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Supplementary information

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

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Supplementary information

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Sections

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		kg CO_2-eq. /t dbm
		grassy biomass	54		
		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

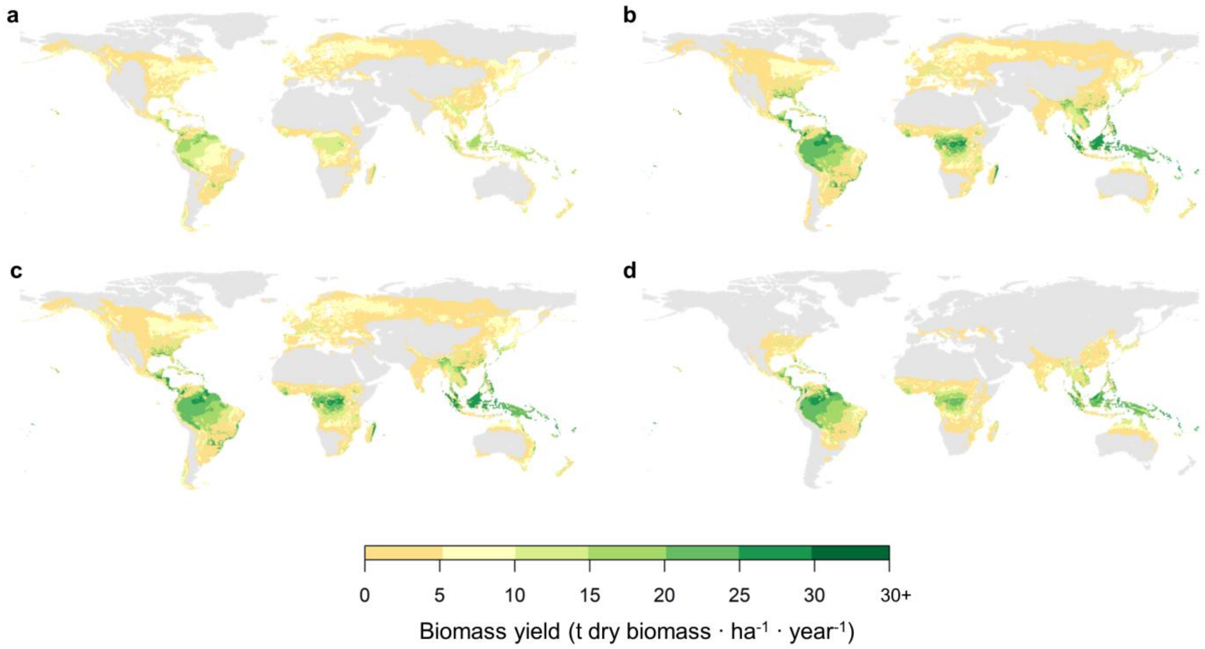

Figure S1 | Modelled annual bioenergy crop yields. a, Woody bioenergy crops (based on SRC willow in temperate and colder areas, SRC Eucalyptus in the tropics). **b,** Grasses (based on *Miscanthus* and switchgrass cultivars). **c,** Lignocellulosic biomass, i.e., woody crops or grasses depending on which 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

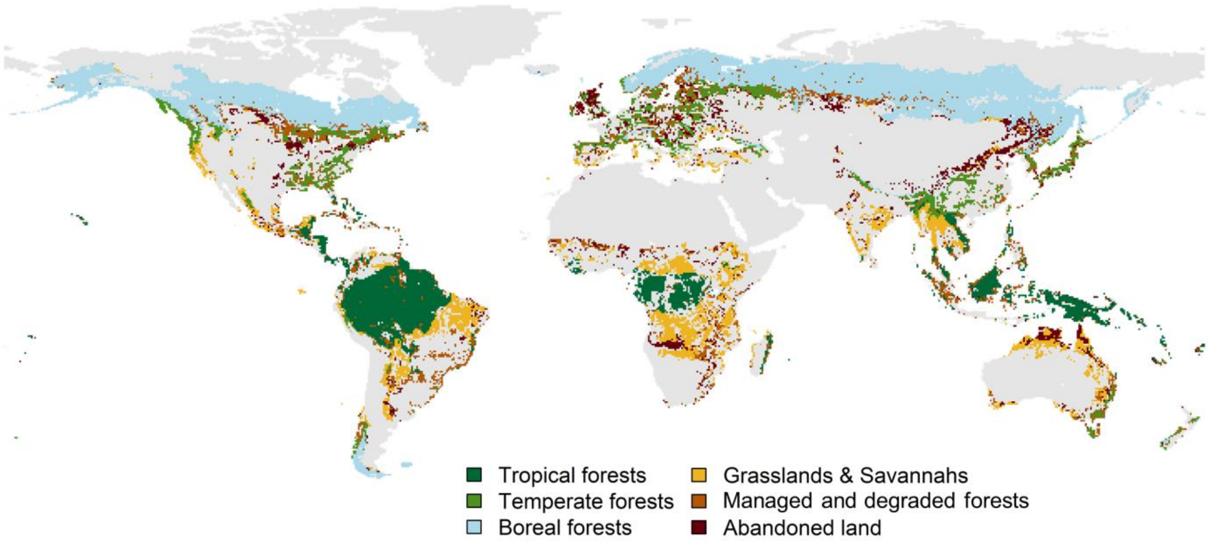

Figure S2 | Map of land cover types in 2020. This is the distribution of land cover types before the modelled conversion to bioenergy crops or natural regrowth. Note that agricultural land (cropland and pastures, according to the default IMAGE-run SSP2 scenario) are excluded from our analysis and this 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.

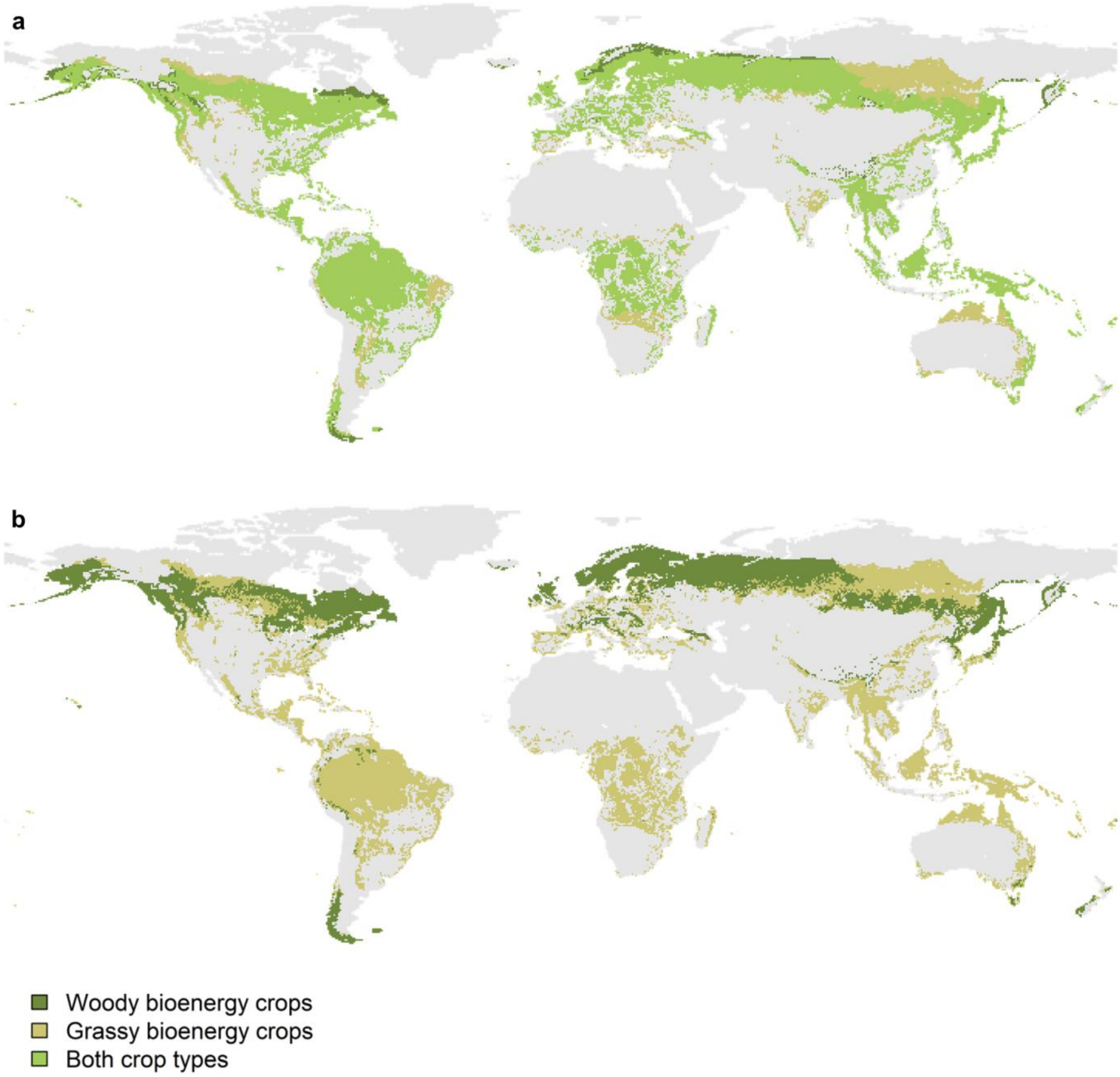

Figure S3 | Lignocellulosic bioenergy crop maps. a, Potential occurrence of grassy bioenergy crops (e.g., *Miscanthus* and switchgrass cultivars) and woody bioenergy crops (short-rotation coppiced *Eucalyptus* in the tropics and willow in colder areas) in LPJml, agricultural land (cropland and pastures, 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.

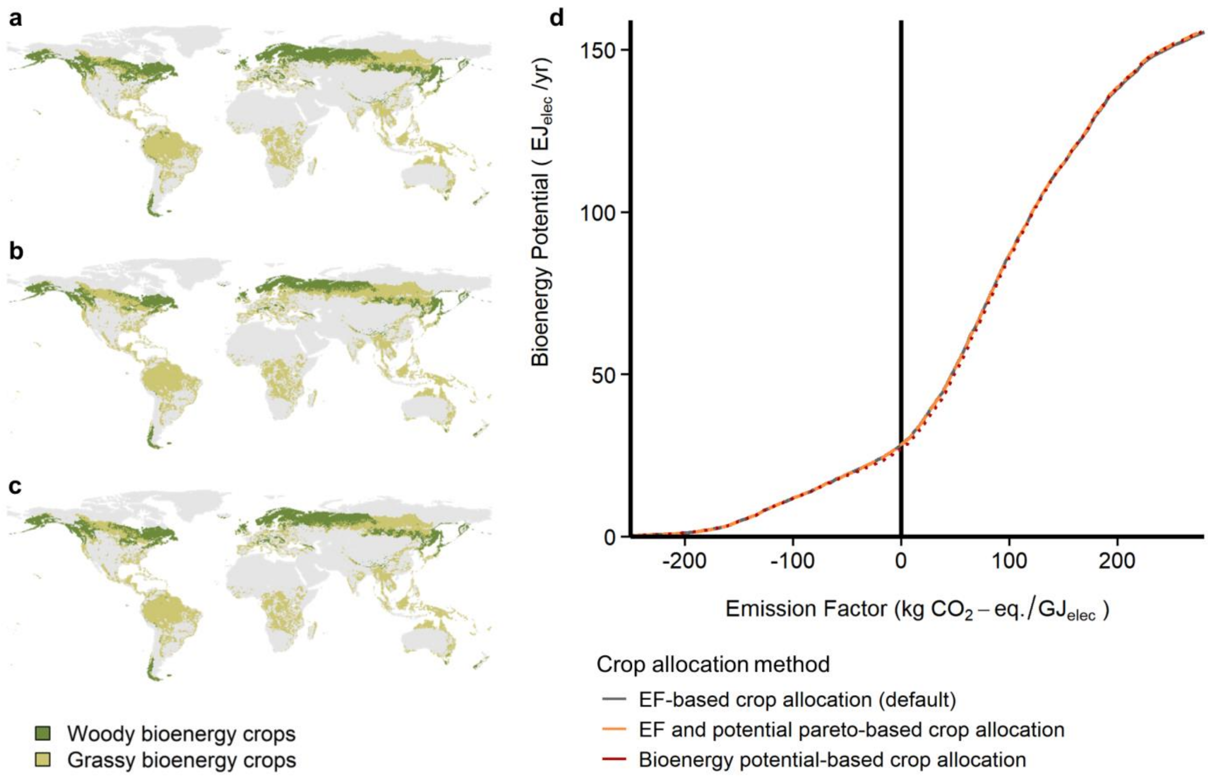

Figure S4 | Effects of alternative lignocellulosic crop type selection methods. Maps indicate whether grassy bioenergy crops (represented by *Miscanthus* and switchgrass cultivars) and woody bioenergy crops (short-rotation coppiced Eucalyptus in the tropics and willow and poplar in colder areas) are 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] (EJ$_{carrier}$ / year)		**Sequestration potential**[b] (Gt CO_2-eq / year)		**Land area used to achieve potential** (Gha)		**Share of which on natural land**[c] (%)	
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).

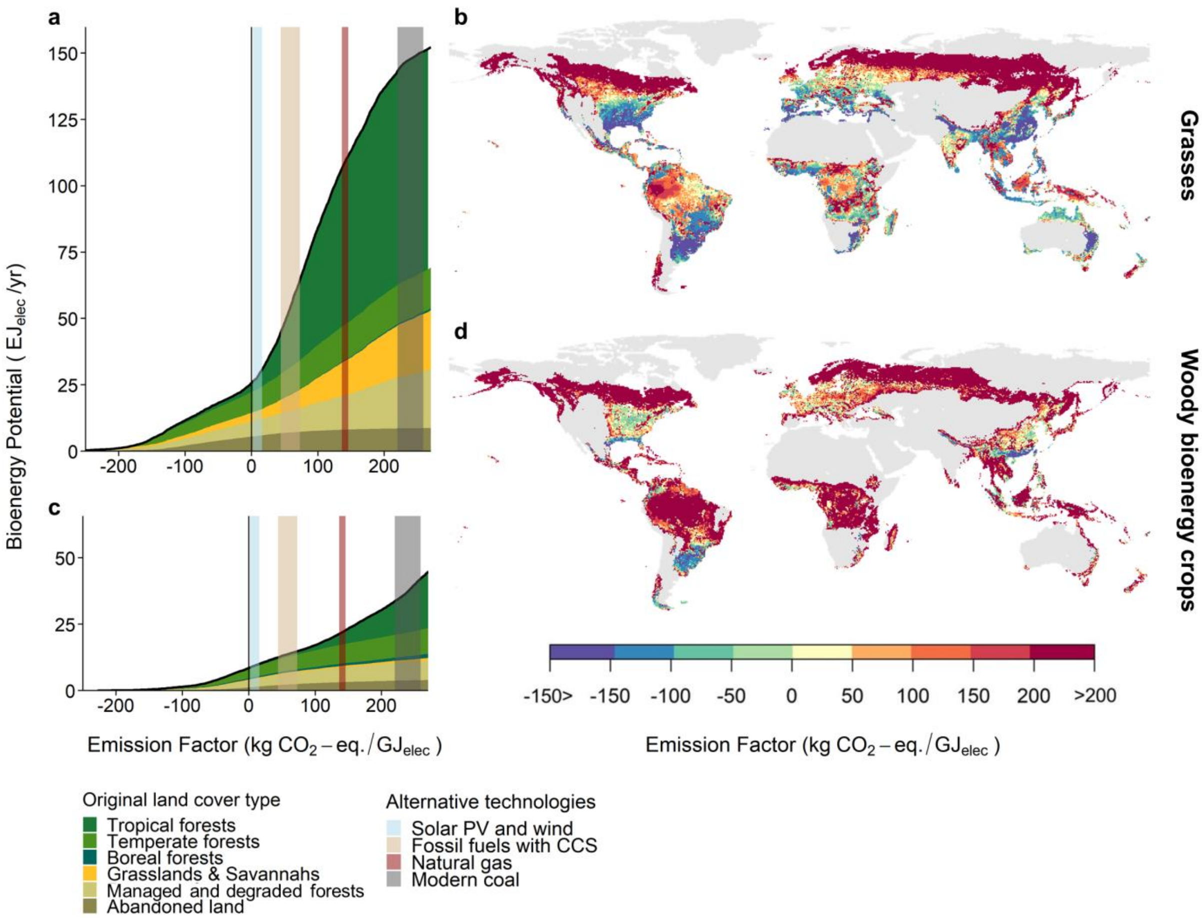

Figure S5 | Global emission factors maps and resulting emission-supply curves of BECCS electricity from grasses and woody bioenergy over a 30 year evaluation time. a, Emission-supply curve of BECCS electricity from grasses (Miscanthus and switchgrass cultivars). **b**, EF map of BECCS electricity from 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.

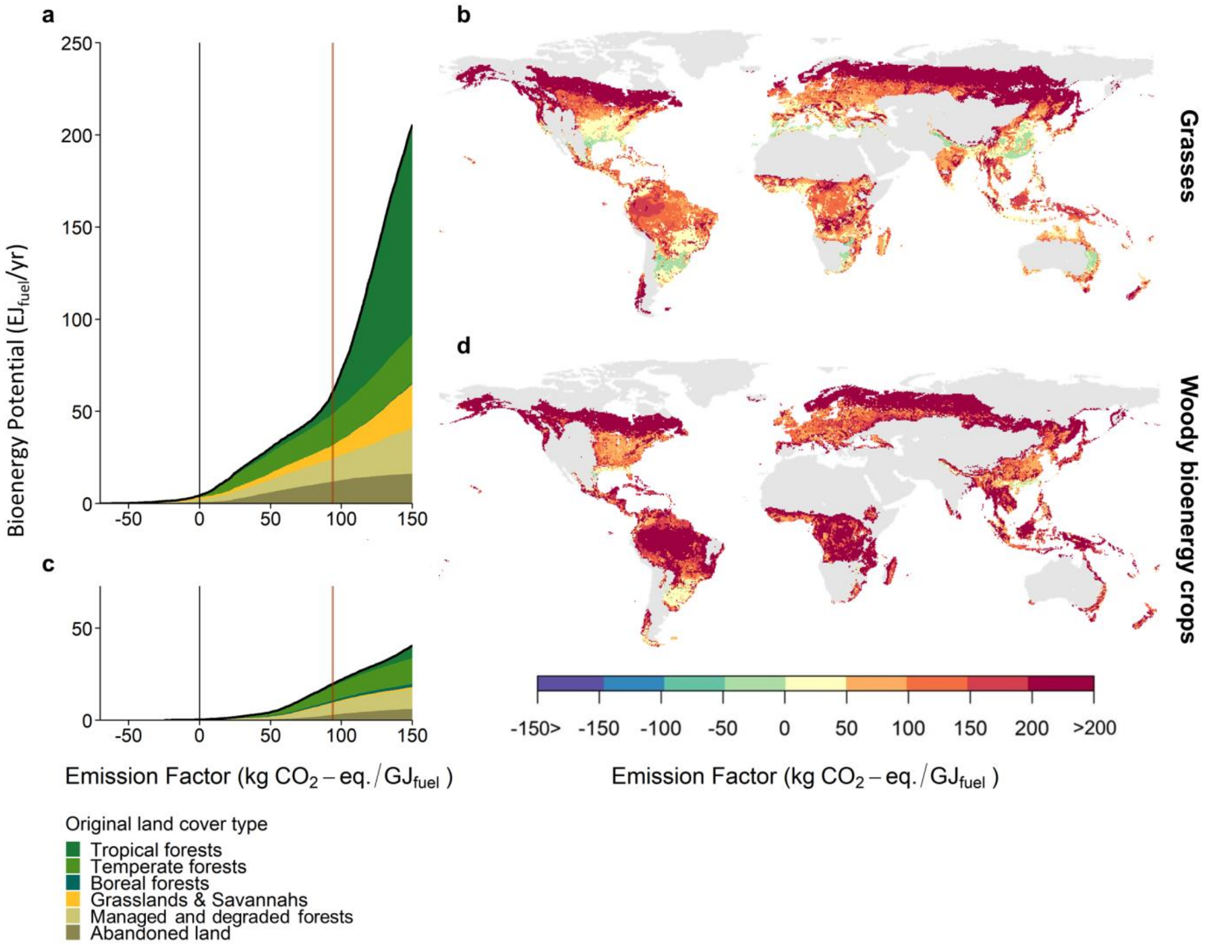

Figure S6 | Global emission factors maps and resulting emission-supply curves for Fischer-Tropsch (FT-)diesel produced with CCS from grasses and woody bioenergy. a, Emission-supply curve of FT-diesel with CCS from grasses (Miscanthus and switchgrass cultivars). **b**, EF map of FT-diesel with CCS from 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.

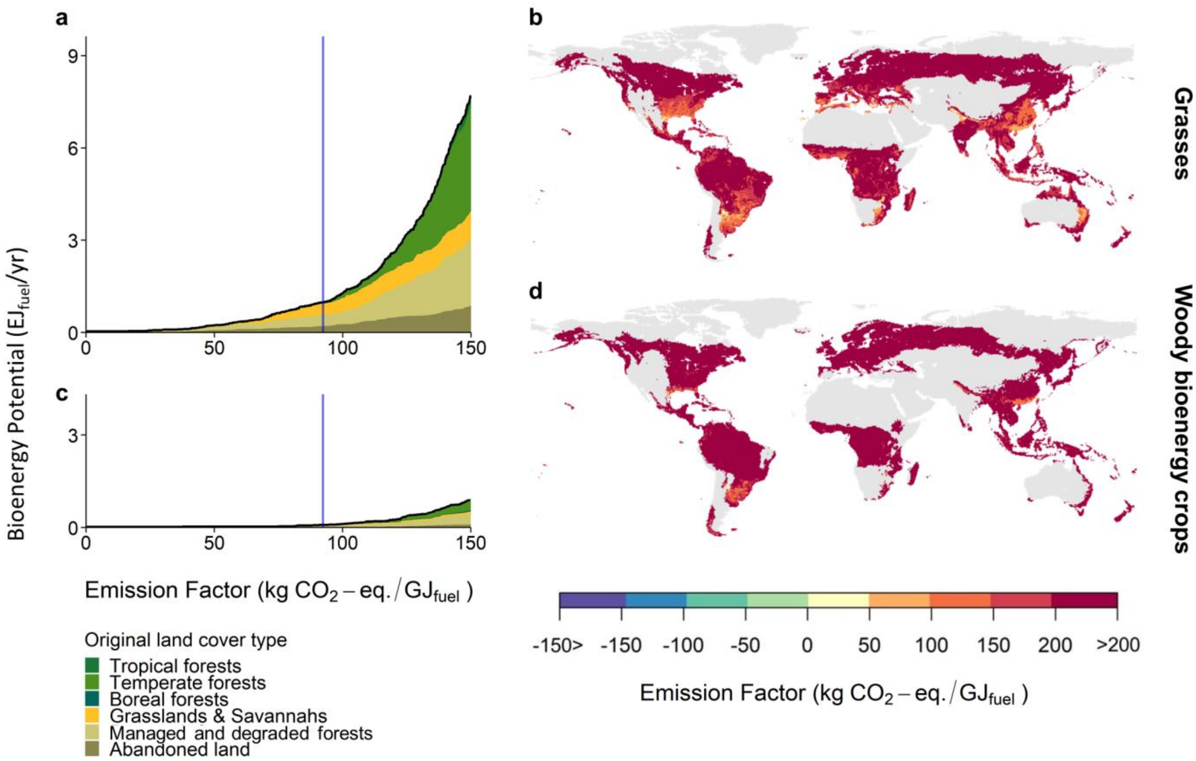

Figure S7 | Global emission factors maps and resulting emission-supply curves for ethanol produced with CCS from grasses and woody bioenergy. a, Emission-supply curve of ethanol with CCS from grasses (Miscanthus and switchgrass cultivars). **b**, EF map of ethanol with CCS from grasses (Miscanthus and 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

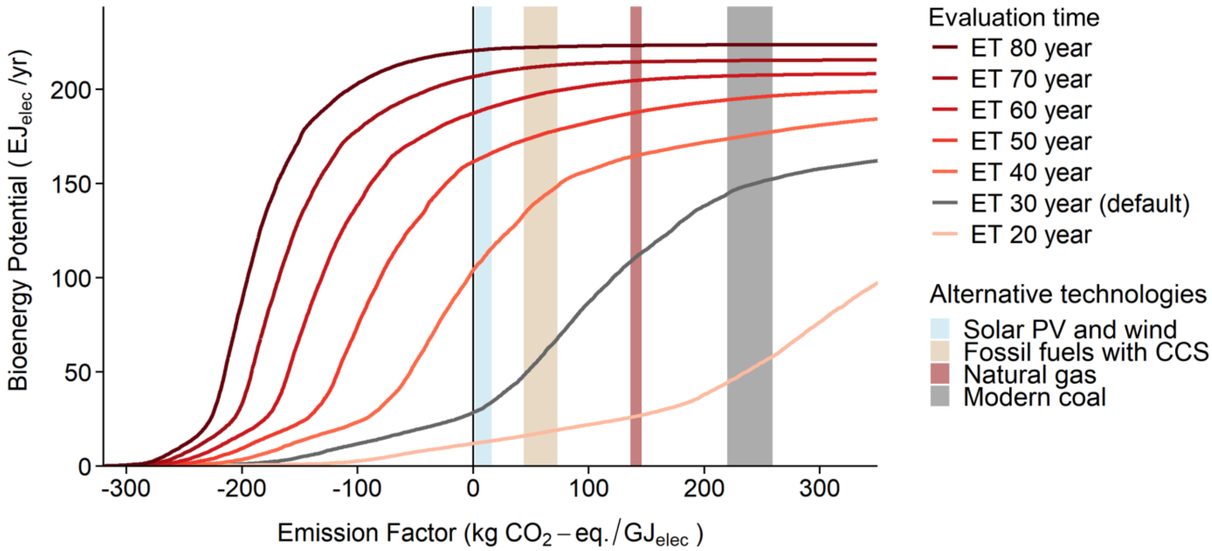

Figure S8 | Global emission-supply curves of BECCS electricity over varying evaluation times. Shaded columns indicate EF ranges for alternative electricity generation technologies (Brückner et al., 2014; Hertwich et al., 2015; TableS2).

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.

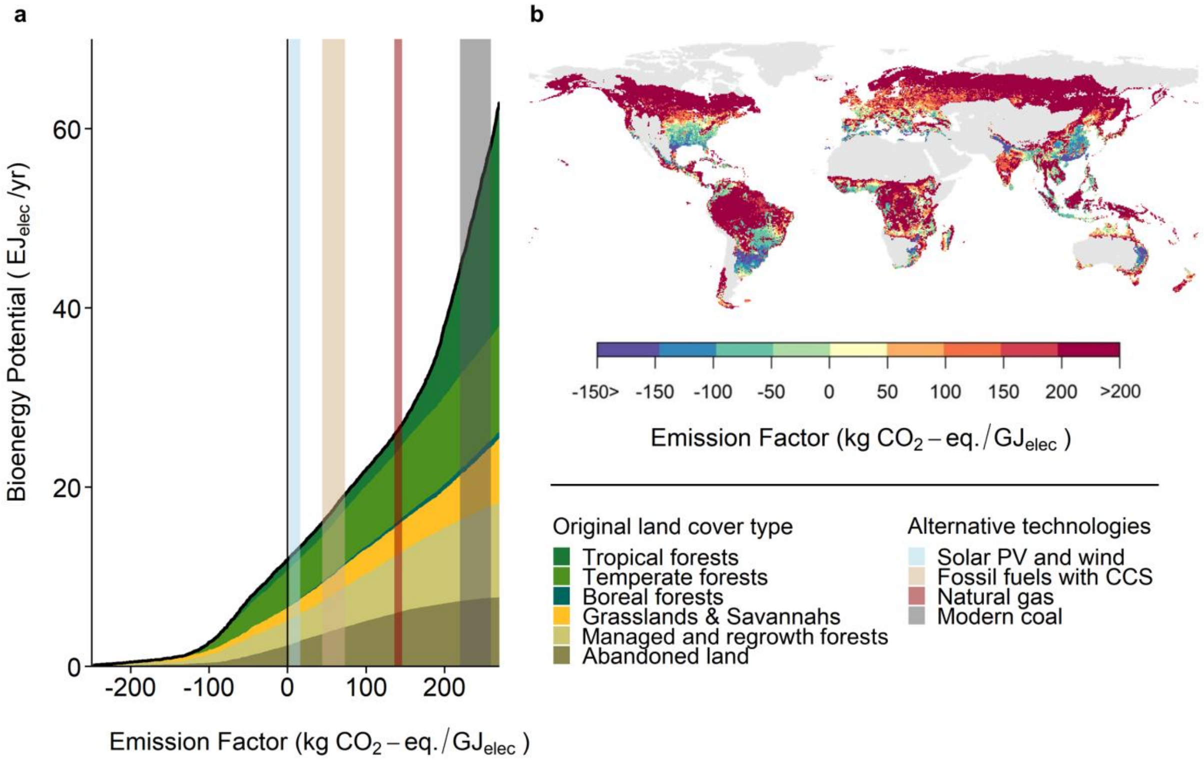

Figure S9 | Global emission factors maps and resulting emission-supply curves of BECCS electricity over a 20 year evaluation time. a, Emission-supply curve of BECCS electricity. Shaded columns indicate EF ranges for alternative electricity generation technologies (Brückner et al., 2014; Hertwich et al., 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

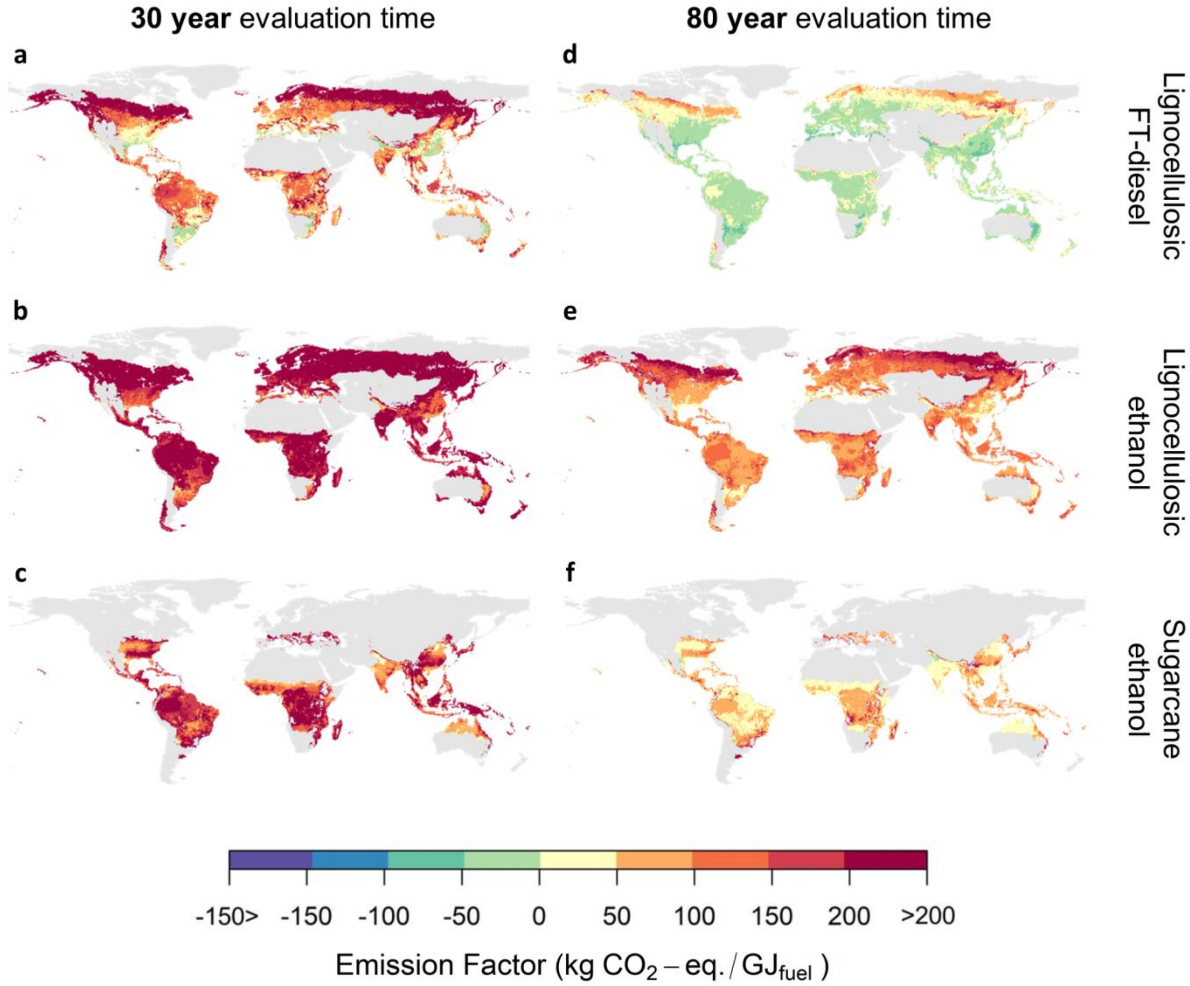

Figure S10 | Global emission factor maps of liquid biofuels with CCS. a, EF map for lignocellulosic bioenergy crop-based Fischer-Tropsch diesel with CCS considered over a 30 year evaluation time. **b,** EF map for lignocellulosic ethanol with CCS over a 30 year evaluation time. **c,** EF map for sugarcane 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

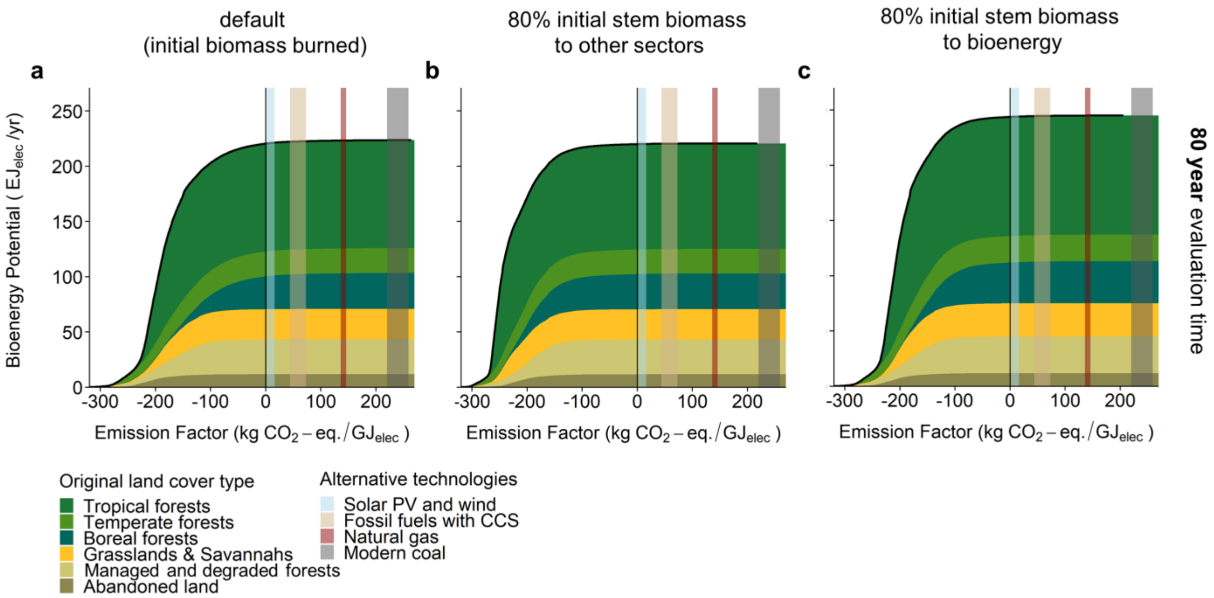

Figure S11 | Global emission-supply curves of BECCS electricity, with alternative uses of initial biomass, considered over an 80 year evaluation time. a, Default BECCS electricity emission-supply curve over an 80 year evaluation time (initial biomass is assumed to be burned). **b**, BECCS electricity 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).

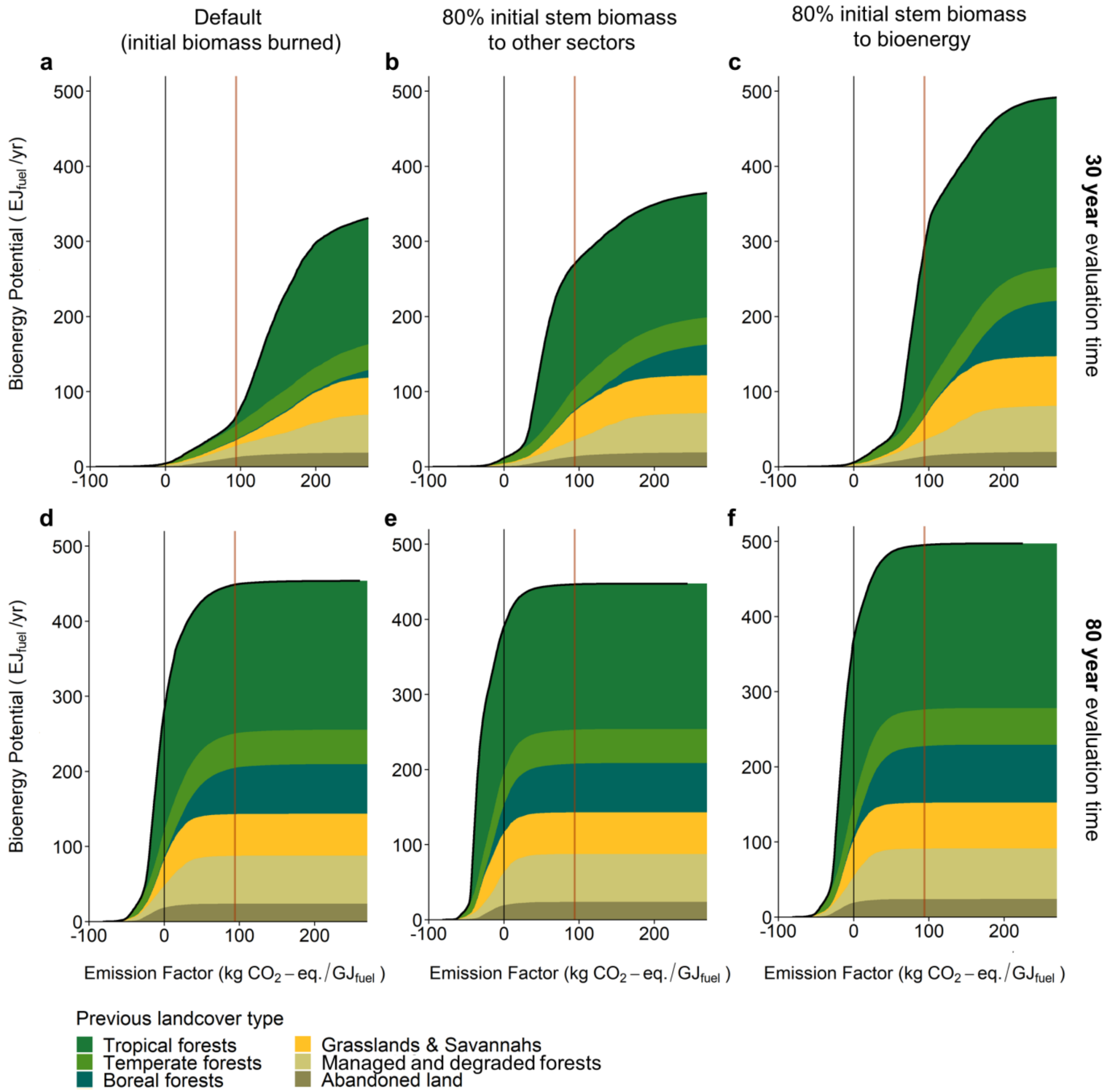

Figure S12 | Global emission-supply curves of lignocellulosic Fischer-Tropsch diesel with CCS, with alternative uses of initial biomass, considered over a 30 and 80 year evaluation times. a, Default emission-supply curve for FT-diesel with CCS over a 30 year evaluation time (initial biomass is assumed 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

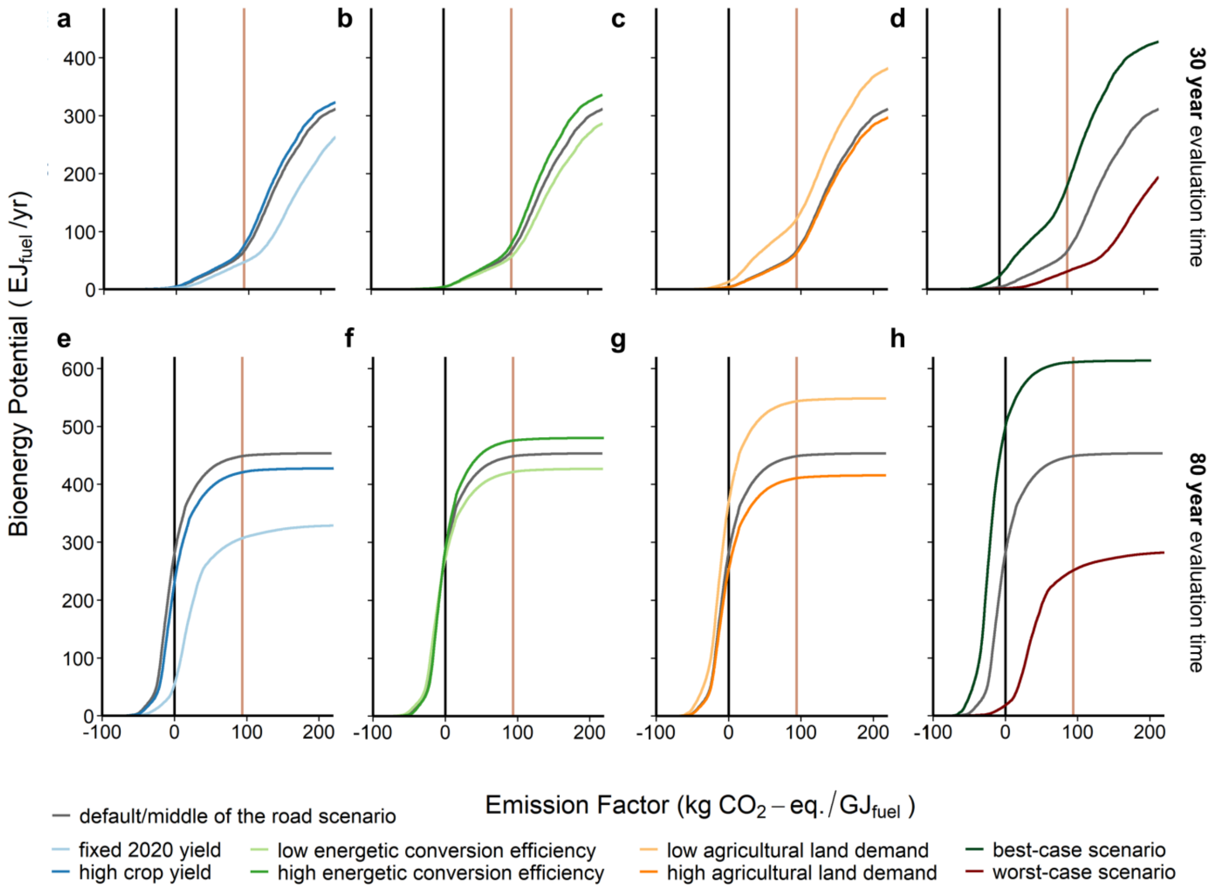

Figure S13 | Sensitivity analysis of emission-supply curves for lignocellulosic Fischer-Tropsch diesel with CCS. The default emission-supply curve is plotted in grey in all panels. **a**, Emission-supply curves at constant 2020 crop yields (light blue) and high crop yields (dark blue) **b**, Emission-supply 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.

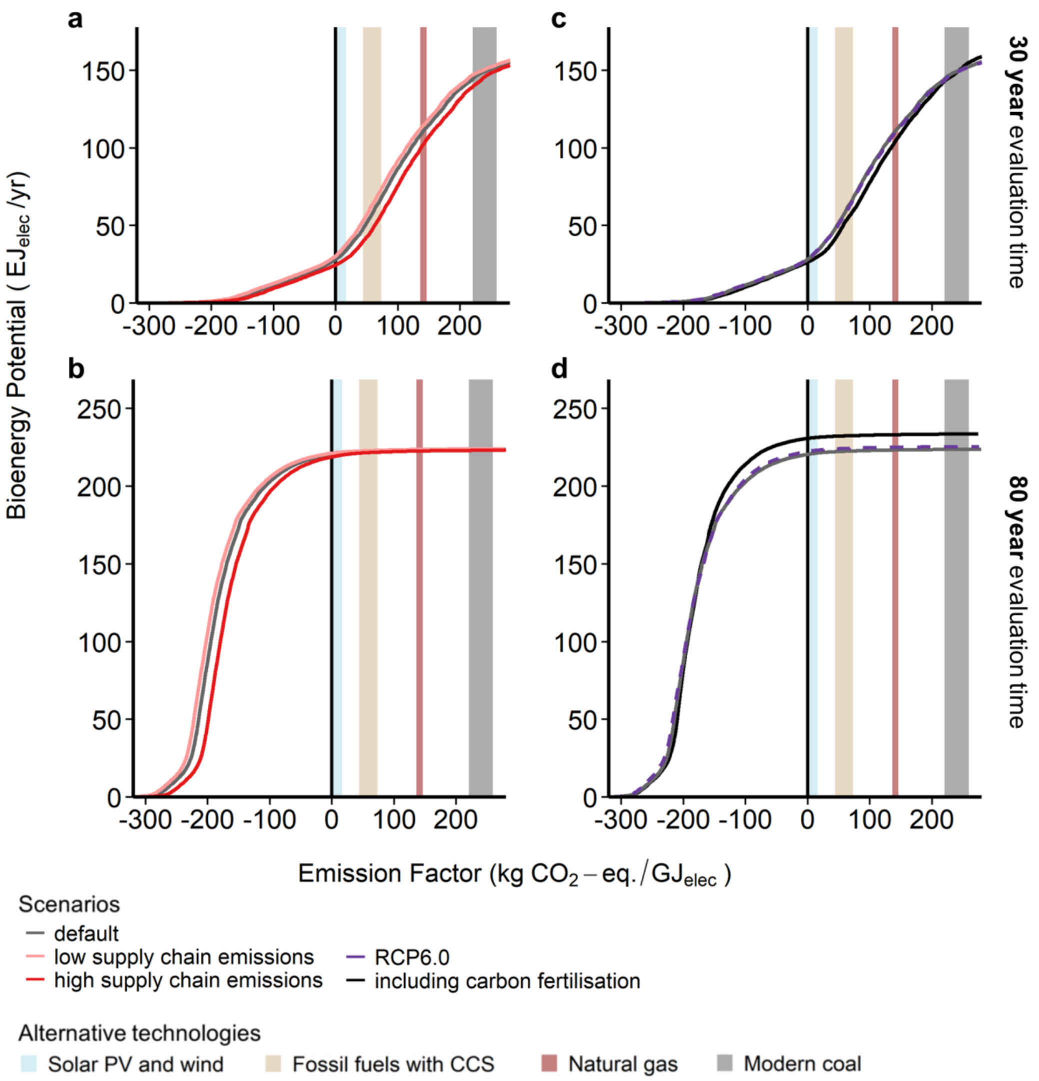

Figure S14 | Sensitivity of BECCS electricity emission-supply curves to parameterisation *extended*. a, Emission-supply curves for low (pink line) and high (red line) supply chain GHG emissions, as compared to default supply chain emissions (grey line; range and default value are based on literature, 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.

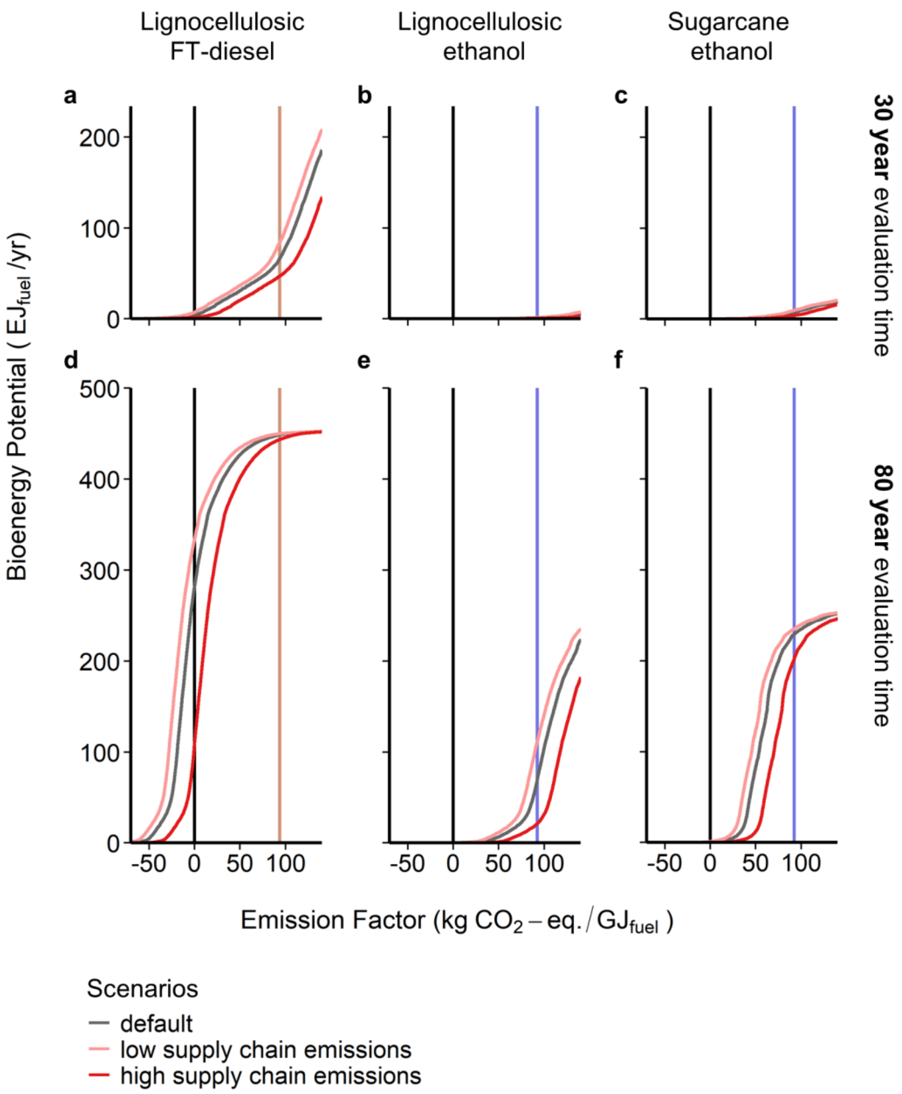

Figure S15 | Sensitivity of liquid biofuels with CCS to supply chain GHG emissions. a, Global emission-supply curves for FT-diesel with CCS considered over a 30 year evaluation period, with either: low supply chain GHG emissions (pink line) or high supply chain GHG emissions (red line), as compared to 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.

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

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.

$$\Delta C_{CCF}(t) = \frac{f(t)}{f(RT)} \cdot \Delta C_{CCF} \qquad \textit{for: } 0 \leq t \geq RT \qquad \textbf{eq. S4}$$

$$= \frac{t \cdot \left(RT - \frac{t}{2}\right)}{\frac{1}{2} \cdot RT^2} \cdot \frac{f_{Red}}{2} \cdot C_{unharvested}$$

$$= \frac{t \cdot \left(RT - \frac{t}{2}\right)}{RT^2} \cdot f_{Red} \cdot C_{unharvested}$$

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 LPJmI 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.

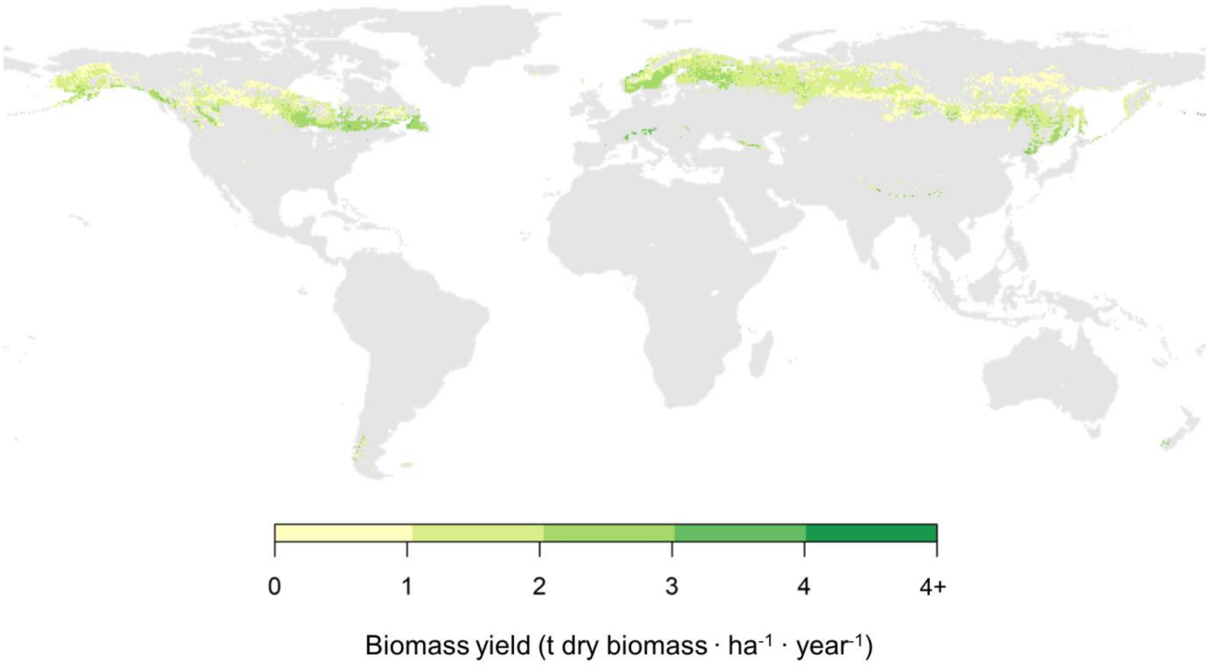

Figure S16 | Annual biomass yields from boreal continuous cover forestry (CCF). Yields are based on natural boreal forest regrowth in rates in the LPJml model, calibrated with literature-based empirical net primary productivity data and a literature-based CCF to conventional forestry yield ratio.

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).

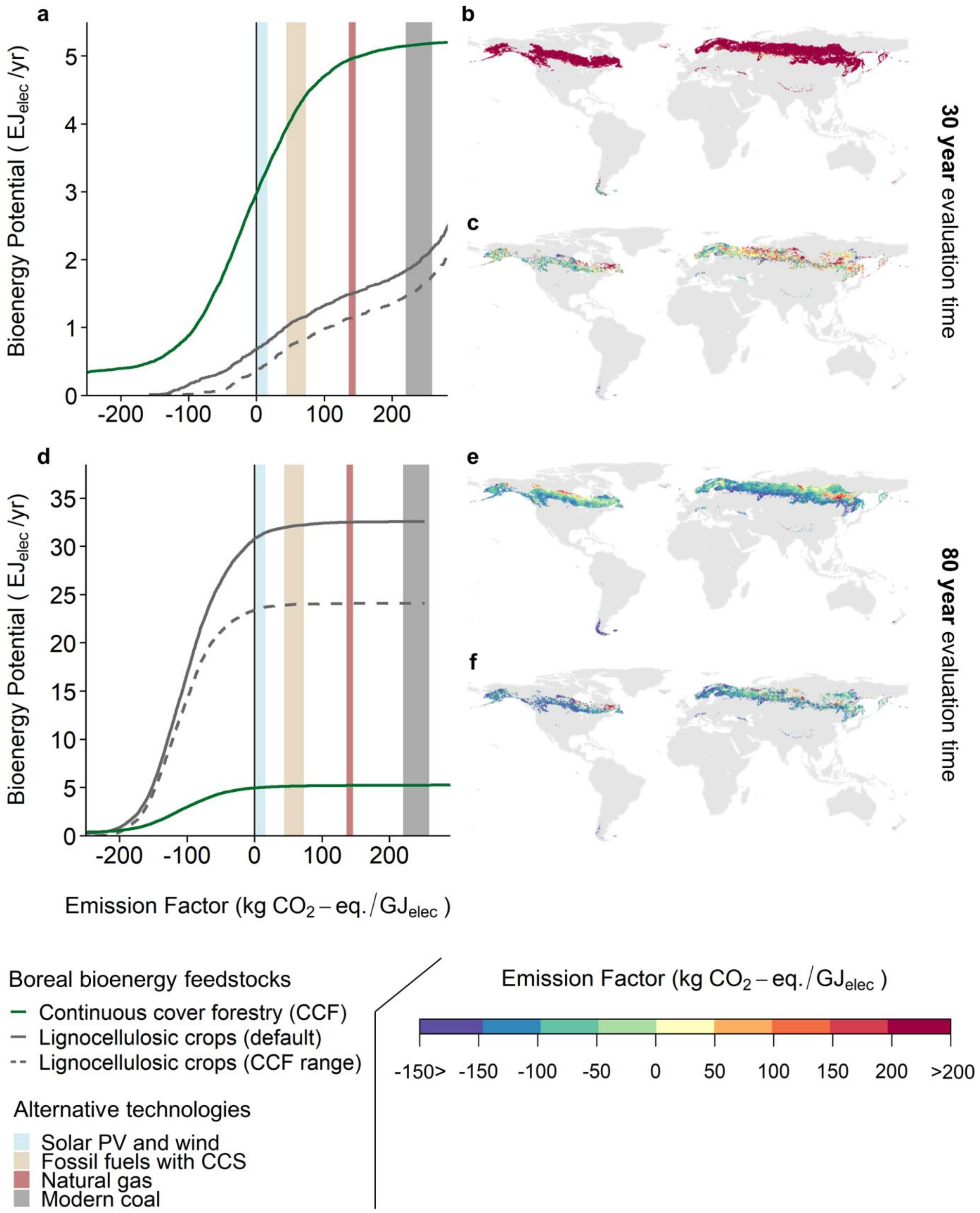

Figure S17 | Emission-supply curves and emission factor maps of bioelectricity with CCS from different boreal feedstocks. a, Boreal emission-supply curves of bioelectricity with CCS over a 30 year evaluation time based on: i) continuous cover forestry (CCF; green line), ii) this study's default feedstock 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.

16. References

Ail, S. S. & Dasappa, S. Biomass to liquid transportation fuel via Fischer Tropsch synthesis - technology review and current scenario. *Renewable and sustainable energy reviews* **58,** 267-286 (2016).

Alonso, M., Diego, M., Pérez, C., Chamberlain, J. & Abanades, J. Biomass combustion with in situ CO_2 capture by CaO in a 300 kW_{th} circulating fluidized bed facility. *International Journal of Greenhouse Gas Control* **29**, 142-152 (2014).

de Andrade, R.B., Balch, J.K., Parsons, A.L., Armenteras, D., Roman-Cuesta, R.M. & Bulkan, J. Scenarios in tropical forest degradation: carbon stock trajectories for REDD+. *Carbon Balance and Management* 12:6 (2017).

Arets, E.J.M.M., van der Meer, P.J., Verwer, C.C., Hengeveld, G.M., Tolkamp, G.W., Nabuurs, G.J. & van Oorschot, M. *Global Wood Production.* (Alterra Wageningen University & Research, Wageningen, the Netherlands, 2011).

Al-Qayim, K., Nimmo, W. & Pourkashanian, M. Comparative techno-economic assessment of biomass and coal with CCS technologies in a pulverized combustion power plant in the United Kingdom. *International Journal of Greenhouse Gas Control* **43**, 82-92 (2015).

Bai, Y., Luo, L. & van der Voet, E. Life cycle assessment of switchgrass-derived ethanol as transport fuel. *The International Journal of Life Cycle Assessment* **15**, 468-477 (2010).

Bonner, M.T.L., Schmidt, S. & Shoo, L.P. A meta-analytical global comparison of aboveground biomass accumulation between tropical secondary forests and monoculture plantations. *Forest Ecology & Management* **291,** 73-86 (2013).

Boschiero, M., Cherubini, F., Nati, C. & Zerbe, S. Life cycle assessment of bioenergy production from orchards woody residues in Northern Italy. *Journal of Cleaner Production* **112**, 2569-2580 (2016).

Bright, R. M. & Strømman, A. H. Fuel-mix, fuel efficiency, and transport demand affects prospects for biofuels in northern Europe. *Environmental Science & Technology* **2010,** 2261-2269 (2010).

Bright, R. M., Strømman, A. H. & Hawkins, T. R. Environmental Assessment of Wood-Based Biofuel Production and Consumption Scenarios in Norway. *Journal of Industrial Ecology* **14**, 422-439 (2010).

Brinkman, N., Wang, M., Weber, T. & Darlington, T. *Well-to-wheels analysis of advanced fuel/vehicle systems: A North American study of energy use, greenhouse gas emissions, and criteria pollutant emissions.* (EERE Publication and Product Library, 2005).

Bruckner, T. et al. in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. et al.) 511–597 (Cambridge Univ. Press, Cambridge, 2014).

Budsberg, E. et al. Life-cycle assessment for the production of bioethanol from willow biomass crops via biochemical conversion. *Forest Products Journal* **62**, 305-313 (2012).

Cadoux, S. et al. Implications of productivity and nutrient requirements on greenhouse gas balance of annual and perennial bioenergy crops. *GCB Bioenergy* **6**, 425-438 (2014).

Cannell, M. G. Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK. *Biomass and Bioenergy* **24**, 97-116 (2003).

Cherubini, F. et al. Energy-and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, conservation and recycling* **53**, 434-447 (2009).

Cherubini, F., Strømman, A. H. & Ulgiati, S. Influence of allocation methods on the environmental performance of biorefinery products—A case study. *Resources, Conservation and Recycling* **55**, 1070-1077 (2011).

Corsten, M., Ramírez, A., Shen, L., Koornneef, J. & Faaij, A. Environmental impact assessment of CCS chains–lessons learned and limitations from LCA literature. *International Journal of Greenhouse Gas Control* **13**, 59-71 (2013).

Creutzig, F. et al. Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy* **7**, 916-944 (2015).

Cruz, P. L., Iribarren, D. & Dufour, J. Exergy analysis of alternative configurations of a system coproducing synthetic fuels and electricity via biomass gasification, Fischer-Tropsch synthesis and a combined-cycle scheme. *Fuel* **194**, 375-394 (2017).

Cuéllar-Franca, R. M. & Azapagic, A. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *Journal of* CO_2 *utilization* **9**, 82-102 (2015).

Damen, K., van Troost, M., Faaij, A. & Turkenburg, W. A comparison of electricity and hydrogen production systems with CO2 capture and storage. Part A: review and selection of promising conversion and capture technologies. *Progress in energy and combustion science* **32**, 215-246 (2006).

Daystar, J., Reeb, C., Gonzalez, R., Venditti, R. & Kelley, S. S. Environmental life cycle impacts of cellulosic ethanol in the Southern US produced from loblolly pine, eucalyptus, unmanaged hardwoods, forest residues, and switchgrass using a thermochemical conversion pathway. *Fuel Processing Technology* **138**, 164-174 (2015).

Daystar, J., Reeb, C., Venditti, R., Gonzalez, R. & Puettmann, M. E. Life-cycle assessment of bioethanol from pine residues via indirect biomass gasification to mixed alcohols. *Forest Products Journal* **62**, 314-325 (2012).

de Visser, E. et al. PlantaCap: A ligno-cellulose bio-ethanol plant with CCS. *Energy Procedia* **4**, 2941-2949 (2011).

de Vries, S. C., van de Ven, G. W., van Ittersum, M. K. & Giller, K. E. Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques. *Biomass and Bioenergy* **34**, 588-601 (2010).

Dias De Oliveira, M. E., Vaughan, B. E. & Rykiel, E. J. Ethanol as fuel: energy, carbon dioxide balances, and ecological footprint. *BioScience* **55**, 593-602 (2005).

Djomo, S. N. et al. Energy and climate benefits of bioelectricity from low-input short rotation woody crops on agricultural land over a two-year rotation. *Applied energy* **111**, 862-870 (2013).

Djomo, S. N., Witters, N., Van Dael, M., Gabrielle, B. & Ceulemans, R. Impact of feedstock, land use change, and soil organic carbon on energy and greenhouse gas performance of biomass cogeneration technologies. *Applied Energy* **154**, 122-130 (2015).

Dwivedi, P., Bailis, R., Bush, T. G. & Marinescu, M. Quantifying GWI of wood pellet production in the southern United States and its subsequent utilization for electricity production in the Netherlands/Florida. *Bioenergy Research* **4**, 180-192 (2011).

Edwards, R., Larivé, J.-F., Rickeard, D. & Weindorf, W. *Well-to-tank report version 4.0 Well-to-wheels analysis of future automotive fuels and powertrains in the European context.* (Joint Research Centre of the European Comission, Ispra, Italy, 2013).

Edwards, R., Larivé, J.-F., Rickeard, D. & Weindorf, W. *Well-to-tank report version 4a Well-to-wheels analysis of future automotive fuels and powertrains in the European context.* (Joint Research Centre of the European Comission, Ispra, Italy, 2014).

Egeskog, A., Freitas, F., Berndes, G., Sparovek, G. & Wirsenius, S. Greenhouse gas balances and land use changes associated with the planned expansion (to 2020) of the sugarcane ethanol industry in Sao Paulo, Brazil. *Biomass and Bioenergy* **63**, 280-290 (2014).

Elsayed, M., Matthews, R. & Mortimer, N. *Carbon and energy balances for a range of biofuels options.* (Resources Research Unit, Sheffield Hallam University & Forest Research, 2003).

Eriksson, M. & Ahlgren, S. *LCAs of petrol and diesel* (Swedish University of Agricultural Science, Uppsala, 2013).

Erlach, B., Harder, B. & Tsatsaronis, G. Combined hydrothermal carbonization and gasification of biomass with carbon capture. *Energy* **45**, 329-338 (2012).

European Parliament. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009. *Off. J. Eur. Union* **140**, 16–62 (2009).

Evans, A., Strezov, V. & Evans, T. J. Sustainability considerations for electricity generation from biomass. *Renewable and sustainable energy reviews* **14**, 1419-1427 (2010).

Farine, D. R. et al. An assessment of biomass for bioelectricity and biofuel, and for greenhouse gas emission reduction in Australia. *GCB Bioenergy* **4**, 148-175 (2012).

Fazio, S. & Monti, A. Life cycle assessment of different bioenergy production systems including perennial and annual crops. *Biomass and Bioenergy* **35**, 4868-4878 (2011).

Forsberg, G. Biomass energy transport: analysis of bioenergy transport chains using life cycle inventory method. *Biomass and Bioenergy* **19**, 17-30 (2000).

Girard, P. & Fallot, A. Review of existing and emerging technologies for the production of biofuels in developing countries. *Energy for Sustainable Development* **10**, 92-108 (2006).

Giuntoli, J., Agostini, A., Edwards, R. & Marelli, L. *Solid and gaseous bioenergy pathways: input values and GHG emissions* (Joint Research Centre of European Commission, Luxemburg, 2014)

Goglio, P. & Owende, P. M. A screening LCA of short rotation coppice willow (Salix sp.) feedstock production system for small-scale electricity generation. *Biosystems Engineering* **103**, 389-394 (2009).

González-García, S. et al. Environmental profile of ethanol from poplar biomass as transport fuel in Southern Europe. *Renewable Energy* **35**, 1014-1023 (2010).

Groode, T. A. & Heywood, J. B. *Ethanol: A look ahead.* Massachusetts Institute of Technology, Cambridge, MA, USA, (2007).

Guest, G., Bright, R. M., Cherubini, F., Michelsen, O. & Strømman, A. H. Life Cycle Assessment of biomass-based combined heat and power plants: centralized versus decentralized deployment strategies. *Journal of Industrial Ecology* **15**, 908-921 (2011).

Hamelinck, C. N., Faaij, A. P., den Uil, H. & Boerrigter, H. Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential. *Energy* **29**, 1743-1771 (2004).

Hamelinck, C.N. & Hoogwijk, M. Future scenarios for first and second generation biofuels. Ecofys, Utrecht, The Netherlands (2007).

Hansen, A., Meyer-Aurich, A. & Prochnow, A. Greenhouse gas mitigation potential of a second generation energy production system from short rotation poplar in Eastern Germany and its accompanied uncertainties. *Biomass and Bioenergy* **56**, 104-115 (2013).

Hanssen, S. V., Duden, A. S., Junginger, M., Dale, V. H. & van der Hilst, F. Wood pellets, what else? Greenhouse gas parity times of European electricity from wood pellets produced in the south-eastern United States using different softwood feedstocks. *GCB Bioenergy* **9**, 1406-1422 (2017).

Heller, M. C., Keoleian, G. A. & Volk, T. A. Life cycle assessment of a willow bioenergy cropping system. *Biomass and Bioenergy* **25**, 147-165 (2003).

Hennig, C. & Gawor, M. Bioenergy production and use: comparative analysis of the economic and environmental effects. *Energy Conversion and Management* **63**, 130-137 (2012).

Hertwich, E.G. et al. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proc. Natl. Acad. Sci.* **112,** 6277-6282 (2015).

Hetland, J., Yowargana, P., Leduc, S. & Kraxner, F. Carbon-negative emissions: Systemic impacts of biomass conversion: A case study on CO2 capture and storage options. *International Journal of Greenhouse Gas Control* **49**, 330-342 (2016).

Hoefnagels, R., Smeets, E. & Faaij, A. Greenhouse gas footprints of different biofuel production systems. *Renewable and Sustainable Energy Reviews* **14**, 1661-1694 (2010).

Hsu, D. D. et al. Life cycle environmental impacts of selected US ethanol production and use pathways in 2022. *Environmental Science & Technology* **44**, 5289-5297 (2010).

Huppman, D. et al. *IAMC 1.5°C Scenario Explorer and Data hosted by IIASA.* https://doi.org/10.5281/zenodo.3363345 (IAMC/IIASA 2019).

IEA. International Energy Agency. *Biomass for Power Generation and CHP.* (IEA, 2007).

IEA GHG. International Energy Agency Greenhouse Gas R&D Programme. *Biomass CCS study* (IEA GHG, Cheltenham, United Kingdom, 2009).

IPCC *2006 Guidelines for National Greenhouse Gas Inventories* (National Greenhouse Gas Inventories Programme, IGES, 2006).

Jonker, J.G.G. et al. Supply chain optimization of sugarcane first generation and eucalyptus second generation ethanol production in Brazil. *Applied Energy* **173**, 494-510 (2016).

Jonker, J.G.G. et al. Outlook for ethanol production costs in Brazil up to 2030, for different biomass crops and industrial technologies. *Applied Energy* **147**, 593-610 (2015).

Jonker, J. G. G., Junginger, M. & Faaij, A. Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States. *GCB Bioenergy* **6**, 371-389 (2013).

Jungbluth, N., Frischknecht, R., Emmenegger, M. F., Steiner, R. & Tuschmid, M. *Life cycle assessment of BTL-fuel production: life cycle impact assessment and interpretation* (ESU-services, Uster, Switzerland, 2007).

Junginger, H.M. et al. The future of biomass and bioenergy deployment and trade: a synthesis of 15 years IEA Bioenergy Task 40 on sustainable bioenergy trade. *Biofuel. Bioprod. & Bior.* **13,** 247-266 (2019).

Knoope, M., Meerman, J., Ramírez, A. & Faaij, A. Future technological and economic performance of IGCC and FT production facilities with and without CO2 capture: Combining component based learning curve and bottom-up analysis. *International journal of greenhouse gas control* **16**, 287-310 (2013).

Koornneef, J. et al. Global potential for biomass and carbon dioxide capture, transport and storage up to 2050. *International Journal of Greenhouse Gas Control* **11**, 117-132 (2012).

Kumar, A. & Sokhansanj, S. Switchgrass (Panicum vigratum, L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. *Bioresource technology* **98**, 1033-1044 (2006).

Kuuluvainen, T. & Gauthier, S. Young and old forest in the boreal: critical stages of ecosystem dynamics and management under global change. *Forest Ecosystems,* 5-26 (2018).

Larson, E. & Jin, H. Biomass conversion to Fischer-Tropsch liquids: preliminary energy balances. Prepared for: *Proceedings of the 4th Biomass Conference of the Americas* (Oakland, USA, Aug. 29 - Sept. 2, 1999).

Larson, E., Williams, R.H., Jin, H. Fuels and electricity from biomass with CO_2 capture and storage. Prepared for: *8th International Conference on Greenhouse Gas Control Technologies* (Trondheim, Norway, June 19-22, 2006)

Laser, M. et al. Comparative analysis of efficiency, environmental impact, and process economics for mature biomass refining scenarios. *Biofuels, Bioproducts and Biorefining* **3**, 247-270 (2009).

Laude, A., Ricci, O., Bureau, G., Royer-Adnot, J. & Fabbri, A. CO_2 capture and storage from a bioethanol plant: carbon and energy footprint and economic assessment. *International Journal of Greenhouse Gas Control* **5**, 1220-1231 (2011).

Liu, G., Larson, E. D., Williams, R. H., Kreutz, T. G. & Guo, X. Making Fischer– Tropsch fuels and electricity from coal and biomass: performance and cost analysis. *Energy & Fuels* **25**, 415-437 (2010).

Lundmark, T., Bergh, J., Nordin, A., Fahlvik, N. & Poudel, B.C. Comparison of carbon balances between continuous-cover and clear-cut forestry in Sweden. *AMBIO,* **45**, 203-213 (2016).

Luyssaert, S. Inglima, I., Jungs, M., Richardson, A.D., Reichstein, M. et al. CO_2 balance of boreal, temperate, and tropical forests derived from a global database. *Global Change Biology* **13**, 2509-2537 (2007).

Macedo, I. C., Seabra, J. E. & Silva, J. E. Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: the 2005/2006 averages and a prediction for 2020. *Biomass and bioenergy* **32**, 582-595 (2008).

Macedo, I. C., Verde, M. R. & Ramos da Silva, J. E. *Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil.* (Government of the State of São Paulo, Brazil, 2004).

Manochio, C., Andrade, B., Rodriguez, R. & Moraes, B. Ethanol from biomass: a comparative overview. *Renewable and Sustainable Energy Reviews* **80**, 743-755 (2017).

Markewitz, P. et al. Worldwide innovations in the development of carbon capture technologies and the utilization of CO_2. *Energy & Environmental Science* **5**, 7281-7305 (2012).

McCalmont, J.P., McNamara, N.P., Donnison, I.S., Farrar, K. & Clifton-Brown, J. C. Partitioning of ecosystem respiration of CO 2 released during land-use transition from temperate agricultural grassland to Miscanthus×giganteus. *GCB Bioenergy* **9**, 710-724 (2017).

McKechnie, J. et al. Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science & Technology,* **45**, 789-759 (2011a).

McKechnie, J. et al. Impacts of co-location, co-production, and process energy source on life cycle energy use and greenhouse gas emissions of lignocellulosic ethanol. *Biofuels, Bioproducts and Biorefining* **5**, 279-292 (2011b).

McMahon, P., Sarshar, D. & Purser, P. *Investigating in Continuous Cover Forestry.* (SLM Partners, New York, 2016).

Meerman, J., Knoope, M., Ramírez, A., Turkenburg, W. & Faaij, A. Technical and economic prospects of coal-and biomass-fired integrated gasification facilities equipped with CCS over time. *International Journal of Greenhouse Gas Control* **16**, 311-323 (2013).

Meerman, J., Ramírez, A., Turkenburg, W. & Faaij, A. Performance of simulated flexible integrated gasification polygeneration facilities. Part A: a technical-energetic assessment. *Renewable and Sustainable Energy Reviews* **15**, 2563-2587 (2011).

Menten, F., Chèze, B., Patouillard, L. & Bouvart, F. A review of LCA greenhouse gas emissions results for advanced biofuels: the use of meta-regression analysis. *Renewable and Sustainable Energy Reviews* **26**, 108-134 (2013).

Modahl, I. S. *et al.* Life cycle assessment of gas power with CCS - a study showing the environmental benefits of system integration. *Energy Procedia* **4**, 2470-2477 (2011).

Moreira, J. R., Romeiro, V., Fuss, S., Kraxner, F. & Pacca, S. A. BECCS potential in Brazil: achieving negative emissions in ethanol and electricity production based on sugar cane bagasse and other residues. *Applied Energy* **179**, 55-63 (2016).

Mu, D., Seager, T., Rao, P. S. & Zhao, F. Comparative life cycle assessment of lignocellulosic ethanol production: biochemical versus thermochemical conversion. *Environmental Management* **46**, 565-578 (2010).

Mullins, K.A., Griffin, W.M. & Matthews, H.S. Policy implications of uncertainty in modeled life-cycle greenhouse gas emissions of biofuels. *Environmental Science & Technology* **45**, 132-138 (2011).

Murphy, C. W. & Kendall, A. Life cycle analysis of biochemical cellulosic ethanol under multiple scenarios. *GCB Bioenergy* **7**, 1019-1033 (2015).

NETL. US Department of Energy, National Energy Technology Laboratory. *Greenhouse Gas Reductions in the Power Industry Using Domestic Coal and Biomass-Volume 2: Pulverized Coal Plants.* (DOE/NETL, 2012).

Odeh, N. A. & Cockerill, T. T. Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. *Energy Policy* **36**, 367-380 (2008).

Oreggioni, G. D. *et al.* Environmental assessment of biomass gasification combined heat and power plants with absorptive and adsorptive carbon capture units in Norway. *International Journal of Greenhouse Gas Control* **57**, 162-172 (2017).

Parkatti, V-P., Assmuth, A., Rämö, J. & Tahvonen, O. Economics of boreal conifer species in continuous cover and rotation forestry. *Forest Policy & Economics* **100**, 55-67 (2019).

Petrescu, L., Bonalumi, D., Valenti, G., Cormos, A.-M. & Cormos, C.-C. Life Cycle Assessment for supercritical pulverized coal power plants with post-combustion carbon capture and storage. *Journal of Cleaner Production* **157**, 10-21 (2017).

Peura, M., Burgas, D., Eyvindson, K., Repo, A. & Mönkkönen, M. Continuous cover forestry is a cost-efficient tool to increase multifunctionality of boreal production forests in Fennoscandia. *Biological Conservation* **217**, 104-112 (2018).

Phyllis2 database. Enery research Centre of the Netherlands/Netherlands Organisation for Applied Scientific Research (ECN/TNO). *Database for biomass and waste.*[accessed October 2019; available online at https://phyllis.nl/].

Poorter, L. et al. Biomass resilience of Neotropical secondary forests. *Nature* **530**, 211-214 (2016).

Prins, M. J., Ptasinski, K. J. & Janssen, F. J. Exergetic optimisation of a production process of Fischer–Tropsch fuels from biomass. *Fuel Processing Technology* **86**, 375-389 (2004).

Pukkala, T., Lähde, E. & Laiho, O. Continuous cover forestry in Finland – recent research results. in *Continuous Cover Forestry* (eds Pukkala, T. & von Gadow, K.) 85-128 (Springer, Dordrecht, 2012).

Pukkala, T., Lähde, E. & Laiho, O. Optimizing the structure and management of uneven-sized stands of Finland. *Forestry* **83**, 129-142 (2010).

Rappaport, D.I., Morton, D.C., Longo, M., Keller, M., Dubayah, R. & Nara dos-Stantos, M. Quantifying long-term changes in carbon stocks and forest structure from Amazon forest degradation. *Environmental Research Letters* **13**, 065013 (2018).

Reichling, J. & Kulacki, F. Comparative analysis of Fischer–Tropsch and integrated gasification combined cycle biomass utilization. *Energy* **36**, 6529-6535 (2011).

Robertson, A. D. *et al.* A Miscanthus plantation can be carbon neutral without increasing soil carbon stocks. *GCB Bioenergy* **9**, 645-661 (2016).

Röder, M., Whittaker, C. & Thornley, P. How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. *Biomass and Bioenergy* **79**, 50-63 (2015).

Rogelj, J. et al. in *Global Warming of 1.5°C* (eds. Masson-Delmotte, V. et al.) 93-174 (In Press).

Sanchez, D. L., Johnson, N., McCoy, S. T., Turner, P. A. & Mach, K. J. Near-term deployment of carbon capture and sequestration from biorefineries in the United States. *Proceedings of the National Academy of Sciences* **115**, 4875-4880 (2018).

Schakel, W., Meerman, H., Talaei, A., Ramírez, A. & Faaij, A. Comparative life cycle assessment of biomass co-firing plants with carbon capture and storage. *Applied Energy* **131**, 441-467 (2014).

Schlömer, S. et al. *in Climate Change 2014: Mitigation of Climate Change* (eds. Edenhofer, O. et al.) 1329-1356 (Cambridge Univ. Press, Cambridge, 2014).

Schmer, M. R., Vogel, K. P., Mitchell, R. B. & Perrin, R. K. Net energy of cellulosic ethanol from switchgrass. *Proceedings of the National Academy of Sciences* **105**, 464-469 (2008).

Seabra, J. E., Macedo, I. C., Chum, H. L., Faroni, C. E. & Sarto, C. A. Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. *Biofuels, Bioproducts and Biorefining* **5**, 519-532 (2011).

Sikkema, R., Junginger, M., Pichler, W., Hayes, S. & Faaij, A. P. The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. *Biofuels, Bioproducts and Biorefining* **4**, 132-153 (2010).

Smeets, E. M., Lewandowski, I. M. & Faaij, A. P. The economical and environmental performance of miscanthus and switchgrass production and supply chains in a European setting. *Renewable and Sustainable Energy Reviews* **13**, 1230-1245 (2009).

Smeets, E.M., Bouwman, L.F., Stehfest, E., van Vuuren, D.P. & Posthuma, A. Contribution of N_2O to the greenhouse gas balance of first-generation biofuels. *Global Change Biology* **15**, 1-23 (2009).

Spatari, S., Bagley, D. M. & MacLean, H. L. Life cycle evaluation of emerging lignocellulosic ethanol conversion technologies. *Bioresource Technology* **101**, 654-667 (2010).

Spatari, S. & MacLean, H. L. Characterizing model uncertainties in the life cycle of lignocellulose-based ethanol fuels. *Environmental Science & Technology* **44**, 8773-8780 (2010).

Spatari, S., Zhang, Y. & MacLean, H. L. Life cycle assessment of switchgrass-and corn stover-derived ethanol-fueled automobiles. *Environmental science & technology* **39**, 9750-9758 (2005).

Spath, P. L. & Mann, M. K. *Biomass Power and Conventional Fossil Systems with and without CO2 Sequestration - Comparing the Energy Balance, Greenhouse Gas Emissions and Economics.* (National Renewable Energy Lab., Golden, CO, USA, 2004).

Stephenson, A., Dupree, P., Scott, S. & Dennis, J. The environmental and economic sustainability of potential bioethanol from willow in the UK. *Bioresource Technology* **101**, 9612-9623 (2010).

Steubing, B., Zah, R. & Ludwig, C. Heat, electricity, or transportation? The optimal use of residual and waste biomass in Europe from an environmental perspective. *Environmental Science & Technology* **46**, 164-171 (2011).

Styles, D. & Jones, M. B. Energy crops in Ireland: quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity. *Biomass and Bioenergy* **31**, 759-772 (2007).

Tahvonen, O. & Rämö, J. Optimality of continuous cover vs. clear-cut regimes in managing forest resources. *Canadian Journal of Forest Research* **46**, 891-901 (2016).

Thakur, A., Canter, C. E. & Kumar, A. Life-cycle energy and emission analysis of power generation from forest biomass. *Applied Energy* **128**, 246-253 (2014).

Thornley, P. *et al.* Integrated assessment of bioelectricity technology options. *Energy Policy* **37**, 890-903 (2009).

Tijmensen, M. J., Faaij, A. P., Hamelinck, C. N. & van Hardeveld, M. R. Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification. *Biomass and Bioenergy* **23**, 129-152 (2002).

Tsiropoulos, I. *et al.* Life cycle assessment of sugarcane ethanol production in India in comparison to Brazil. *The International Journal of Life Cycle Assessment* **19**, 1049-1067 (2014).

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

Volkart, K., Bauer, C. & Boulet, C. Life cycle assessment of carbon capture and storage in power generation and industry in Europe. *International Journal of Greenhouse Gas Control* **16**, 91-106 (2013).

Walle, I. V., Van Camp, N., Van de Casteele, L., Verheyen, K. & Lemeur, R. Short-rotation forestry of birch, maple, poplar and willow in Flanders (Belgium) II. Energy production and CO_2 emission reduction potential. *Biomass and Bioenergy* **31**, 276-283 (2007).

Wang, M., Han, J., Dunn, J. B., Cai, H. & Elgowainy, A. Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. *Environmental Research Letters* **7**, 045905 (2012).

Weih, M. Intensive short rotation forestry in boreal climates: present and future perspectives. *Canadian Journal of Forest Research,* **34**, 1369-1379 (2004).

Wetterlund, E., Pettersson, K. & Magnusson, M. Implications of system expansion for the assessment of well-to-wheel CO_2 emissions from biomass-based transportation. *International Journal of Energy Research* **34**, 1136-1154 (2010).

Whitaker, J., Ludley, K. E., Rowe, R., Taylor, G. & Howard, D. C. Sources of variability in greenhouse gas and energy balances for biofuel production: a systematic review. *GCB Bioenergy* **2**, 99-112 (2010).

Whittaker, C., Macalpine, W., Yates, N. E. & Shield, I. Dry matter losses and methane emissions during wood chip storage: the impact on full life cycle greenhouse gas savings of short rotation coppice willow for heat. *BioEnergy Research* **9**, 820-835 (2016).

Whittaker, C., Mortimer, N., Murphy, R. & Matthews, R. Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. *Biomass and Bioenergy* **35**, 4581-4594 (2011).

Woods, J. et al. *Technology status review and carbon abatement potential of renewable transport fuels in the UK.* (UK Department of Trade and Industry New and Renewable Energy Programme, London, 2003).

Wu, M., Wu, Y. & Wang, M. *Mobility chains analysis of technologies for passenger cars and light duty vehicles fueled with biofuels: application of the Greet model to project the role of biomass in America's energy future (RBAEF) project.* (Argonne National Lab, Argonne, IL, USA, 2005).

Wu, M., Wu, Y. & Wang, M. Energy and emission benefits of alternative transportation liquid fuels derived from switchgrass: a fuel life cycle assessment. *Biotechnology Progress* **22**, 1012-1024 (2006).

Xie, X., Wang, M. & Han, J. Assessment of fuel-cycle energy use and greenhouse gas emissions for Fischer–Tropsch diesel from coal and cellulosic biomass. *Environmental Science & Technology* **45**, 3047-3053 (2011).

Zhuang, Q., Qin, Z. & Chen, M. Biofuel, land and water: maize, switchgrass or Miscanthus? *Environmental Research Letters* **8**, 015020 (2013).