
		0.41	dimensionless	Fazio & Monti, 2011
		0.31	dimensionless	Jungbluth et al., 2007
		0.43	dimensionless	Wu et al., 2005
Lifecycle supply chain GHG emissions[e,f]	Electricity from woody biomass (SRC)	12	kg CO_2-eq. / GJ_{elec}	Cannell, 2003
		8	kg CO_2-eq. / GJ_{elec}	Creutzig et al., 2015
		12	kg CO_2-eq. / GJ_{elec}	Hennig & Gawor, 2012

Lifecycle supply chain GHG emissions^{e,f}	Electricity from woody biomass (SRC)	16	kg CO$_2$-eq. / GJ$_{elec}$	Elsayed et al., 2003
		15	kg CO$_2$-eq. / GJ$_{elec}$	Cherubini et al., 2009
		11	kg CO$_2$-eq. / GJ$_{elec}$	Edwards et al., 2014
		13	kg CO$_2$-eq. / GJ$_{elec}$	Djomo et al., 2015
		18	kg CO$_2$-eq. / GJ$_{elec}$	Whittaker et al., 2016
		58	kg CO$_2$-eq. / GJ$_{elec}$	Goglio & Owende 2009
		29	kg CO$_2$-eq. / GJ$_{elec}$	Styles & Jones, 2007
		11	kg CO$_2$-eq. / GJ$_{elec}$	Heller et al., 2003
		26	kg CO$_2$-eq. / GJ$_{elec}$	Giuntoli et al., 2014
		12	kg CO$_2$-eq. / GJ$_{elec}$	Hansen et al., 2013
		4	kg CO$_2$-eq. / GJ$_{elec}$	McCalmont et al., 2017
	Electricity from grasses (Miscanthus/switchgrass)	21	kg CO$_2$-eq. / GJ$_{elec}$	Creutzig et al., 2015
		26	kg CO$_2$-eq. / GJ$_{elec}$	Elsayed et al., 2003
		15	kg CO$_2$-eq. / GJ$_{elec}$	Fazio & Monti, 2011
		30	kg CO$_2$-eq. / GJ$_{elec}$	Styles & Jones, 2007
		11	kg CO$_2$-eq. / GJ$_{elec}$	Smeets et al., 2009
		22	kg CO$_2$-eq. / GJ$_{elec}$	Robertson et al., 2016
		9	kg CO$_2$-eq. / GJ$_{elec}$	Djomo et al., 2015
		32	kg CO$_2$-eq. / GJ$_{elec}$	Djomo et al., 2013
	FT-diesel from woody biomass (SRC)	16	kg CO$_2$-eq. / GJ$_{fuel}$	Woods et al., 2003
		44	kg CO$_2$-eq. / GJ$_{fuel}$	Jungbluth et al., 2007
		10	kg CO$_2$-eq. / GJ$_{fuel}$	Edwards et al., 2014
		24	kg CO$_2$-eq. / GJ$_{fuel}$	Ail & Dasappa, 2016
		29	kg CO$_2$-eq. / GJ$_{fuel}$	Menten et al., 2013
	FT-diesel from grasses (Miscanthus/switchgrass)	19	kg CO$_2$-eq. / GJ$_{fuel}$	Hoefnagels et al., 2010
		14	kg CO$_2$-eq. / GJ$_{fuel}$	Hoefnagels et al., 2010
		9	kg CO$_2$-eq. / GJ$_{fuel}$	Fazio & Monti, 2011
		58	kg CO$_2$-eq. / GJ$_{fuel}$	Jungbluth et al., 2007
		13	kg CO$_2$-eq. / GJ$_{fuel}$	Wu et al., 2005
		29	kg CO$_2$-eq. / GJ$_{fuel}$	Menten et al., 2013
	Ethanol from woody biomass (SRC)	22	kg CO$_2$-eq. / GJ$_{fuel}$	Woods et al., 2003
		20	kg CO$_2$-eq. / GJ$_{fuel}$	Brinkman et al., 2005
		17	kg CO$_2$-eq. / GJ$_{fuel}$	Whitaker et al., 2010
		25	kg CO$_2$-eq. / GJ$_{fuel}$	McKechnie et al., 2011b
		10	kg CO$_2$-eq. / GJ$_{fuel}$	Mu et al., 2010
		20	kg CO$_2$-eq. / GJ$_{fuel}$	Stephenson et al., 2010
		10	kg CO$_2$-eq. / GJ$_{fuel}$	Budsberg et al., 2012
		23	kg CO$_2$-eq. / GJ$_{fuel}$	Edwards et al., 2014
		19	kg CO$_2$-eq. / GJ$_{fuel}$	Menten et al., 2013
	Ethanol from grasses (Miscanthus/switchgrass)	20	kg CO$_2$-eq. / GJ$_{fuel}$	Hoefnagels et al., 2010
		17	kg CO$_2$-eq. / GJ$_{fuel}$	Hoefnagels et al., 2010
		14	kg CO$_2$-eq. / GJ$_{fuel}$	Spatari & Maclean, 2010
		24	kg CO$_2$-eq. / GJ$_{fuel}$	Daystar et al., 2015
		26	kg CO$_2$-eq. / GJ$_{fuel}$	Wang et al., 2012

Lifecycle supply chain GHG emissions[e,f]	Ethanol from grasses (Miscanthus/switchgrass)	26	kg CO_2-eq. / GJ_{fuel}	Whitaker et al., 2010
		17	kg CO_2-eq. / GJ_{fuel}	Fazio & Monti, 2011
		47	kg CO_2-eq. / GJ_{fuel}	Gonzalez-Garcia et al., 2010
		56	kg CO_2-eq. / GJ_{fuel}	Murphy et al., 2015
		43	kg CO_2-eq. / GJ_{fuel}	Hsu et al., 2010
		6	kg CO_2-eq. / GJ_{fuel}	Groode & Heywood, 2007
		20	kg CO_2-eq. / GJ_{fuel}	Brinkman et al., 2005
		16	kg CO_2-eq. / GJ_{fuel}	Wu et al., 2005
		15	kg CO_2-eq. / GJ_{fuel}	Mullins et al., 2011
		23	kg CO_2-eq. / GJ_{fuel}	Spatari et al., 2005
		32	kg CO_2-eq. / GJ_{fuel}	Spatari et al., 2010
		28	kg CO_2-eq. / GJ_{fuel}	Bai et al., 2010
		41	kg CO_2-eq. / GJ_{fuel}	Cherubini et al., 2011
		19	kg CO_2-eq. / GJ_{fuel}	Menten et al., 2013
	Electricity from boreal forestry	24	kg CO_2-eq. / GJ_{elec}	Creutzig et al., 2015
		19	kg CO_2-eq. / GJ_{elec}	McKechnie et al., 2011a
		13	kg CO_2-eq. / GJ_{elec}	Oreggioni et al., 2017
Additional lifecycle supply chain GHG emissions from CCS	Electricity	9.0	kg CO_2-eq. / GJ_{elec}	Creutzig et al., 2015
		12.8	kg CO_2-eq. / GJ_{elec}	Modahl et al., 2011
	Liquid fuels	3.0	kg CO_2-eq. / GJ_{fuel}	Creutzig et al., 2015
Biomass carbon content	Lignocellulosic biomass	0.50	t C / t dbm	Phyllis2, 2019
Sucrose content of sugarcane		0.15	t sucrose/ t wbm	Jonker et al., 2015
		0.14	t sucrose/ t wbm	Macedo et al., 2008
		0.14	t sucrose/ t wbm	Seabra et al., 2011
Bagasse content of sugarcane		0.14	t bagasse / t dbm	Jonker et al., 2015
		0.13	t bagasse / t dbm	Macedo et al., 2008
		0.13	t bagasse / t dbm	Seabra et al., 2011
Sucrose carbon content		0.42	t C / t sucrose	*stoichiometrics*
Bagasse carbon content		0.49	t C / t bagasse	Phyllis2, 2019
Carbon capture rate	Lignocellulosic electricity[g]	0.79	t CO_2 cap. /t CO_2 prod.	Erlach et al., 2012
		0.85	t CO_2 cap. /t CO_2 prod.	Koorneef et al., 2012
		0.90	t CO_2 cap. /t CO_2 prod.	Schakel et al., 2014
		0.95	t CO_2 cap. /t CO_2 prod.	Meerman et al., 2013
		0.87	t CO_2 cap. /t CO_2 prod.	Al Qayim et al., 2015
		0.99	t CO_2 cap. /t CO_2 prod.	NETL, 2012
		0.90	t CO_2 cap. /t CO_2 prod.	Cuellar-France & Azapagic, 2015
		0.90	t CO_2 cap. /t CO_2 prod.	Hetland et al., 2016
		0.90	t CO_2 cap. /t CO_2 prod.	NTL, 2012
		0.90	t CO_2 cap. /t CO_2 prod.	IEA GHG, 2009

Carbon capture rate	Lignocellulosic electricity[g]	0.88	t CO_2 cap. /t CO_2 prod.	Markewitz et al., 2012
		0.90	t CO_2 cap. /t CO_2 prod.	Damen et al., 2006
		0.90	t CO_2 cap. /t CO_2 prod.	Al Qayim et al., 2015
	Fossil fuel based-electricity[h]	0.90	t CO_2 cap. /t CO_2 prod.	Koorneef et al., 2012
		0.83	t CO_2 cap. /t CO_2 prod.	Alonso et al., 2014
		0.90	t CO_2 cap. /t CO_2 prod.	Odeh & Cockerill, 2008
		0.90	t CO_2 cap. /t CO_2 prod.	Schakel et al., 2014
		0.90	t CO_2 cap. /t CO_2 prod.	Volkart et al., 2013
		0.90	t CO_2 cap. /t CO_2 prod.	Volkart et al., 2013
		0.95	t CO_2 cap. /t CO_2 prod.	Volkart et al., 2013
		0.89	t CO_2 cap. /t CO_2 prod.	Petrescu et al., 2017
		0.92	t CO_2 cap. /t CO_2 prod.	Corsten et al.,2013
		0.90	t CO_2 cap. /t CO_2 prod.	Knoope et al., 2013
		0.90	t CO_2 cap. /t CO_2 prod.	Cuellar-France & Azapagic, 2015
	Lignocellulosic FT-diesel	0.53	t CO_2 cap. /t CO_2 prod.	Meerman et al., 2013
		0.50	t CO_2 cap. /t CO_2 prod.	Van Vliet et al., 2009
		0.54	t CO_2 cap. /t CO_2 prod.	Koorneef et al., 2012
	Lignocellulosic ethanol	0.11	t CO_2 cap. /t CO_2 prod.	Koorneef et al., 2012; Laude et al., 2011; De Visser et al., 2011
		0.13	t CO_2 cap. /t CO_2 prod.	Wetterlund et al., 2010
	Sugarcane ethanol[i]	0.24	t CO_2 cap. /t CO_2 prod.	*note **i***
Loss factor		0.09	dimensionless	Röder et al., 2015
		0.07	dimensionless	Sikkema et al., 2010
		0.088	dimensionless	Forsberg, 2000
		0.08	dimensionless	Kumar & Sokhansanj, 2006

Abbreviations | t = metric tonne, dbm= dry biomass, wbm = wet biomass, CCS = carbon capture and storage, SRC = short-rotation coppicing, cap. = captured, prod. = produced. **Notes | a,** Energetic conversion efficiencies of lignocellulosic ethanol production were based on studies on both fermentation and thermochemical pathways. **b,** Conversion efficiencies presented for sugarcane are often not as reported in literature, but rather calculated from other metrics that were reported (e.g., ethanol production in litres per tonne of wet sugarcane). Conversion efficiencies ($GJ_{ethanol}$/ tonne dry sugarcane biomass) were derived assuming a typical moisture content of 75%, an ethanol energy density of 27 GJ/kg and an ethanol density of 0.789 kg/L. **c,** The energetic conversion efficiency of lignocellulosic biomass to FT-diesel is not or hardly reduced by adding CCS (Van Vliet et al., 2009; Xie et al., 2011; Meerman et al., 2011; Koorneef et al., 2012), as a relatively pure stream of CO_2 is already produced in the FT-process. The CCS energetic conversion efficiency penalty was therefore set to zero. **d,** For lignocellulosic ethanol, the energetic conversion efficiency penalty due to CCS was determined using the difference between energetic conversion efficiency with CCS and energetic conversion efficiency without CCS. **e,** The reported literature-based supply chain GHG emissions in Table S2 include N_2O emissions. In the final parameterisation (Table S1) however, N_2O emissions are deducted from supply chain emissions to avoid double counting fertiliser emissions, which form the large majority of N_2O emissions. In this calculation the share of N_2O emissions in supply chain emissions was assumed to be 24%, based on the mean share of N_2O emissions across literature reported in Table S2, while using GWP-100 based characterisation factors for the different GHGs. **f,** Reported supply chain GHG emissions represent a well-to-tank perspective for fuels, and a cradle to factory gate perspective for electricity (i.e., all steps up until electricity generation, not including electricity distribution). **g,** The carbon capture rate of lignocellulosic electricity was estimated using studies on all main CCS technologies: oxyfuel, pre-combustion, and post-combustion CCS. **h,** BECCS electricity carbon capture rates were co-determined using results on fossil-based electricity with CCS (which hardly differed from BECCS-specific estimates). **i,** This is based on the assumptions that all sucrose is fermented, that half the carbon content of sucrose forms CO_2 during fermentation, and that fermentation of sucrose creates a near pure stream of CO_2 that can be captured entirely (based on Moreira et al., 2016; Laude et al., 2011; Sanchez et al., 2018).

Table S3 | Benchmark emission factors for electricity and liquid fuels. Emission factors include full life cycle GHG emissions. Emission factor (ranges) of benchmark electricity generation technologies and liquid fossil fuels are based on median values for emission intensities reported in literature.

Benchmark	Emission factor	Unit	Reference
Solar (PV, CSP) and wind (on/offshore)	2 - 16	kg CO_2-eq./GJ_{elec}	Brückner et al. (2014) Hertwich et al. (2015)
Fossil with CCS (natural gas and coal-based[a])	44 - 73		
Natural gas w/o CCS (NGCC)	136 - 146		
Coal w/o CCS (IGCC, PC, Sub-critical)	220 - 259		
Petrol	92.4	kg CO_2-eq./GJ_{fuel}	Giuntoli et al. (2014)[b]
Diesel	93.9		

Abbreviations | PV = Photovoltaics; CSP = Concentrated Solar Power; CCS = Carbon Capture and Storage; NGCC = Natural Gas Combined Cycle; IGCC = Integrated Gasification Combined Cycle; PC = Pulverised Coal. **Notes | a**, EFs of electricity from natural-gas fired power plants with CCS lie within the same range as EFs of electricity from coal-fired power plants with CCS. **b,** Lifecycle GHG emission estimates of fossil diesel and petrol vary significantly in literature (Eriksson & Ahlgren, 2013), the values from Giuntoli et al. (2014) used in this study are European benchmark values and in the middle of the range of GHG emission estimates.

Carbon stocks of degraded forests

This section details how the fraction of aboveground carbon stocks in degraded forests was estimated, as compared to the forests' untouched state. This estimate was based on i) the reduction in carbon stocks after forest degradation, ii) the subsequent biomass regrowth and associated carbon uptake rate in degraded forests, and iii) the time since the last degradation event. First, the aboveground carbon stock reduction in degraded forests varies widely from approximately 20% to 90%; we use the cross-literature average reduction of 45%, as compared to the unharvested state (Andrade et al., 2017; Rappaport et al., 2018). Second, the recovery of aboveground carbon stocks in tropical degraded forests is also highly variable (Bonner et al., 2013; Poorter et al., 2016), but carbon stocks on average recover to 52% of their pre-disturbance state within 20 years (estimated from Poorter et al., 2016 who analysed tropical South and Central America). Third, we assumed that the last degradation event on average took place within the last 20 years (Poorter et al., 2016). Using these parameters, we then estimated current aboveground carbon stocks of degraded forests as a fraction of unharvested forests following equation S1:

$$f_{C\ degraded} = f_{C\ remaining} + f_{C\ removed} \cdot f_{regrowth, 20\ years} \cdot ½ \qquad \textbf{eq. S1}$$

Where: $f_{C\ degraded}$ is the fraction of carbon stocks present in a forest that has been degraded within the last 20 years, as compared to its untouched state, $f_{C\ remaining}$ is the fraction of carbon stocks remaining directly after a degradation event, $f_{C\ removed}$ is the fraction of carbon stocks that is removed after degradation (and therefore the fraction that will regrow), $f_{regrowth\ 20\ years}$ is the fraction of removed carbon stocks that regrows in 20 years; the latter part of the equation is multiplied with ½ to reflect that a degradation on average took place *within* the last 20 years, rather than 20 years ago.

When filling in the right hand side of this equation with the literature-based average parameter values reported above, this equation becomes: $0.55 + 0.45 \cdot 0.52 \cdot ½ = 0.667 \approx 2/3$. We thus estimated that aboveground carbon stocks in forests that have been degraded within the last 20 years are at approximately two-thirds of their untouched state.

2. Global bioenergy crop yields

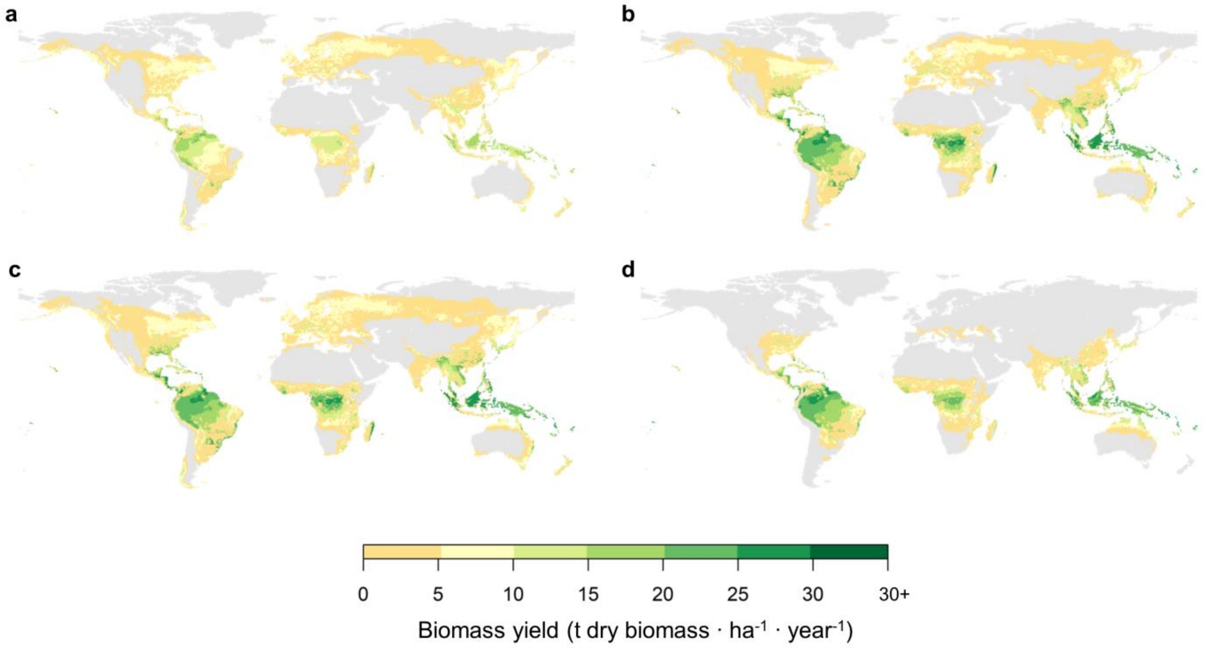

Figure S1 | Modelled annual bioenergy crop yields. a, Woody bioenergy crops (based on SRC willow in temperate and colder areas, SRC Eucalyptus in the tropics). **b,** Grasses (based on *Miscanthus* and switchgrass cultivars). **c,** Lignocellulosic biomass, i.e., woody crops or grasses depending on which crop type results in the lowest EF (see figure S3). **d,** Sugar cane. Note that the displayed modelled yields are annualised average yields for the period of 2020-2050 and that agricultural areas are included in these maps.

3. Previous land cover types

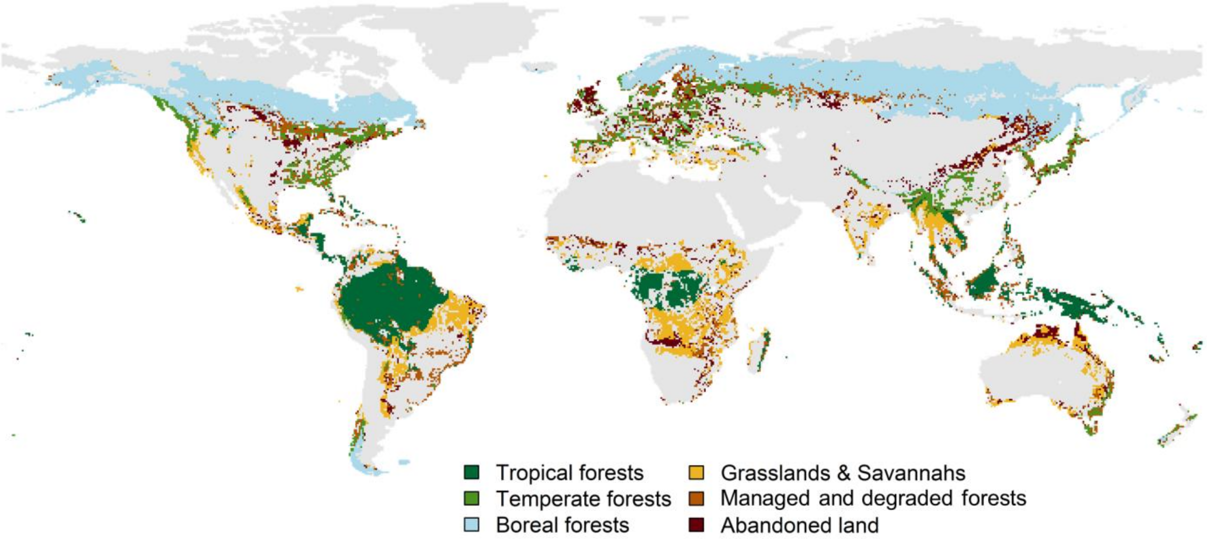

Figure S2 | Map of land cover types in 2020. This is the distribution of land cover types before the modelled conversion to bioenergy crops or natural regrowth. Note that agricultural land (cropland and pastures, according to the default IMAGE-run SSP2 scenario) are excluded from our analysis and this map, and that areas with bioenergy crop yields below 5% of the global maximum yield are excluded from our analysis as well. Abandoned lands are based on what 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 re-growing state after recent human interventions. It encompasses: i) *managed forests* for wood production, which predominantly occur in temperate and boreal zones, and ii) re-growing *degraded forests* that remain after logging for the most valuable trees or slash-and-burn practices, predominantly in tropical areas.

4. Lignocellulosic bioenergy crops selection

Our default results in the main text represent lignocellulosic bioenergy crops in general, selecting grasses or woody crops for each grid cell depending on which results in the lowest EF. Figure S3a shows where these two crop types can grow (excluding agricultural and unproductive areas). Figure S3b shows which crop type is selected based on the aforementioned criterion of resulting in the lowest EF. This spatial pattern is the same for all investigated bioenergy pathways.

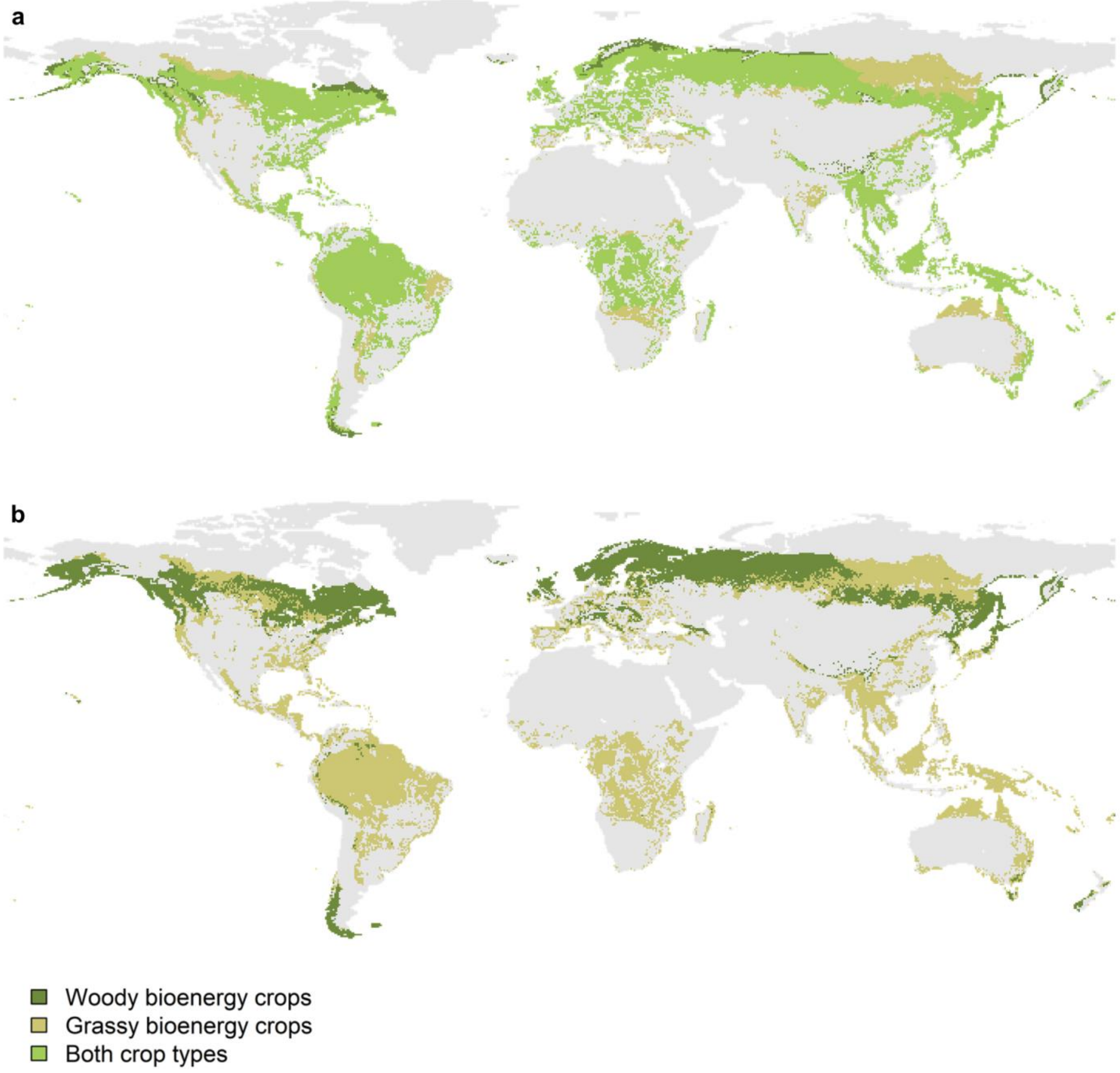

Figure S3 | Lignocellulosic bioenergy crop maps. a, Potential occurrence of grassy bioenergy crops (e.g., *Miscanthus* and switchgrass cultivars) and woody bioenergy crops (short-rotation coppiced *Eucalyptus* in the tropics and willow in colder areas) in LPJml, agricultural land (cropland and pastures, according to the default IMAGE-run SSP2 scenario) and areas with yields below 5% of the global maximum are excluded. **b**, Map showing which lignocellulosic bioenergy crop is used in our default results for "lignocellulosic" bioenergy, which is based on which crop yields the lowest EF. Agricultural and unproductive areas are again excluded.

Beside our default EF-based selection (Figure S3b and S4a), we investigated two alternative methods to select a crop type per location: i) based on which crop type results in highest bioenergy potential (Figure S4b), and ii) which crop type has an “optimal” combination of low EF and high potential, using a pareto front of bioenergy potential and inverse, scaled EFs (Figure S4c). Emission-supply curves are not visibly altered under different crop selection methods (Figure S4d). Few locations change crop type under different selection methods (Figure S4a-c), as EF and bioenergy potential are strongly correlated. Locations that do change from woody to grassy biomass (predominantly in mountainous and sub-boreal areas) hardly affect emission-supply curves, as bioenergy potential is relatively low in these areas.

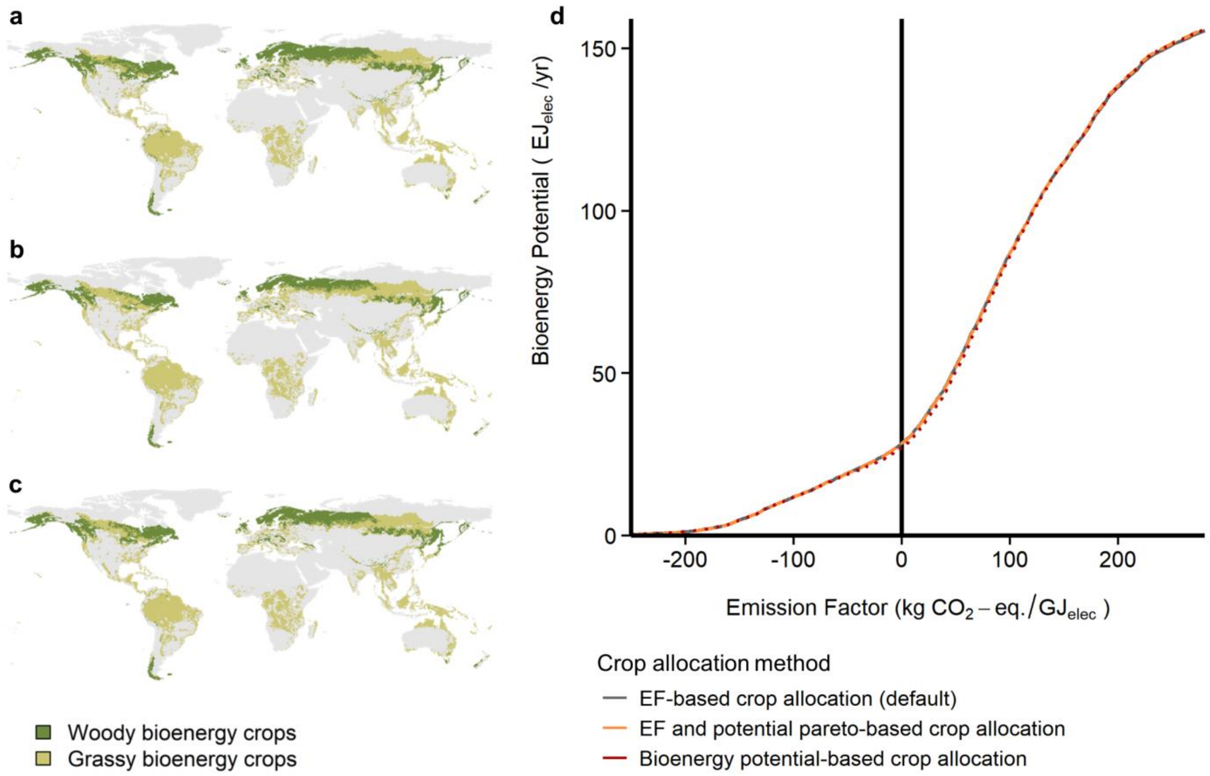

Figure S4 | Effects of alternative lignocellulosic crop type selection methods. Maps indicate whether grassy bioenergy crops (represented by *Miscanthus* and switchgrass cultivars) and woody bioenergy crops (short-rotation coppiced Eucalyptus in the tropics and willow and poplar in colder areas) are selected for each grid cell, based on: **a**, which crop type results in lowest EFs (as used in our analysis), **b**, which crop type results in highest bioenergy potential, or **c**, which crop type has an “optimal” combination of low EF and high potential (using a pareto front of bioenergy potential and inverse, scaled EFs). **d**, Emission-supply curves of ligno-cellulosic bioelectricity with CCS with different lignocellulosic crop selection methods.

5. Biomass residues available for bioenergy

We analysed the carbon sequestration potential of BECCS, using our EFs and BECCS supply potentials, in two illustrative climate change mitigation pathways in the IPCC SR1.5°C: the S2 middle-of-the-road pathway and the S5 high-energy-demand pathway (Rogelj et al., 2018; Huppman et al., 2019). When also including biomass residues in this analysis, 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 SSP2 baseline scenario modelled in the IMAGE integrated assessment model (Table S4). Residue availability for bioenergy included both agricultural and forestry residues and accounted for competing, non-energy uses of biomass residues.

Table S4 | Residue availability over time following the SSP2 baseline scenario in the IMAGE integrated assessment model. Residue availability for bioenergy included both agricultural and forestry residues and accounted for competing, non-energy uses of biomass residues.

Year	Biomass residues availability ($EJ_{primary}$/year)
2020	59.2
2030	69.2
2040	77.0
2050	82.8
2060	84.8
2070	86.3
2080	86.8
2090	88.8
2100	90.3

6. Overview of BECCS potentials and land area requirements

Table S5 | Global energy potential, sequestration potential and land area results for various forms of BECCS over 30 and 80 year evaluation times.

Scenario	**Energy potential at EF<0**[a]		**Sequestration potential**[b]		**Land area used to achieve potential**		**Share of which on natural land**[c]	
	($EJ_{carrier}$ / year)		(Gt CO_2-eq / year)		(Gha)		(%)	
evaluation period	*30 years*	*80 years*	*30 years*	*80 years*	*30 years*	*80 years*	*30 years*	*80 years*
Default								
lign. crop electricity	28	220	2.5	40	0.76	4.43	53%	79%
lign. crop FT-diesel	4.4	282	0.1	4.8	0.09	2.22	53%	75%
lign. crop ethanol	0	0	0	0	-	-	-	-
sugarcane ethanol	0	0	0	0	-	-	-	-
IB used for energy								
lign. crop electricity	125	244	5.9	48	1.80	4.55	77%	79%
lign. crop FT-diesel	5.9	370	0.1	7.0	0.10	2.66	55%	78%
IB used in other sectors								
lign. crop electricity	129	220	11	50	2.31	4.58	81%	80%
lign. crop FT-diesel	12	391	0.2	12	0.14	3.46	66%	81%

Abbreviations | lign.= lignocellulosic; IB = initial biomass (i.e., biomass present before plantation establishment). **Notes | a**, Energy potential of BECCS with negative emission factors, i.e., energy potential that would lead to net negative emissions. **b**, Carbon sequestration potential of BECCS with negative emission factors. **c**, Percentages reported in this table refer to the share of natural land within the total land area used for BECCS sequestration (i.e., considering only areas with negative EFs). Note that this is *not* the same as the percentage of energy supplied or carbon sequestered via BECCS on natural lands, as compared to the total energy supplied or carbon sequestered via BECCS. The definition of natural land includes natural grassland and forests, it excludes abandoned agricultural land and managed and degraded forests (see Methods); agricultural land is excluded in the entire analysis.

7. Lignocellulosic bioenergy crop type-specific results

Results in the main text represent lignocellulosic crops in general, which was implemented by selecting the crop type for each grid cell that results in the lowest EF. Details on this approach and alternative selection methods are provided in this supplementary information on pages 15-16 (Figures S3-4). Here we provide crop type-specific results.

In most parts of the world except for boreal areas, grassy bioenergy crops (Miscanthus and switchgrass cultivars) would result in lower EFs than woody crops (Eucalyptus in the tropics, poplar and willow in colder areas), mostly due to higher yields. Results for lignocellulosic crops in general are therefore largely similar to those of grasses only, while global emission-supply curves of woody bioenergy show lower potential and/or higher EFs (Figure S5). For liquid biofuels, overall crop type-specific patterns are similar to those of bioelectricity (Figure S6-7).

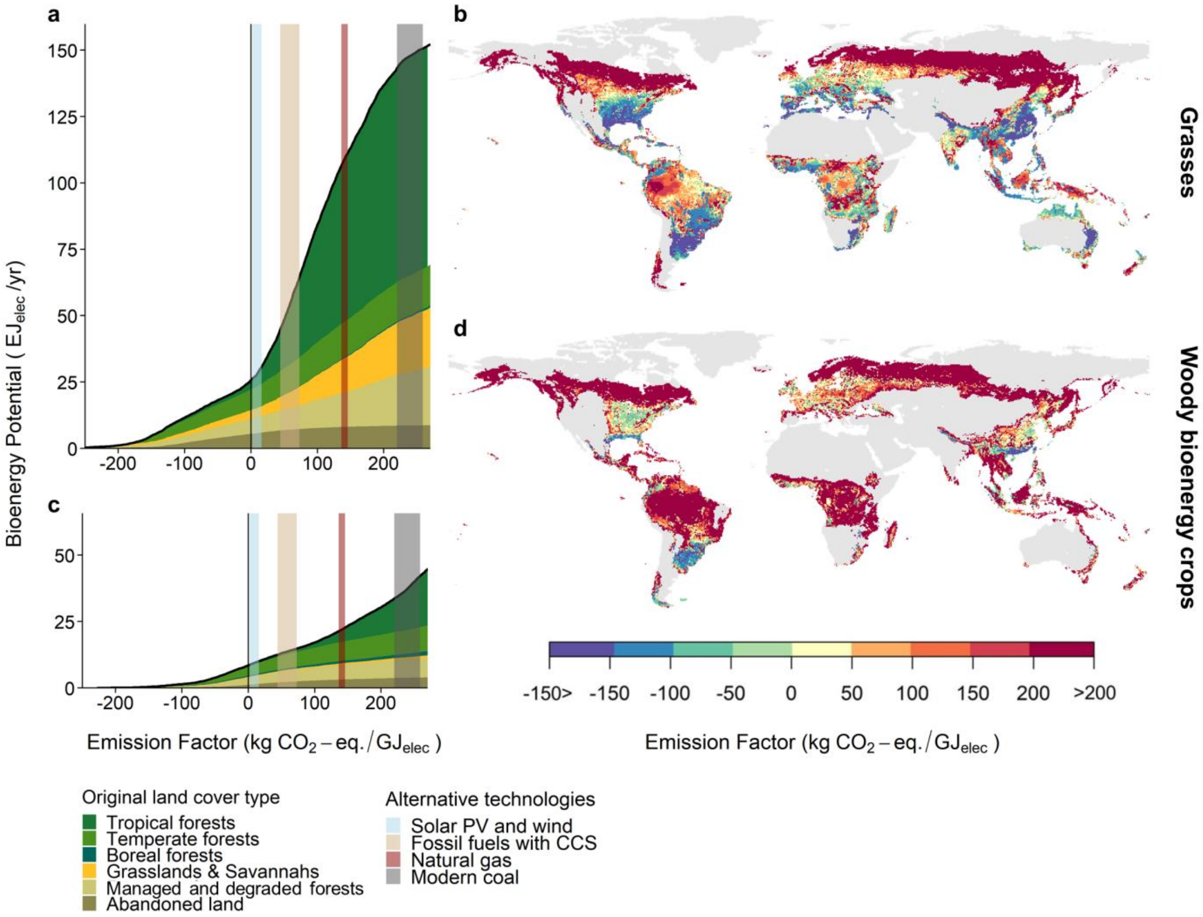

Figure S5 | Global emission factors maps and resulting emission-supply curves of BECCS electricity from grasses and woody bioenergy over a 30 year evaluation time. **a**, Emission-supply curve of BECCS electricity from grasses (Miscanthus and switchgrass cultivars). **b**, EF map of BECCS electricity from grasses (Miscanthus and switchgrass cultivars). **c**, Emission-supply curve of BECCS electricity from woody bioenergy crops (poplar, willow, Eucalyptus). **d**, EF map of BECCS electricity from woody bioenergy crops (poplar, willow, Eucalyptus). Note that agricultural areas are included in the EF maps, but do not contribute to the global bioenergy potential in the emission-supply curves.

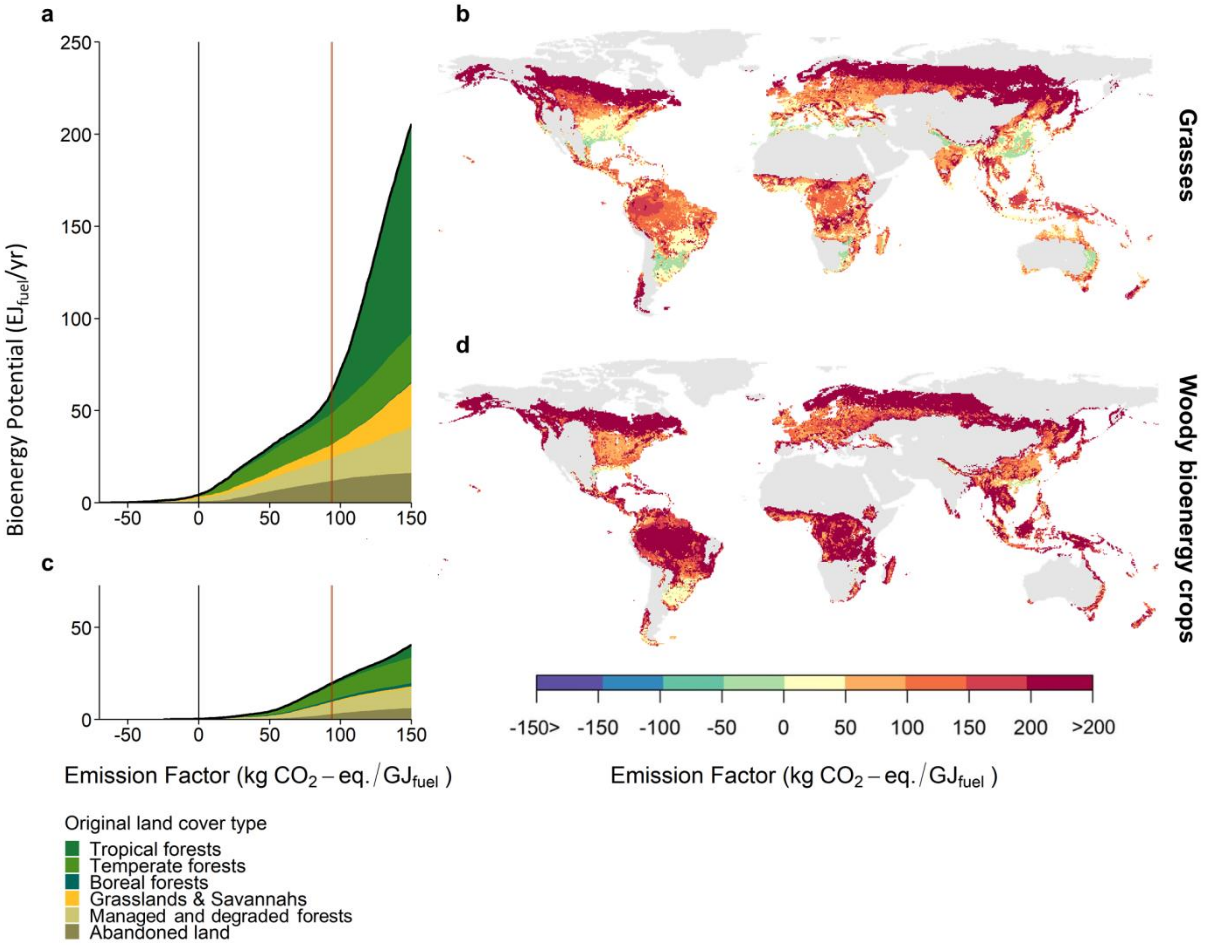

Figure S6 | Global emission factors maps and resulting emission-supply curves for Fischer-Tropsch (FT-)diesel produced with CCS from grasses and woody bioenergy. a, Emission-supply curve of FT-diesel with CCS from grasses (Miscanthus and switchgrass cultivars). **b**, EF map of FT-diesel with CCS from grasses (Miscanthus and switchgrass cultivars). **c**, Emission-supply curve of FT-diesel with CCS from woody bioenergy crops (poplar, willow, Eucalyptus). **d**, EF map of FT-diesel with CCS from woody bioenergy crops (poplar, willow, Eucalyptus). For reference, the orange lines indicate the 94 kg CO_2-eq./GJ_{fuel} EF of fossil diesel (Giuntoli et al., 2014). Note that agricultural areas are included in the EF maps, but do not contribute to the global bioenergy potential in the emission-supply curves.

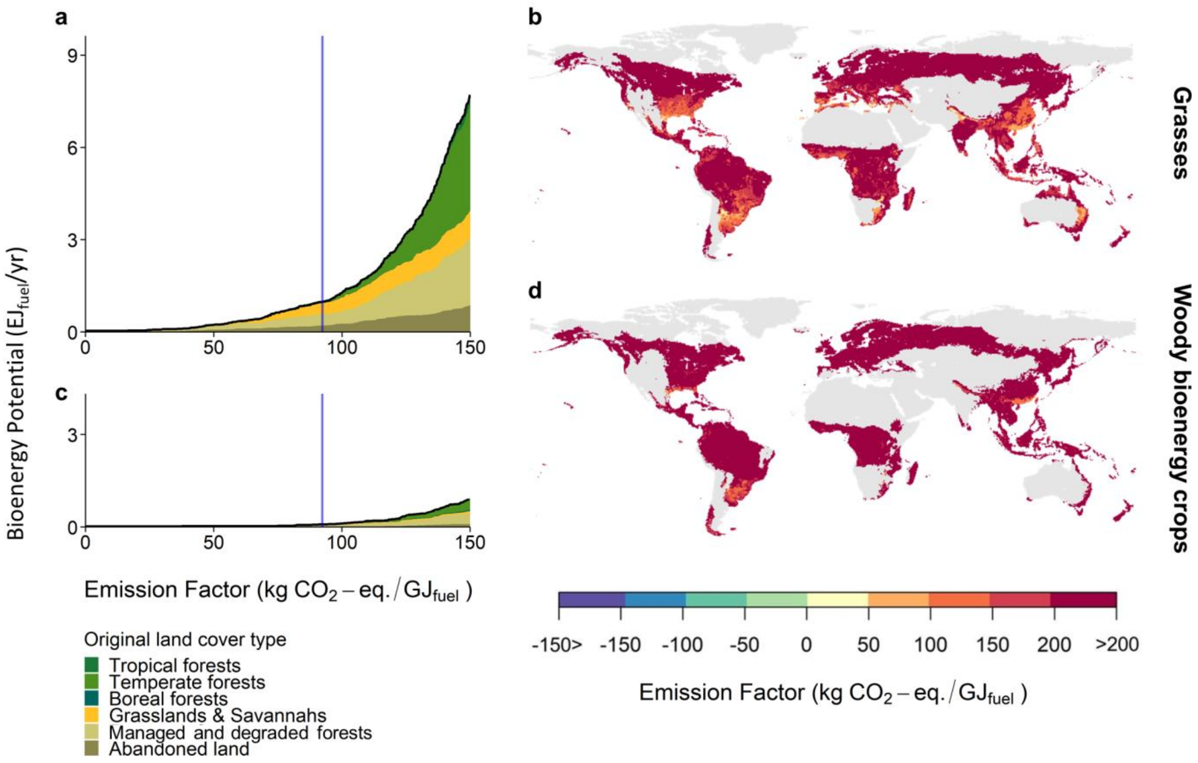

Figure S7 | Global emission factors maps and resulting emission-supply curves for ethanol produced with CCS from grasses and woody bioenergy. a, Emission-supply curve of ethanol with CCS from grasses (Miscanthus and switchgrass cultivars). **b**, EF map of ethanol with CCS from grasses (Miscanthus and switchgrass cultivars). **c**, Emission-supply curve of ethanol with CCS from woody bioenergy crops (poplar, willow, Eucalyptus). **d**, EF map of ethanol with CCS from woody bioenergy crops (poplar, willow, Eucalyptus). For reference, the blue lines indicate the 92 kg CO_2-eq./GJ_{fuel} EF of petrol (Giuntoli et al., 2014). Note that agricultural areas are included in the EF maps, but do not contribute to the global bioenergy potential in the emission-supply curves.

8. Evaluation times of BECCS

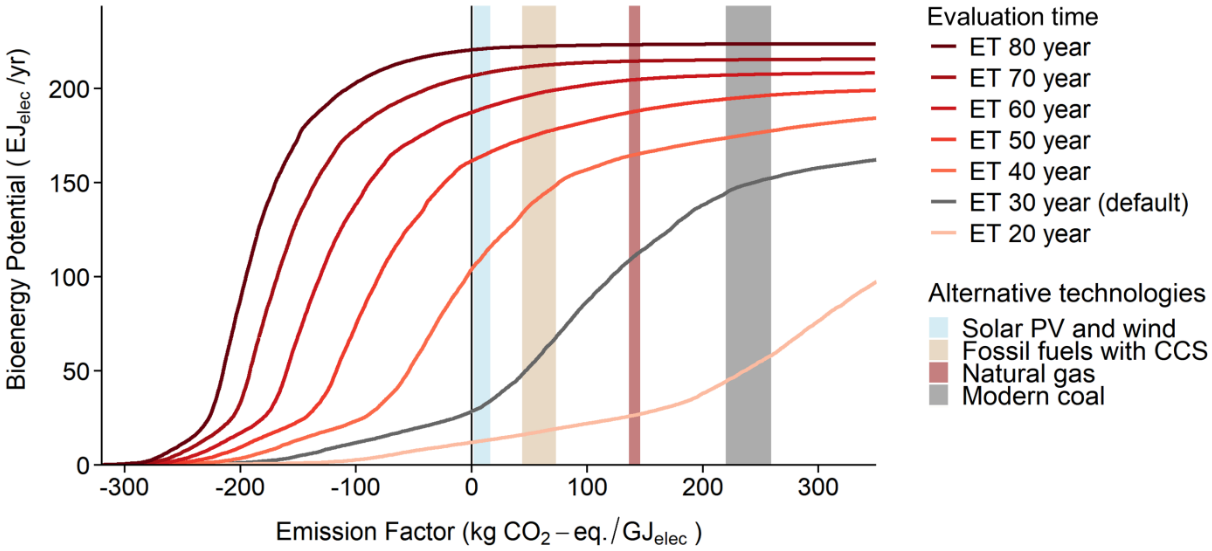

Figure S8 | Global emission-supply curves of BECCS electricity over varying evaluation times. Shaded columns indicate EF ranges for alternative electricity generation technologies (Brückner et al., 2014; Hertwich et al., 2015; TableS2).

9. BECCS electricity over a 20 year evaluation time

When using 20 year evaluation time, as used by the IPCC and EU (IPCC, 2006; EU, 2009), LUC emissions are amortised over a shorter time period and fewer locations remain attractive for climate change mitigation via BECCS. BECCS electricity potential is reduced to 12 EJ_{elec}/year at EFs below zero and to 18 EJ_{elec}/year at EFs of fossil CCS electricity, both predominantly on abandoned lands and managed and degraded forests (Figure S9). For FT-diesel with CCS, negative emissions are negligible at this 20 year evaluation time and potential below the 94 kg CO_2-eq./GJ_{fuel} EF of fossil diesel is reduced to 27 EJ/year. All ethanol pathways have negligible potential at EFs below that of petrol when considered over a 20 year evaluation time.

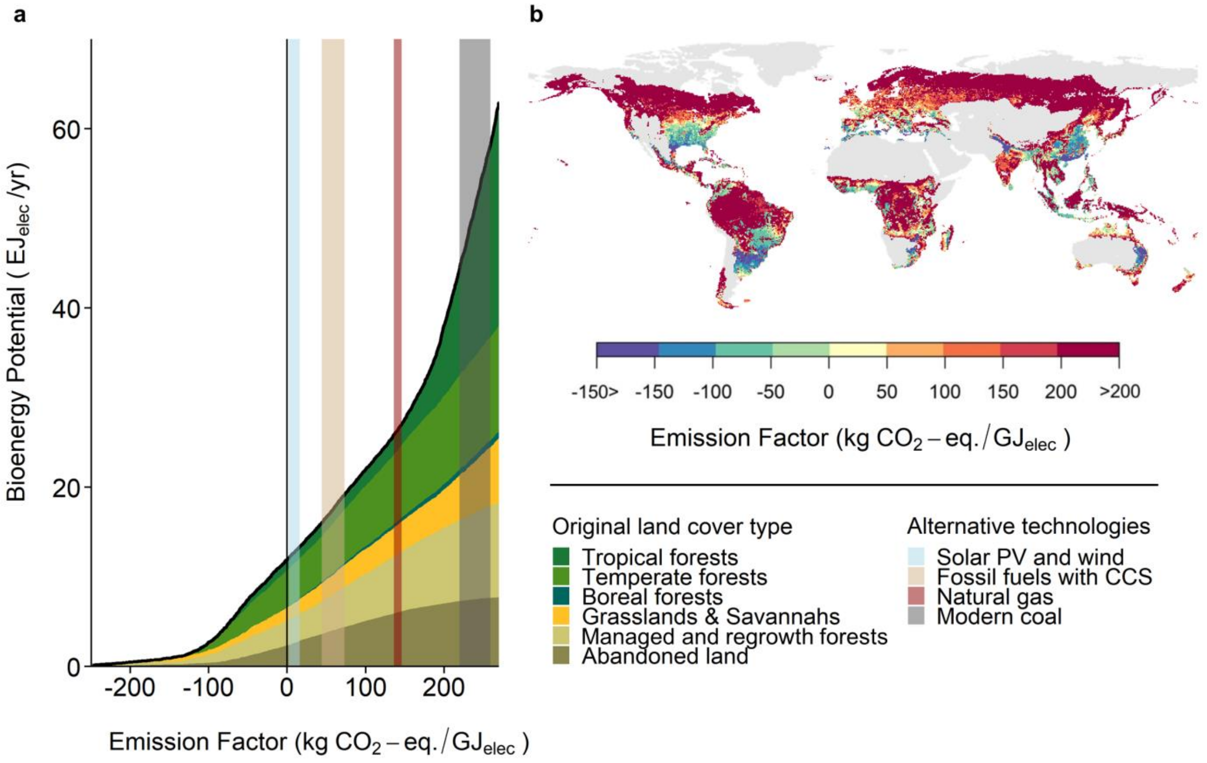

Figure S9 | Global emission factors maps and resulting emission-supply curves of BECCS electricity over a 20 year evaluation time. a, Emission-supply curve of BECCS electricity. Shaded columns indicate EF ranges for alternative electricity generation technologies (Brückner et al., 2014; Hertwich et al., 2015; Table S2). **b**, EF map for BECCS electricity. Agricultural areas are included in the EF maps, but do not contribute to the global bioenergy potential in the emission-supply curves.

10. Global emission factor maps of liquid biofuels with CCS

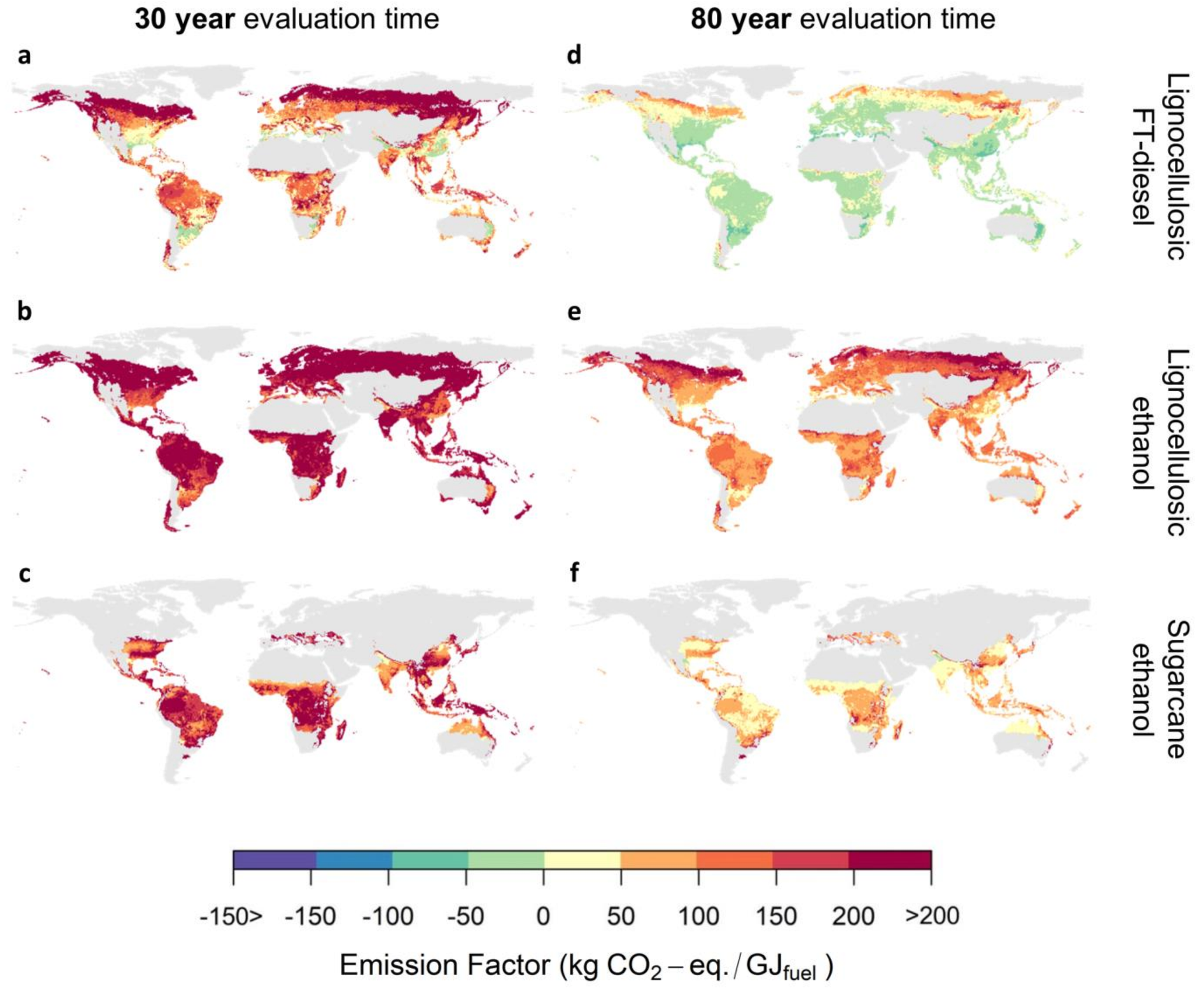

Figure S10 | Global emission factor maps of liquid biofuels with CCS. a, EF map for lignocellulosic bioenergy crop-based Fischer-Tropsch diesel with CCS considered over a 30 year evaluation time. **b,** EF map for lignocellulosic ethanol with CCS over a 30 year evaluation time. **c,** EF map for sugarcane ethanol with CCS over a 30 year evaluation time. **d-f,** EF maps for these liquid biofuels with CCS over an 80 year evaluation time. Agricultural areas are included in the EF maps, but do not contribute to the global bioenergy potential presented in the main text and the emission-supply curves (Figure 2).

11. Alternative uses of initial biomass: additional results

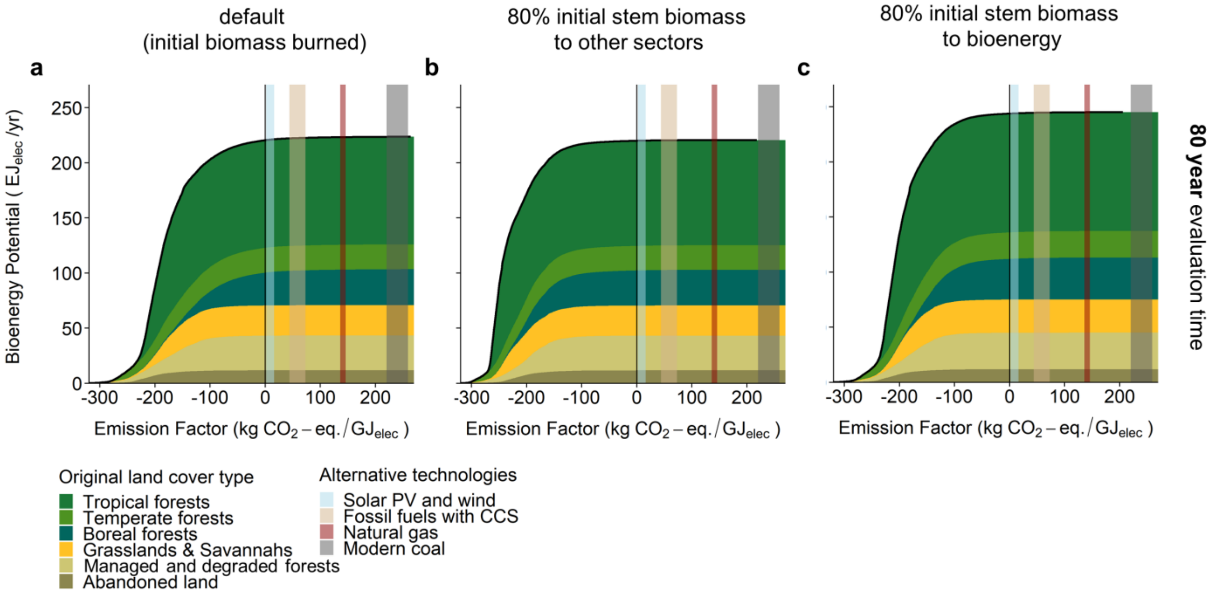

Figure S11 | Global emission-supply curves of BECCS electricity, with alternative uses of initial biomass, considered over an 80 year evaluation time. a, Default BECCS electricity emission-supply curve over an 80 year evaluation time (initial biomass is assumed to be burned). **b**, BECCS electricity emission-supply curve over an 80 year evaluation time, with 80% of initial stem biomass used in others sectors (e.g. timber or pulp; eventual biogenic carbon emission from this 80% of initial stem biomass are allocated to these sectors). **c**, BECCS electricity emission-supply curve over an 80 year evaluation time, with 80% of initial stem biomass used to produce additional bioelectricity. Shaded columns indicate EF ranges for alternative electricity generation technologies (Brückner et al., 2014; Hertwich et al., 2015; Table S2).

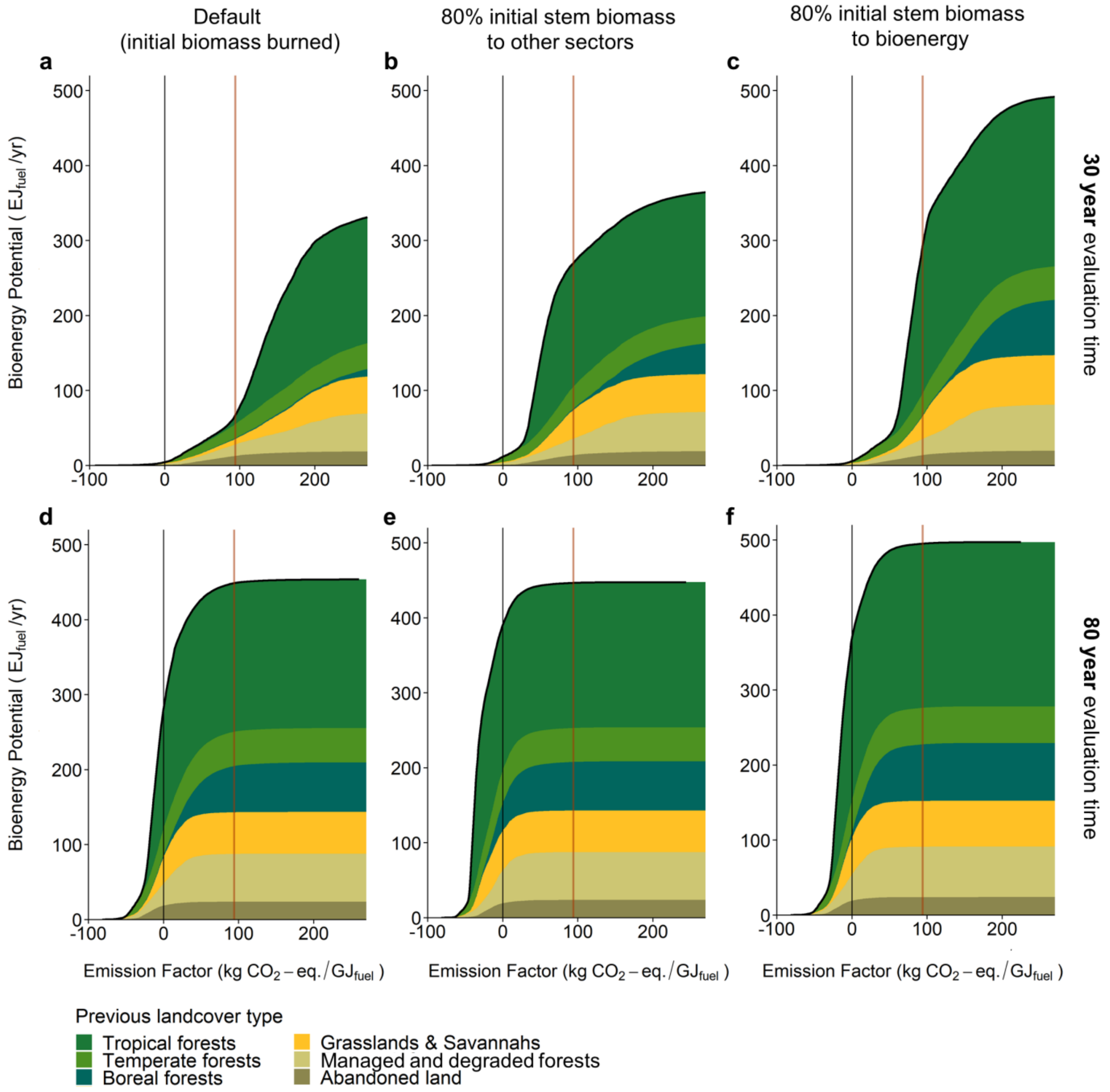

Figure S12 | Global emission-supply curves of lignocellulosic Fischer-Tropsch diesel with CCS, with alternative uses of initial biomass, considered over a 30 and 80 year evaluation times. **a**, Default emission-supply curve for FT-diesel with CCS over a 30 year evaluation time (initial biomass is assumed to be burned). **b**, Emission-supply curve for FT-diesel with CCS over a 30 year evaluation time, with 80% of initial stem biomass used in others sectors (e.g. timber or pulp; eventual biogenic carbon emission from this 80% of initial stem biomass are allocated to these sectors). **c**, Emission-supply curve for FT-diesel with CCS over a 30 year evaluation time, with 80% of initial stem biomass used to produce additional diesel. **d-f**, these same emission-supply curves over an 80 year evaluation time. The orange line indicates the emission factor of fossil diesel (94 kg CO_2-eq./GJ_{fuel}; Giuntoli et al., 2014).

12. Sensitivity analysis: lignocellulosic FT-diesel with CCS

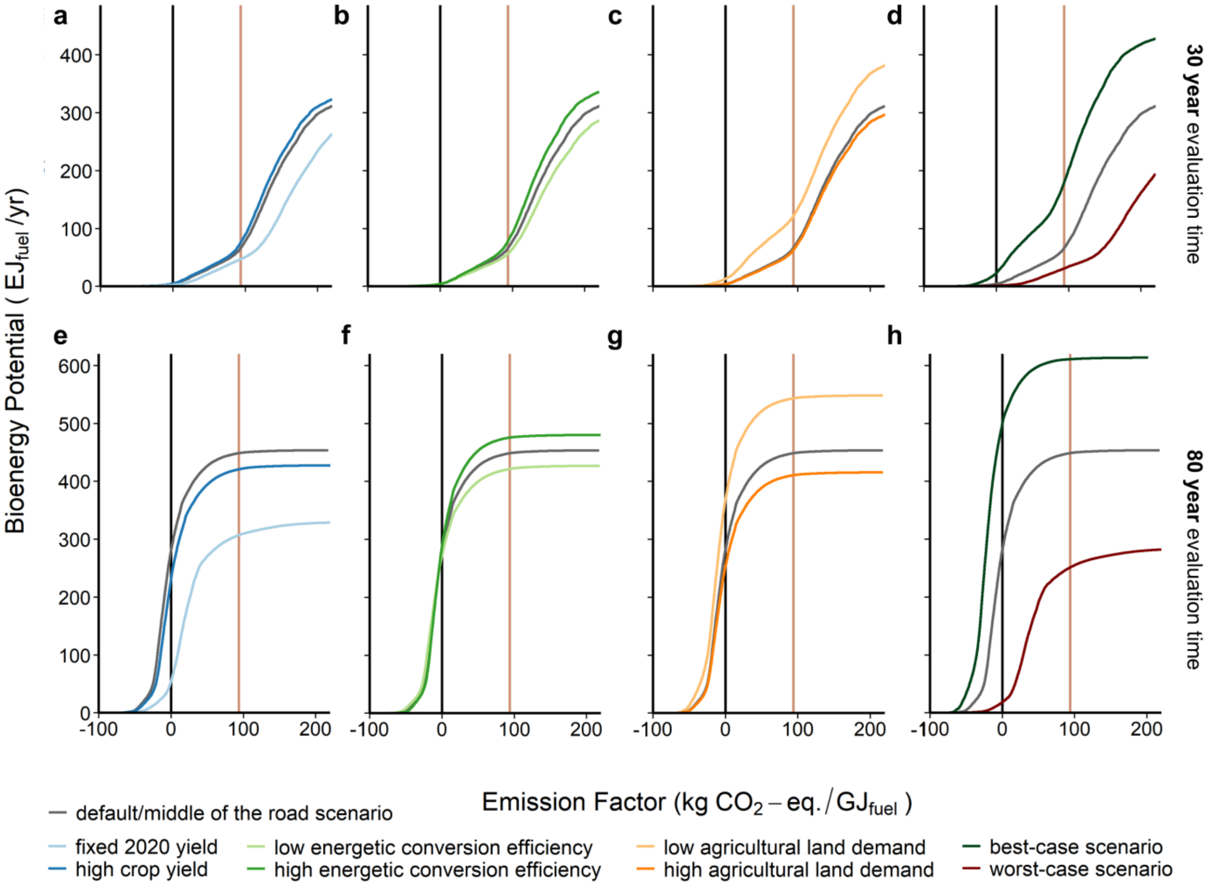

Figure S13 | Sensitivity analysis of emission-supply curves for lignocellulosic Fischer-Tropsch diesel with CCS. The default emission-supply curve is plotted in grey in all panels. **a**, Emission-supply curves at constant 2020 crop yields (light blue) and high crop yields (dark blue) **b**, Emission-supply curves for low (light green) and high (dark green) biomass to energy carrier conversion efficiencies (based on literature, Table S1). **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; see Methods). **d**, Emission-supply curves for a best-case (green) and worst-case (red) scenario. **e-h**, these same emission-supply curves for evaluation times of 80 years, rather than 30 years. The orange vertical line indicates the emission factor of fossil diesel (94 kg CO_2-eq./GJ$_{fuel}$; Giuntoli et al., 2014).

13. Sensitivity analysis: extension for BECCS electricity

Supply chain GHG emissions

Default supply chain GHG emissions were based on the average emissions reported in literature per feedstock-carrier combination (Tables S1 and S2). Future global BE(CCS) development will likely require large-scale interregional trade in biomass or energy carriers to match regions that supply biomass with centres of population that demand energy (Junginger et al., 2019), which could increase GHG emissions of some supply chains. On the other hand, decarbonisation of the energy and transport sectors could also reduce emissions. To account for this uncertainty and variability, we estimate minimum and maximum supply chain emissions in our sensitivity analysis by taking half or double (50-200%) the default emissions, respectively. The resulting range is larger than a range estimated based on current literature, which would be approximately 60-140% (following the approach in Table S1, note b). After doubling supply chain emissions, the resulting increase in emissions on top of default emissions is 13-20 kg CO2/GJ_{elec} depending on the exact feedstock-carrier combination (Table S1). To put this in perspective, this increase in emissions is similar to the emissions associated with transatlantic shipping of wood pellets, which are around 13 kg CO_2-eq./GJ_{elec} for wood-pellet based electricity (Hanssen et al., 2017).

Supply chain GHG emissions make up a small share of overall emissions of BECCS electricity. Doubling or halving these emissions has a limited effect on BECCS emission-supply curves (Figure S14ab). Doubling supply chain emissions results in a reduction of BECCS energy potential at negative EFs of 1% for a 30 year evaluation period (Figure S14a) and of 5% over an 80 year evaluation period (Figure S14b).

Climate regime

By default a representative concentration pathway (RCP) leading to 2.6 $W{\cdot}m^{-2}$ radiative forcing in 2100 is used in the LPJml global vegetation model runs in this study (see Methods). When forcing a warmer RCP6.0 climate, emission-supply curves do not visibly change when looking at a 30 year evaluation time (Figure S14c), as RCP2.6 and RCP6.0 hardly differ between 2020 and 2040, and only slowly diverge thereafter. At longer evaluation times, the global effect of climate on emission-supply curves is still very limited (Figure S14d), predominantly because i) the difference in climate regime is limited in the first decades, and ii) the eventual warmer climate affects both bioenergy crop yields and carbon stocks of the natural vegetation benchmark, i.e., foregone sequestration, in the same way.

Carbon fertilisation

Plant growth can be enhanced due to higher atmospheric CO_2 concentrations. This so-called carbon fertilisation is controversial and excluded in our default runs in the LPJml model. Over a 30 year evaluation time, including carbon fertilisation slightly decreases BECCS potential up to EFs of around 240 kg CO_2-eq./GJ_{elec}, and increases potential at higher EFs (Figure S14c). At longer evaluation times, carbon fertilisation increases BECCS potential by about 5% even at negative EFs (Figure S14d). This increase in potential occurs because of increased yields under carbon fertilisation. At shorter evaluation times, yields also increase, but they do not outweigh the increase in EFs that carbon fertilisation brings about by enlarging carbon stocks of the natural vegetation benchmark, i.e. by enhancing foregone sequestration.

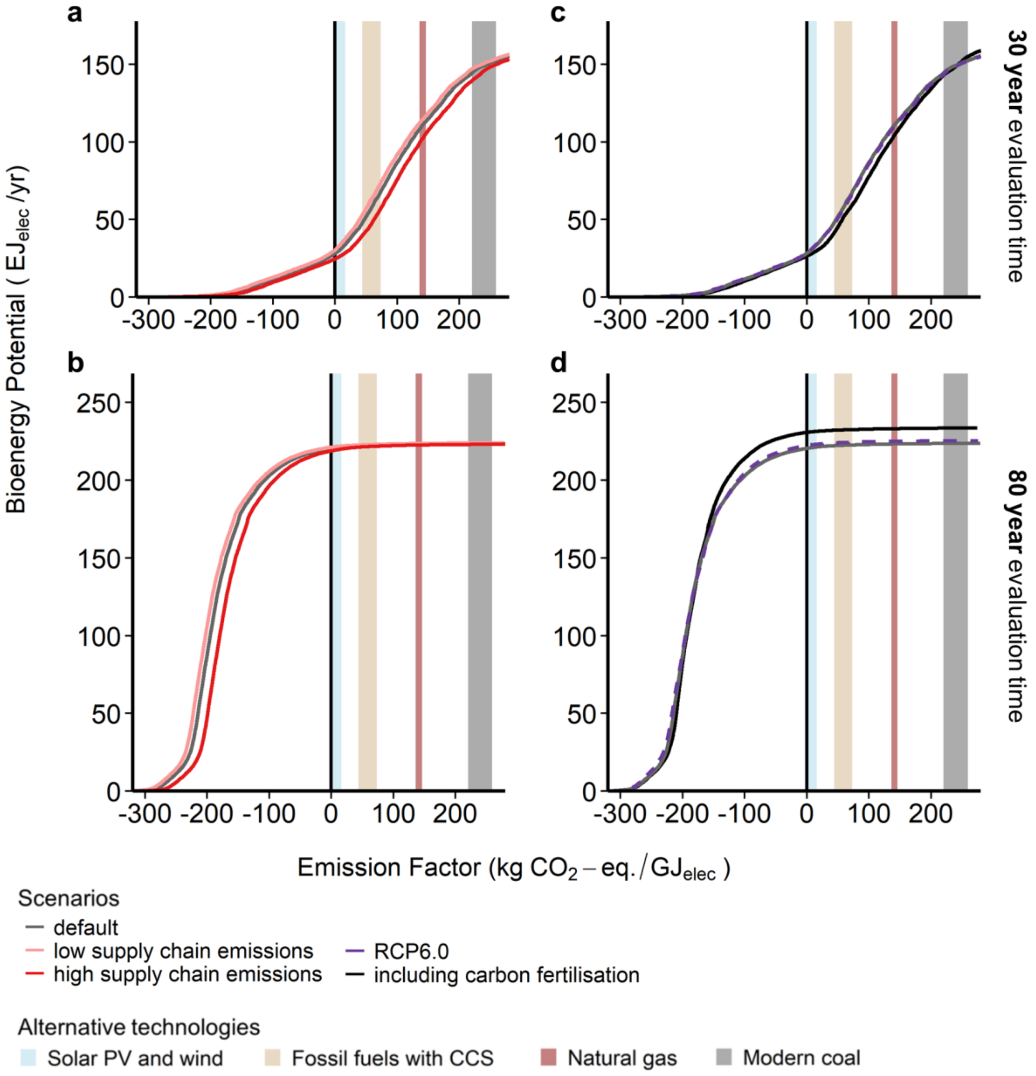

Figure S14 | Sensitivity of BECCS electricity emission-supply curves to parameterisation *extended*. a, Emission-supply curves for low (pink line) and high (red line) supply chain GHG emissions, as compared to default supply chain emissions (grey line; range and default value are based on literature, Table S1). **b**, these same emission-supply curves for evaluation times of 80 years, rather than 30 years. **c,** Emission-supply curves for a scenario with a fixed RCP6.0 climate (purple dashed line) that is warmer than the default RCP2.6 climate (grey), and for a scenario that includes carbon fertilisation, i.e., assumed enhanced plant growth due to higher atmospheric CO_2 concentrations (black line). **d**, these same emission-supply curves for evaluation times of 80 years, rather than 30 years. Shaded columns indicate EF ranges for alternative electricity generation technologies (Brückner et al., 2014; Hertwich et al., 2015; Table S2).

14. Sensitivity analysis: supply chain GHG emissions of liquid biofuels

Default supply chain GHG emissions were based on the average emissions reported in literature per feedstock-carrier combination (Tables S1 and S2). As noted in section 13, we estimated minimum and maximum supply chain emissions in our sensitivity analysis by taking half or double (50-200%) these default emissions, which is more than the 60-140% range found in literature (following the approach in Table S1, note b). Future BECCS supply chain emissions could for instance increase through more long-distance transport of biomass, but could decrease through decarbonisation of the transport and power sectors. For liquid biofuels with CCS specifically, there is an additional way in which supply chain emissions could be reduced. In line with literature (Wetterlund et al., 2010; Koorneef et al., 2012; Moreira et al., 2016; Sanchez et al., 2018), our study includes CO_2 capture from the FT-process or fermentation step to ethanol, but excludes the capture of other, smaller flows of CO_2 at the FT-plant or bio-refinery, e.g. from biomass or fossil fuel combustion for process heat or auxiliary power. Capturing these flows would reduce supply chain GHG emissions.

When halving supply GHG emissions, supply potential of FT-diesel with negative emissions increases up to 18%, while its supply potential at the emission factor of fossil diesel increases up to 26% (Figure S15a,d). For bio-ethanol with CCS, halving supply chain GHG emissions still does not result in negative emissions, regardless of evaluation period. It does increase lignocellulosic ethanol supply potential at the EF of petrol by up to 60%, when considered over an 80 year time horizon (Figure S15e). This effect is smaller for sugarcane (Figure S15f). At shorter evaluation periods ethanol supply potential remains minimal (Figure S15b-c).

Capturing the low-volume flows of less concentrated CO_2 from process heat and auxiliary power would increase the energy penalty of CCS, which could reduce the benefits of additional CO_2 capture. Yet, capturing the additional CO_2 would likely still cause an overall reduction of emission factors. Therefore, if large-scale biofuel production with CCS is pursued, additional research is required into the benefits of also capturing these smaller flows of CO_2 at the FT-plant or biorefinery.

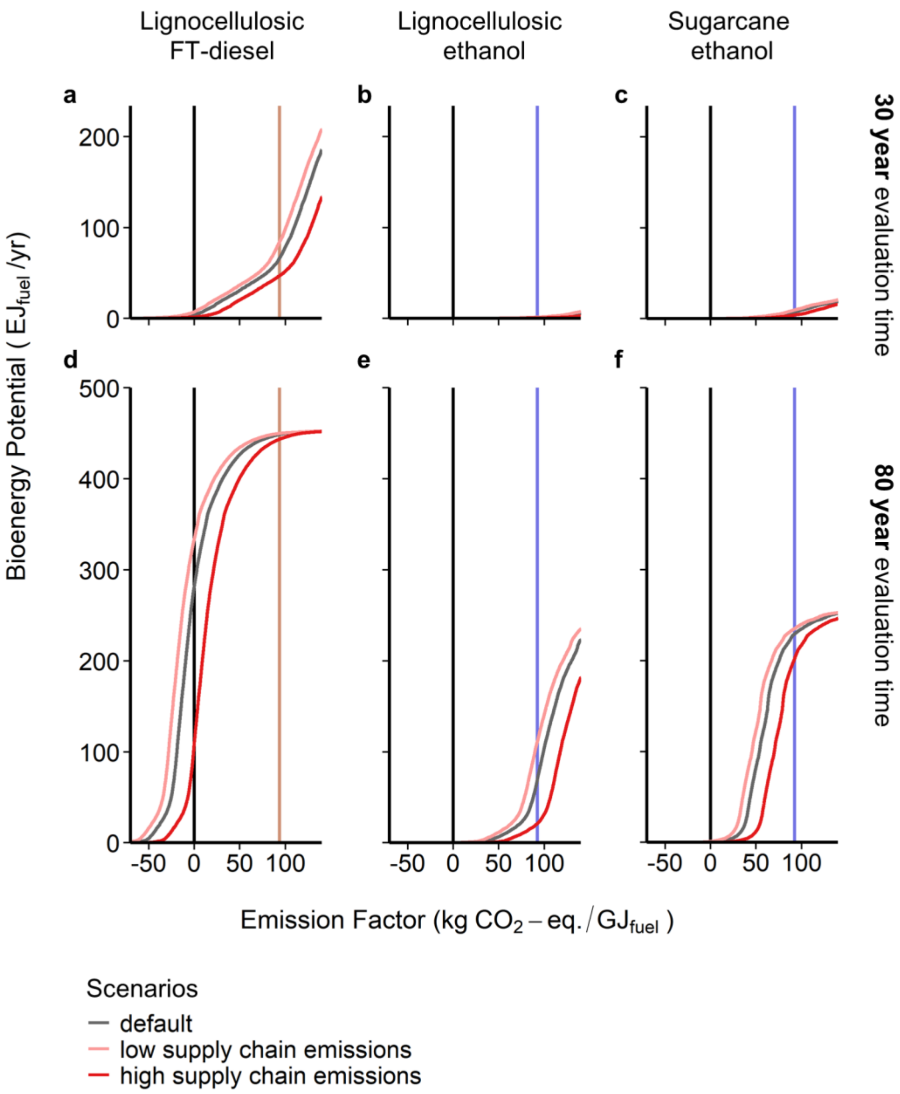

Figure S15 | Sensitivity of liquid biofuels with CCS to supply chain GHG emissions. a, Global emission-supply curves for FT-diesel with CCS considered over a 30 year evaluation period, with either: low supply chain GHG emissions (pink line) or high supply chain GHG emissions (red line), as compared to default supply chain emissions (grey line; default values and ranges can be found in Table S1). **b-c**, Global emission-supply curves with different levels of GHG supply chain emissions over a 30 year evaluation period, for lignocellulosic ethanol and sugarcane ethanol, respectively. **d-f**, These same global emission-supply curves over an 80 year evaluation time. Orange and blue lines indicate the emission factors of fossil diesel (94 kg CO_2-eq./GJ_{fuel}) and petrol (92 kg CO_2-eq./GJ_{fuel}; Giuntoli et al., 2014).

15. BECCS based on continuous cover forestry (CCF) in boreal forests

This study's main analysis focuses on bioenergy derived from lignocellulosic bioenergy crops and sugarcane. Growing these crops requires clearing original vegetation, but due to their high yields (Figure S1) these crops still result in high bioenergy potential at low emission factors. In boreal areas however, a different bioenergy feedstock may be more optimal, as boreal areas are typically characterised by high natural carbon stocks and low potential bioenergy crop yields. The sustainable management of boreal forests via so-called continuous cover forestry (CCF) leaves natural carbon stocks largely intact, while also yielding biomass that can be used for energy generation (Peura et al., 2018, Kuuluvainen & Gauthier, 2018; Parkatti et al., 2019). In CCF, only a fraction of mature trees is periodically harvested, creating a naturally growing mixed-age forest with a large standing stock (Parkatti et al., 2019). In this section we analysed whether in boreal areas CCF is a more optimal BECCS feedstock than lignocellulosic crops, in terms of both reducing emission factors and increasing bioenergy potential.

Approach

To compare CCF against our default lignocellulosic bioenergy crops, we created emission-supply curves and emission factor maps for boreal CCF-based electricity with CCS. We focused on the electricity with CCS pathway, as it typically results in the largest net sequestration of carbon. Emission factors and bioenergy potentials for CCF-based BECCS were calculated following the approach and equations outlined in the main text's *Methods* section. Parameterisation was based on literature (Table S6), except for CCF yields and carbon stocks which were also partially based on LPJml, as detailed below. It was assumed that CCF forests are not fertilised and agricultural areas were excluded from our analysis (see Methods).

CCF yields (in tonne dry biomass/ha/yr) were estimated spatially explicitly at 0.5°x0.5° resolution across the boreal forests region, considering both natural forests and forests that are already under some form of management (Figure S2). CCF yields were based on the aboveground wood component of the 100 year average natural regrowth rates of boreal forests in LPJml. These growth rates were calibrated using a factor 1.86 based on an extensive database of empirical observations of the aboveground wood component of net primary productivity in boreal forests (Luyssaert et al., 2007). This resulted in the potential yields of conventional boreal forestry. In CCF forestry however, less wood is extracted from the forests and yields are reduced. Conventional boreal forestry yields were therefore multiplied with a yield reduction factor f_{Red} of 0.82 (0.57-0.96 range; based on: Tahvonen & Rämö, 2016; Peura et al., 2018; Parkatti et al., 2019) to determine final CCF yields (Figure S16). Based on the lowest reported CCF yields in literature, grid cells with an annual yield below 0.5 dry tonne of biomass per hectare were considered uneconomical for CCF and excluded from the analysis. Calculated CCF yields were typically in the 0.5-3 tonne dry biomass/ha/yr range in the Fennoscandian peninsula (Figure S16), this is in line with empirical observations in literature for this area, which range between 0.5 and 2.8 tonne dry biomass/ha/yr and average at around 1.5 tonne dry biomass/ha/yr (Pukkala et al., 2010, 2011; Peura et al., 2018; Parkatti et al., 2019).

The calculation of emission factors for CCF requires the difference in above and belowground carbon stocks (ΔC in tonne C/ha) between a CCF forest and the natural regrowth benchmark at the end of the considered evaluation time. Assuming a symmetrical sigmoid growth curve (e.g., logistic growth), forests that are re-growing after a clear-cut have on average half the carbon stocks of a fully regrown forest. Under conventional forestry, the reduction in aboveground carbon stocks at landscape scale can therefore be estimated as ½ times the unharvested carbon stocks (as determined in LPJml). Under CCF forestry, less biomass is extracted compared to conventional forestry, meaning that this carbon stocks reduction is lowered by the yield reduction factor f_{Red} (0.82; see above). The landscape-scale, steady-state aboveground carbon stock reduction for CCF forests can thus be estimated following equation S2.

$$\Delta C_{CCF} = \frac{f_{Red}}{2} \cdot C_{unharvested} \qquad \textbf{eq. S2}$$

Where: ΔC = carbon stock reduction (tonne C/ha), f_{Red} =factor by which wood extraction is reduced in CCF forestry (*dimensionless*), C = carbon stock (tonne C/ha)

The conversion of a natural boreal forest into a steady-state mixed age CCF forests would by definition be gradual, as only a limited amount of trees are taken out per harvest. This conversion takes the length of one conventional forestry rotation cycle (following Jonker et al., 2013), which is assumed to be 100 years in boreal areas (based on Arets et al., 2011). During this period, the *pattern* of carbon stock reduction associated with the gradual deployment of natural forests can be estimated by the function described in equation S3.

$$f(t) = t \cdot \left(RT - \frac{t}{2}\right) \qquad \textit{for: } 0 \le t \ge RT \qquad \textbf{eq. S3}$$

Where: t = time (in years), RT = rotation time (in years)

When equation S3 is scaled to the steady-state aboveground carbon stock reduction (equation S2) and to the duration of the conversion (i.e., one rotation period), the landscape-scale aboveground carbon stock reduction over time can be described by equation S4.

$$\begin{aligned} \Delta C_{CCF}(t) &= \frac{f(t)}{f(RT)} \cdot \Delta C_{CCF} \qquad \textit{for: } 0 \le t \ge RT \qquad \textbf{eq. S4} \\ &= \frac{t \cdot \left(RT - \frac{t}{2}\right)}{\frac{1}{2} \cdot RT^2} \cdot \frac{f_{Red}}{2} \cdot C_{unharvested} \\ &= \frac{t \cdot \left(RT - \frac{t}{2}\right)}{RT^2} \cdot f_{Red} \cdot C_{unharvested} \end{aligned}$$

This carbon stock reduction, as compared to a natural forest benchmark, was used to derive emission factors for CCF (following the equations in the *Methods* section). Belowground carbon stocks of CCF forests were assumed to remain the same as those of natural forests, following Lundmark et al. (2016).

Table S6 | Parameterisation for electricity produced with CCS from boreal forestry biomass. *Values are means across literature and references per parameter are listed in Table S2. Yields and carbon stocks are partially based on LPJml and are discussed in the (SI) text.*

Parameter	Abbreviation	Value	Unit
Biomass to energy carrier conversion efficiency[a]	η	5.8	GJ_{elec}/t dbm
Conversion efficiency penalty due to CCS	π	1.8	GJ_{elec}/t dbm
Supply chain emissions[b]	$Em_{Supply\ Chain}$	21[c]	kg CO_2-eq./GJ_{elec}
Additional supply chain emissions CCS	$Em_{Supply\ Chain\ CCS}$	11	kg CO_2-eq./GJ_{elec}
Biomass carbon content	cc	0.50	t C / t dbm
Carbon capture efficiency	κ	0.90	t biogenic CO_2 captured / t CO_2 produced[d]
Loss factor[e]	f_{loss}	0.92	*dimensionless*

Abbreviations | t = metric tonne, dbm= dry biomass, FT = Fischer-Tropsch. **Notes | a**, The calculation of the literature-derived biomass to final energy carrier conversion efficiency ('conversion efficiency') is explained on page 4 of the supplementary materials. **b,** Supply chain GHG emissions include all GHG emissions along the supply chain: from cultivation and harvesting up to transport handling and processing of forest biomass. **c,** This value is a weighted mean across literature, in which the value reported by Creutzig et al. (2015) is weighted four times, as it is based on four previous studies. **d,** CO_2 produced refers to the CO_2 produced in the power plant or refinery, and during liquid fuel use. **e,** The loss fraction refers to the fraction of biomass that remains after losses along the supply chain.

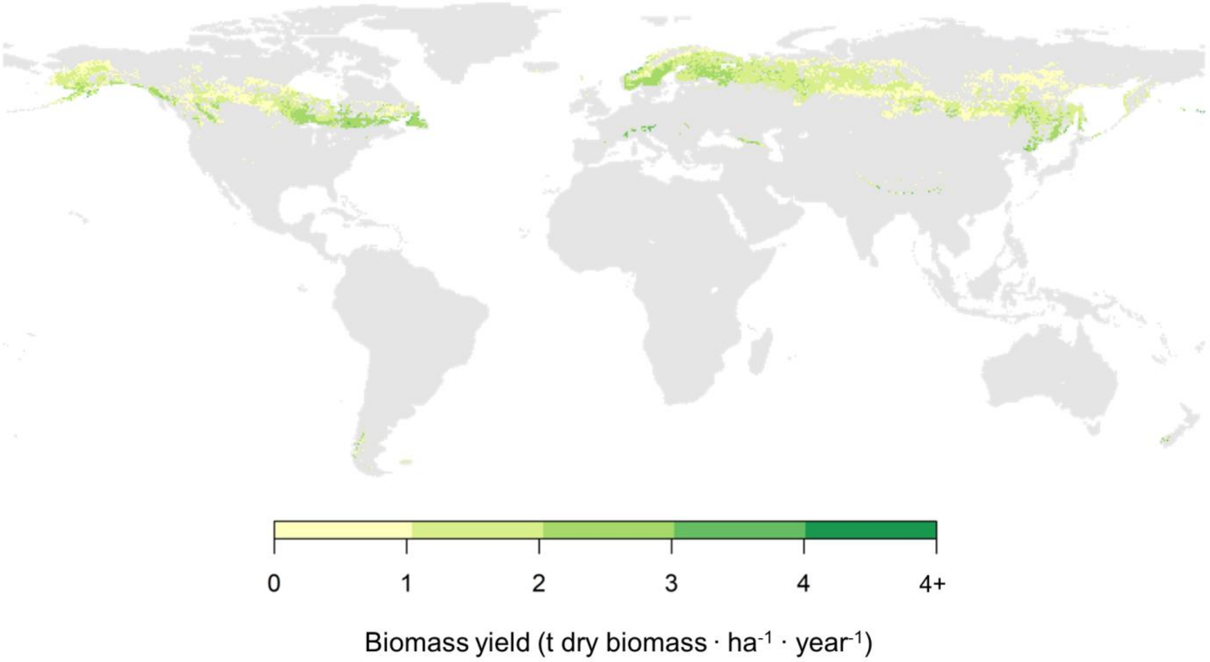

Figure S16 | Annual biomass yields from boreal continuous cover forestry (CCF). Yields are based on natural boreal forest regrowth in rates in the LPJml model, calibrated with literature-based empirical net primary productivity data and a literature-based CCF to conventional forestry yield ratio.

Results

Figure S17a shows that over a 30 year evaluation period, CCF outperforms lignocellulosic crops as boreal feedstock for BECCS electricity. CCF leads to a bioenergy potential of 3 EJ at negative emission factors in the boreal region, compared to 0.5 EJ/yr for lignocellulosic crops. The main reason for this is that under CCF management carbon stocks are much less affected and EFs are therefore lower (compare Figures S17b-c). For lignocellulosic BECCS total potential is higher, however, but only at very high EFs (larger than those of coal-based electricity without CCS).

Figure S17d shows that for an 80 year evaluation period, BECCS sourced from CCF in the boreal region has a potential of 5 EJ/yr at negative EFs, while lignocellulosic crops have a potential of around 30 EJ/yr at negative EFs. The sharp increase in bioenergy potential at negative EFs for lignocellulosic crops originates from a strong reduction in EFs (Figure S17e), which is in turn caused by amortising initial carbon stock losses over a longer evaluation period.

It is important to note that a literature-based minimum economical yield threshold was used for both feedstock types (0.5 tonne dry biomass/ha/yr for CCF and 1.25 tonne dry biomass/ha/yr for lignocellulosic crops, see the *Approach* and the general *Methods* sections respectively). CCF has a smaller geographical range with yields above its threshold (compare Figure S17b/e vs. S17c/f). We therefore also compared CCF against lignocellulosic crops within the CCF range only (Figure S17a,d, dashed grey lines), which showed that lignocellulosic bioenergy crops would still outperform CCF over longer evaluation times, though the difference is smaller.

Implications

Using boreal CCF as a BECCS feedstock option increases our estimated *global* biophysical potential for negative emission from BECCS electricity from 28 EJ/yr to 30.5 EJ/yr, when considered over a 30 year evaluation period. Over longer evaluation times, using CCF rather than lignocellulosic crops in boreal areas *reduces* the global negative emission potential, e.g., from 220 EJ/yr to 195 EJ/yr over an 80 year evaluation period.

It is important to note that data on CCF is relatively limited. In particular, the regrowth rates of trees form an important knowledge gap (Parkatti et al., 2019). Our results do, however, show a large difference between CCF and lignocellulosic crops. This makes it likely that in the long run, from a climate change mitigation perspective, lignocellulosic crops do not perform worse - and likely even better than CCF. Previous work has also indicated that short rotation woody crops, including willow, are well suited for cultivation in boreal areas (Weih, 2004). However, from a wider environmental sustainability perspective, there are more trade-offs to consider. Recent research has shown that CCF likely has several key benefits compared to clear-cut systems, including enhanced ecosystem functioning, provision of ecosystem services, and biodiversity conservation (Lundmark et al., 2016; Kuuluvainen et al., 2018; Peura et al., 2018), while also providing commercial opportunities (McMahon et al., 2016).

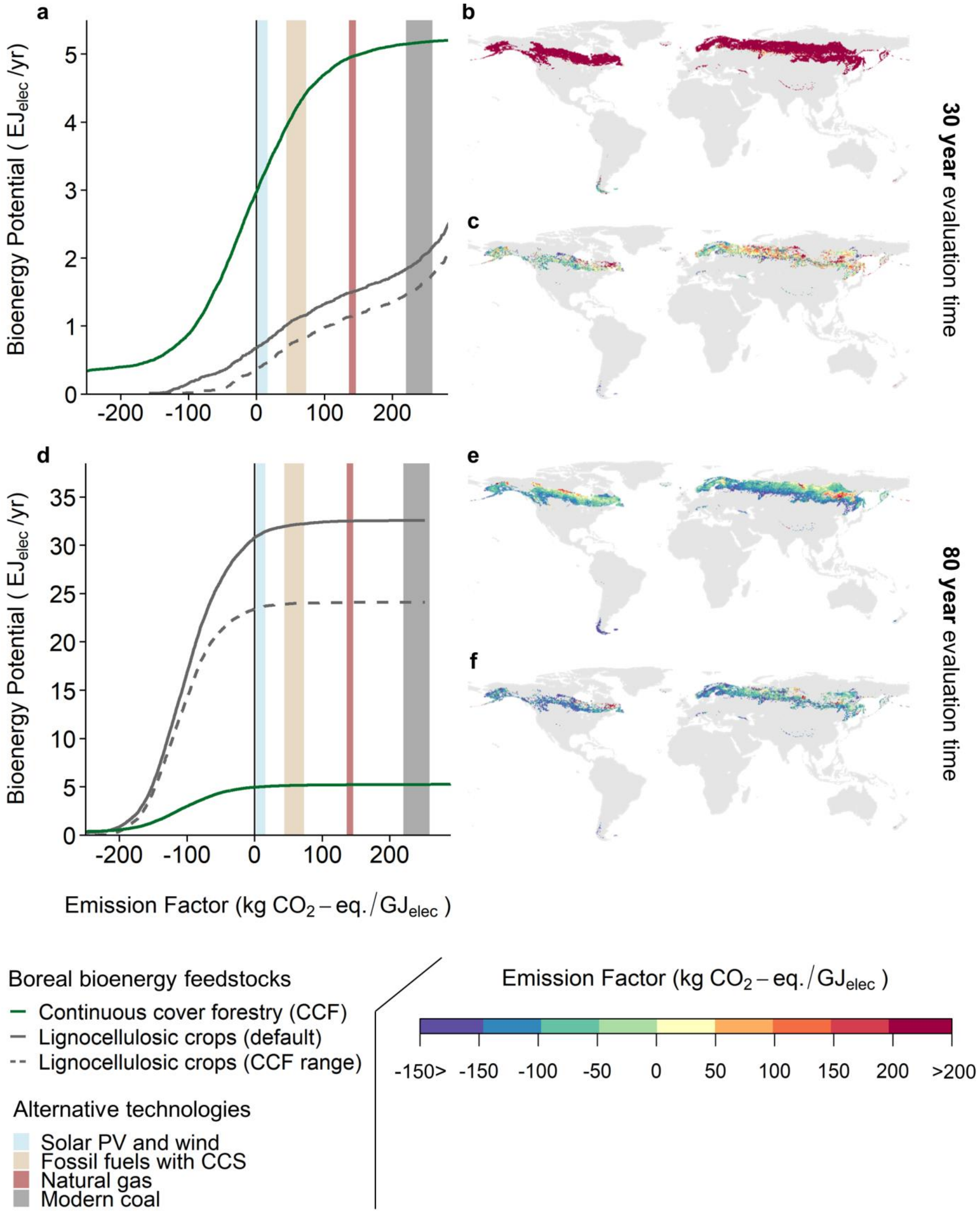

Figure S17 | Emission-supply curves and emission factor maps of bioelectricity with CCS from different boreal feedstocks. a, Boreal emission-supply curves of bioelectricity with CCS over a 30 year evaluation time based on: i) continuous cover forestry (CCF; green line), ii) this study's default feedstock of lignocellulosic bioenergy crops (grey line), or iii) lignocellulosic bioenergy crops grown only in areas suitable for CCF (i.e., where CCF yields would exceed of 0.5 tonne dry biomass/ha/yr; grey dashed line). Shaded columns indicate EF ranges for alternative electricity generation technologies (Brückner et al., 2014; Hertwich et al., 2015; Table S2). **b**, Boreal emission factor maps of bioelectricity with CCS over a 30 year evaluation time for lignocellulosic bioenergy crops, **c**, Boreal emission factor maps of bioelectricity with CCS over a 30 year evaluation time for CCF, **d-f**, these same results over an 80 year evaluation time.

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7

Global biodiversity implications of negative emissions from lignocellulosi crop-based bioenergy with carbon capture and storage

Supplementary Information

Global biodiversity implications of negative emissions from lignocellulosic crop-based bioenergy with carbon capture and storage

Supplementary Information

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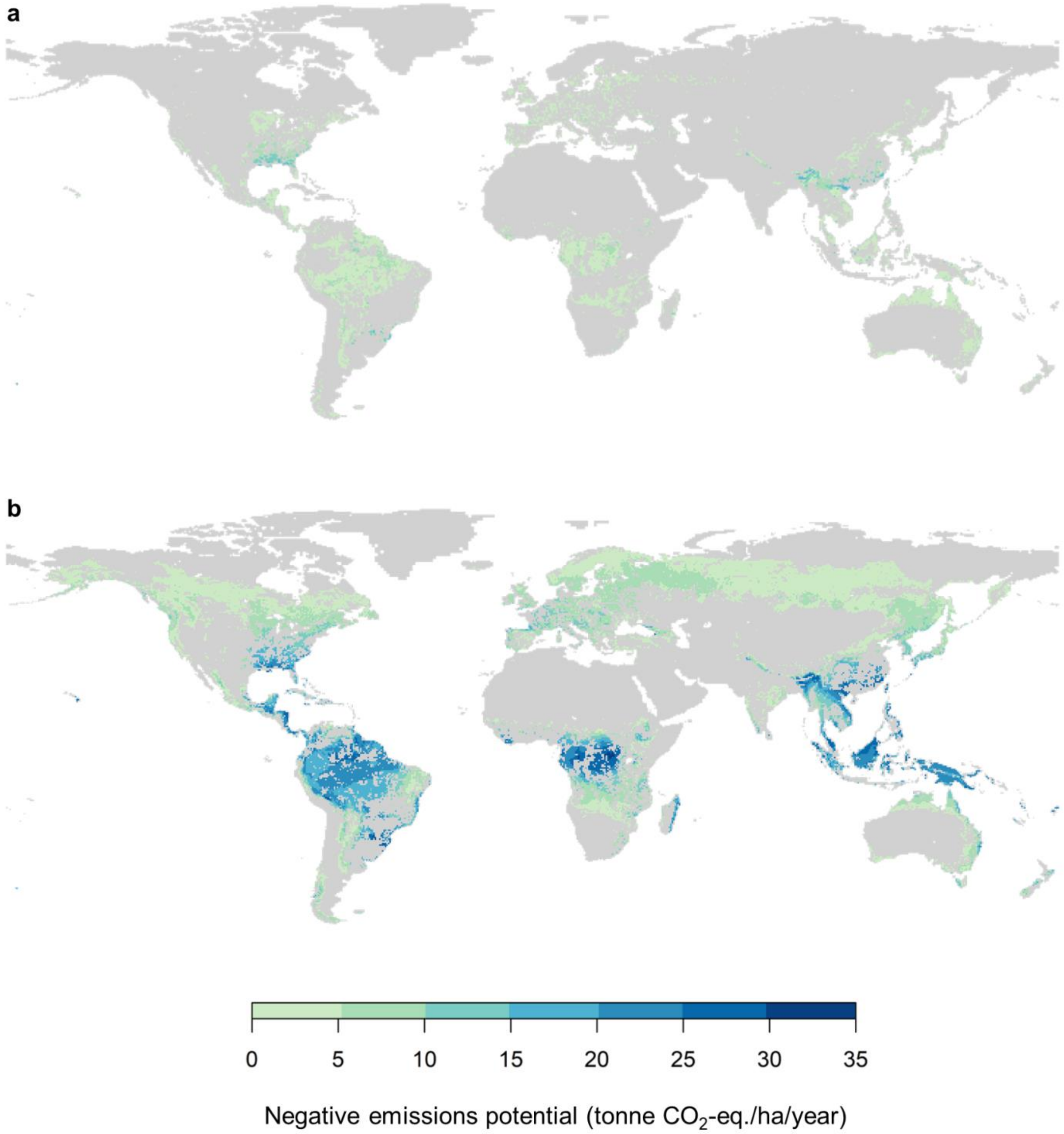

Figure S1 | Net negative emission potential (kg CO2-eq. / ha / year) of BECCS electricity. Negative emission potential is shown (**a**) over a 30 year evaluation time, and (**b**) over an 80 year evaluation time, and is based on Hanssen et al., (2020). It is assumed that 80% of stem biomass in the original vegetation is used for BECCS.

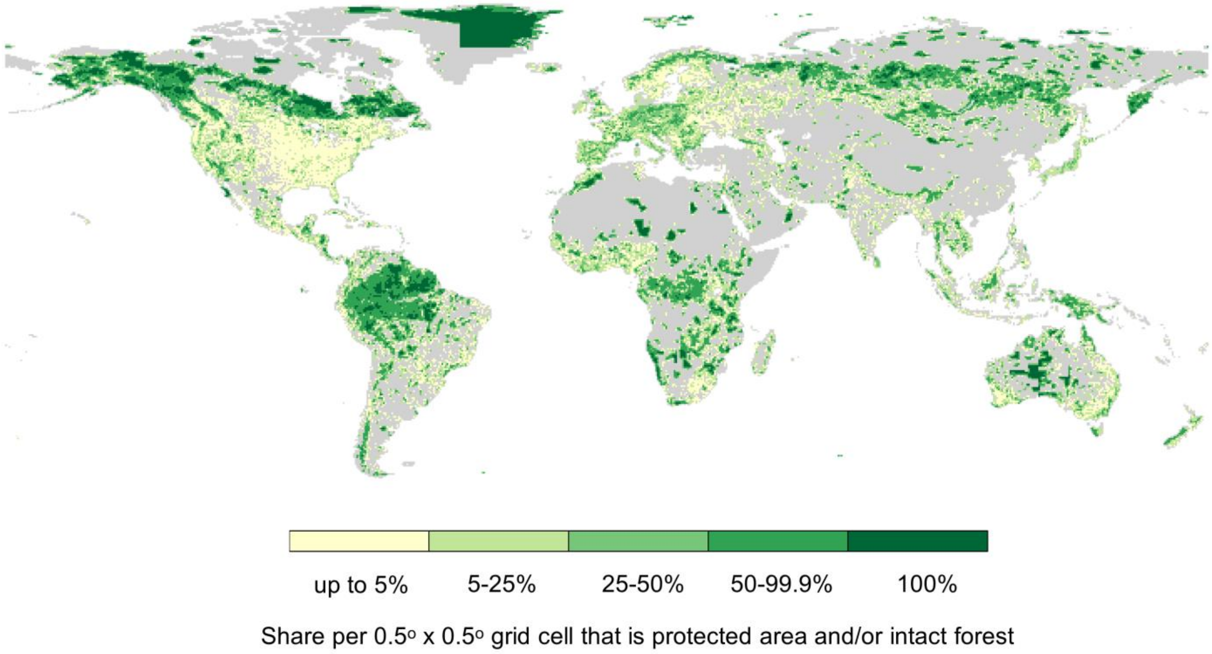

Figure S2 | Share of protected area and/or intact forest per 0.5° x 0.5° grid cell. Currently protected areas were based on UN WCMC (2019). So-called intact forests were based on Potapov et al. (2017) and are defined as natural areas, including non-forest ecosystems, without human activity that are large enough to maintain all native biodiversity. All protected areas and intact forests were excluded from our analysis. When entire cells are covered by protected areas and/or intact forests, they were altogether excluded, when part of a cell is covered, that share of the cell was excluded from negative emissions production and associated biodiversity loss.

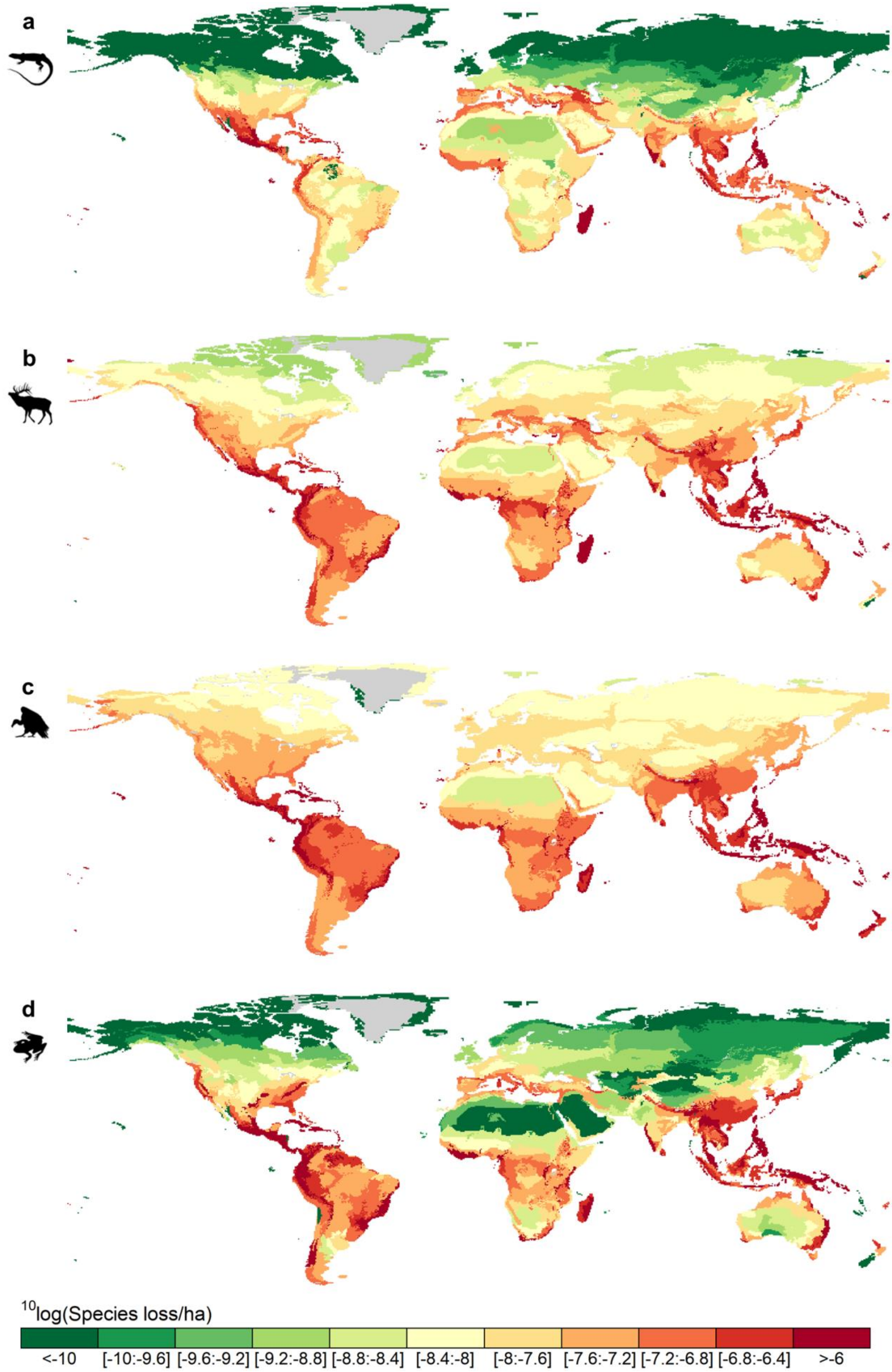

Figure S3 | Global-equivalent potential species loss factors for the conversion to intensive plantation forestry. Intensive plantation forestry represents bioenergy crop plantations in our study. Loss factors were determined by Chaudhary & Brooks, 2018. They are shown for: (**a**) reptiles, (**b**) mammals, (**c**) birds, and (**d**) amphibians. Note that a log scale is used.

Table S1 | Estimated terrestrial biodiversity loss due to global warming. Biodiversity loss refers to species committed to global extinction. All values are based on Urban (2015). We looked at two scenarios for global temperature increase: 2.8 °C and 4.3 °C, representing the approximate amount of warming expected by 2100 as compared to pre-industrial temperatures in representative concentration pathways (RCPs) 6.0 and 8.5, respectively (Clarke et al., 2014). The 95% confidence interval (Urban, 2015) is indicated in brackets. Note that a temperature interval of 1 °C was used in estimating biodiversity loss due to warming over an 80 year evaluation period, corresponding to the approximate temperature reduction BECCS could achieve with maximum cumulative negative emissions over this evaluation period. For the 30 year evaluation period an interval of 0.2 °C was used.

Scenario	**Temperature interval**[1]		**Biodiversity loss**[2] **due to warming**	**Biodiversity loss**[2] **prevented by mitigating warming**
	°C		% of species	% of species / °C
30 year evaluation period	from	to	def. *(2.5 - 97.5th %)*	def. *(2.5 - 97.5th %)*
2.8 °C biodiversity impact	2.6	2.8	0.7 *(0.6 - 0.9)*	3.5 *(3.2 - 4.4)*
4.3 °C biodiversity impact	4.1	4.3	1.3 *(1.1 - 1.8)*	6.4 *(5.4 - 8.9)*
80 year evaluation period				
2.8 °C biodiversity impact	1.8	2.8	3.1 *(2.5 – 3.7)*	3.1 *(2.5 – 3.7)*
4.3 °C biodiversity impact	3.3	4.3	5.8 *(4.7 – 7.5)*	5.8 *(4.7 – 7.5)*

Abbreviations: def. = default. **Notes:** [1] as compared to pre-industrial temperatures; [2] terrestrial biodiversity.

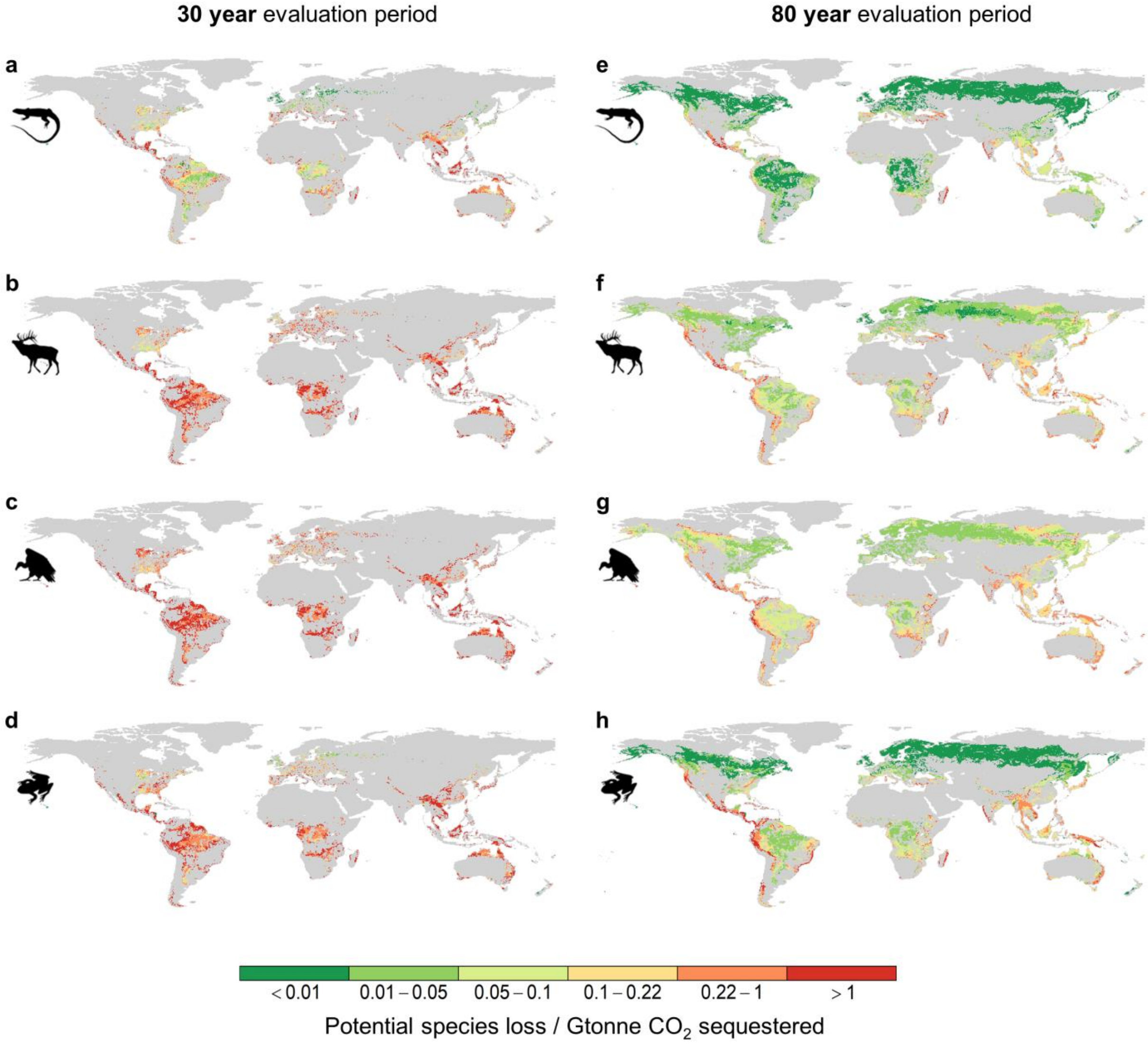

Figure S4 | Maps of global biodiversity loss due to negative emissions from crop-based BECCS for four classes of terrestrial vertebrates. Indicated are the potential number of species that become committed to global extinction due to LUC, expressed per Gigatonne of CO_2 sequestered with BECCS over a 30 year evaluation period, for: (**a**) reptiles, (**b**) mammals, (**c**) birds, and (**d**) amphibians. Results for an 80 year evaluation period are shown in panels (**e-h**). Grey areas were excluded from our analysis and comprise: agricultural land (cropland and pasture), urban areas, inland waters, protected areas, intact forests, areas with low bioenergy crop yields (<5% of global maximum yields) and areas that do not achieve net CO_2 sequestration over the time period considered. Grid cells (0.5° x 0.5°) that are partially protected areas or intact forests are plotted, but their negative emissions and biodiversity loss are scaled to reflect that these areas are not used for BECCS. *Note that the legend scale differs from Figure 1 in the main text.*

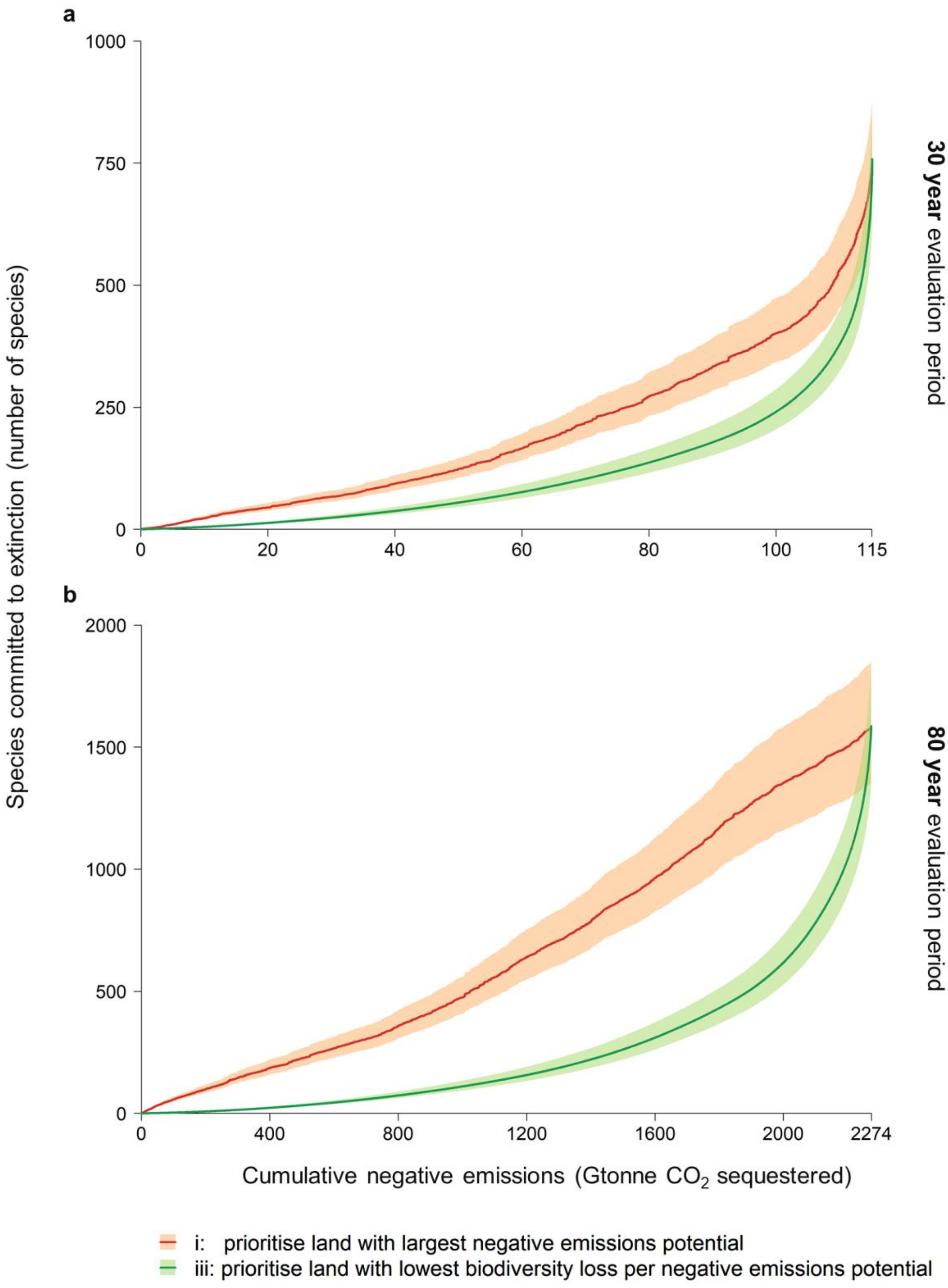

Figure S5 | Uncertainty in global terrestrial vertebrate biodiversity loss due to land-use change for BECCS. The amount of species that become committed to extinction is shown as a function of cumulative negative emissions from crop-based BECCS. The shaded area represents the 2.5 to 97.5th percentile uncertainty range for the impacts of land-use change on biodiversity, as determined by Chaudhary & Brooks (2018), considered for all ecoregions simultaneously. Results are presented for (**a**) a 30 year evaluation period and (**b**) an 80 year evaluation period. The relation between biodiversity loss and negative emissions differs depending on which land allocation criterion (i or iii) is used.

Geographical patterns resulting from different land allocation criteria

What areas are converted to bioenergy plantations to achieve a certain amount of cumulative negative emissions from BECCS differs when using the three different land allocation criteria, but is fairly similar across different evaluation periods (Figure S6). When applying criterion i (minimise land-use) the areas in the US South-East, southern parts of South America, small parts of South-East Asia, and eastern parts of Australia are used first. For criterion ii (prioritise least biodiverse lands), almost all available land in Europe and a large portion of land in the Americas and Africa is converted to prevent land conversions in the biodiversity richest areas. With criterion iii (minimising biodiversity loss per negative emissions potential) spatial patterns are in between those of the first two criteria: warm and sub-tropical areas with large negative emission potential are used earlier on, along with European areas with low biodiversity loss.

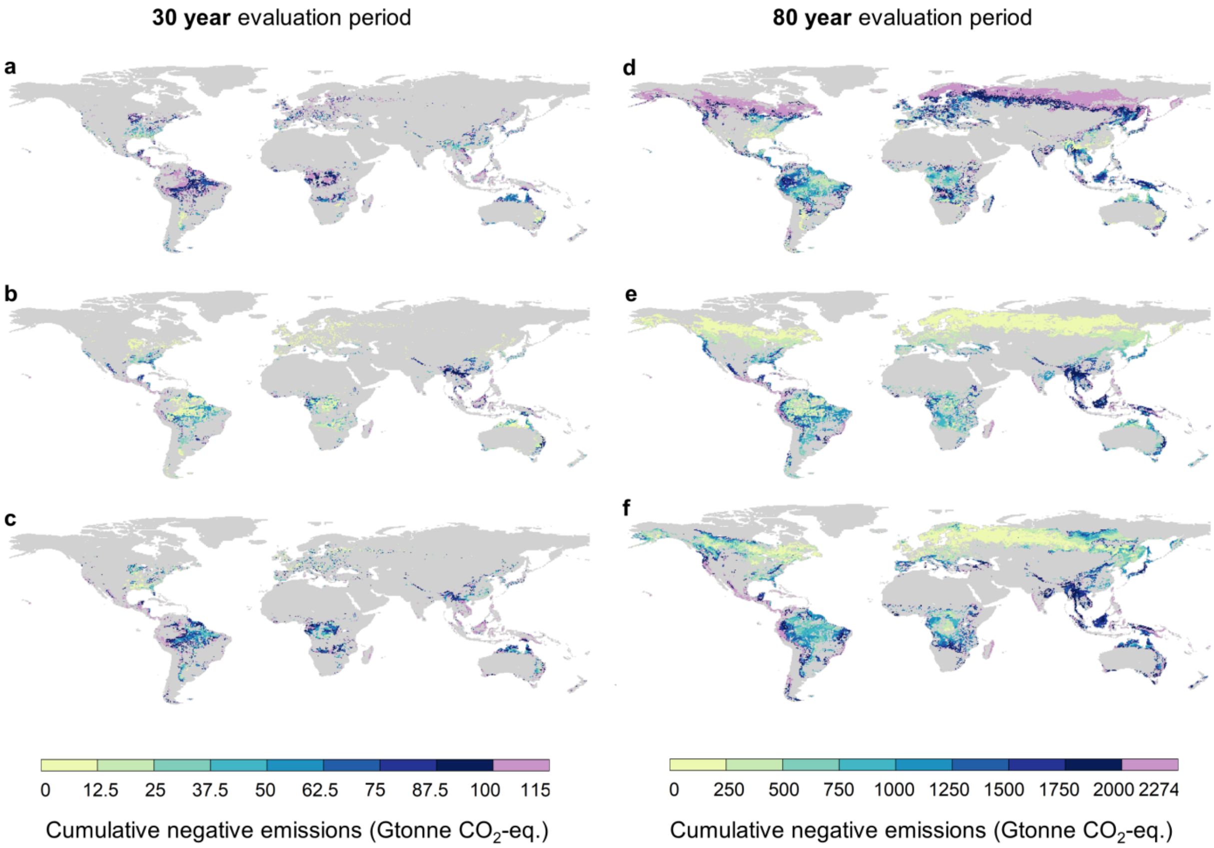

Figure S6 | Locations required to achieve cumulative negative emissions via BECCS under different land allocation criteria. Maps on the left display land areas that would be required for BECCS to achieve a certain level of cumulative negative emissions over a 30 year evaluation period, when (**a**) prioritising land with the largest negative emissions potential (criterion i), (**b**) prioritising land with lowest biodiversity (criterion ii), and (**c**) prioritising land with lowest biodiversity loss per negative emission potential (criterion iii). Maps on the right (**d-f**) display land areas required to achieve a certain amount of cumulative negative emissions over an 80 year evaluation period, under these same three criteria (i-iii) respectively.

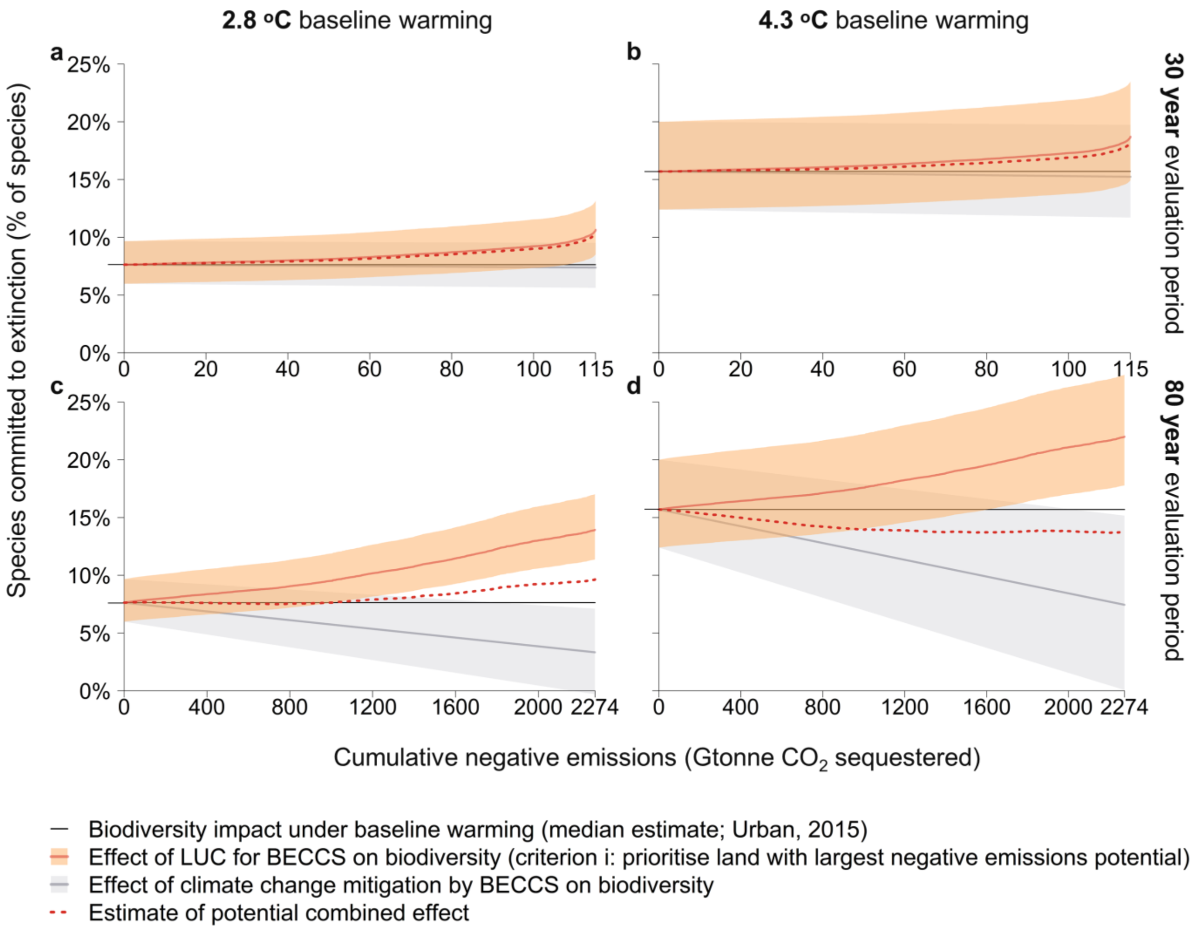

Figure S7 | Exploration of the combined effect of land-use change *for* BECCS and climate change mitigation *by* BECCS on global terrestrial vertebrate biodiversity, prioritising land with largest negative emission potential. The amount of species that become committed to extinction is shown as a function of cumulative negative emissions from crop-based BECCS. Results are presented for the use of BECCS over 30 and 80 years (panel **a-b** and **c-d**, respectively; note the different x-axis scaling), and for two baseline warming scenarios: 2.8 °C and 4.3 °C warming by 2100, as compared to pre-industrial levels (in line with RCP 6 and 8.5; Clarke et al., 2014). The y-axis intercept shows the assumed biodiversity impact of climate change under baseline warming, without BECCS (based on median estimates by Urban [2015]). With increasing negative emissions from BECCS come increasing effects of land-use change (red line; assuming land allocation criterion i: prioritise land with largest negative emission potential), but also effects of mitigated climate (grey line). An estimation of their combined (added) effect is shown in the red dotted line, but this excludes any interaction effects. Shading represents the 2.5 to 97.5th percentile uncertainty range for the impacts of land-use change on biodiversity (based on Chaudhary & Brooks [2018]; starting from the uncertainty in the biodiversity impact of baseline warming) and the effect of mitigated climate change on biodiversity (based on Van Vuuren et al. [2020] and Urban[2015]).

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