Supplemental information

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

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Supplemental figures

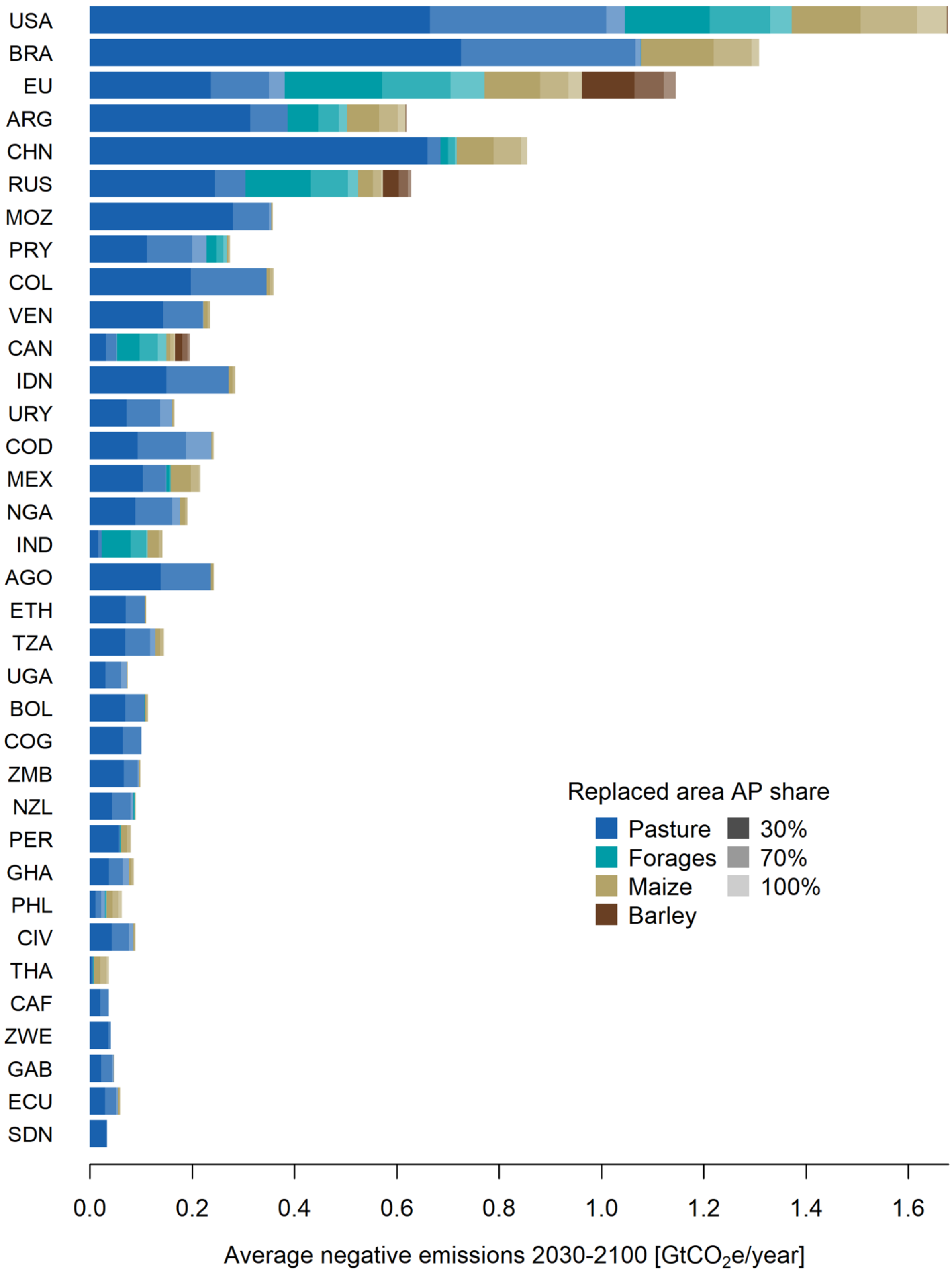

Figure S1. Negative emission potential of countries (only Europe as a whole) at three levels of alternative protein (AP) adoption for BECCS electricity. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

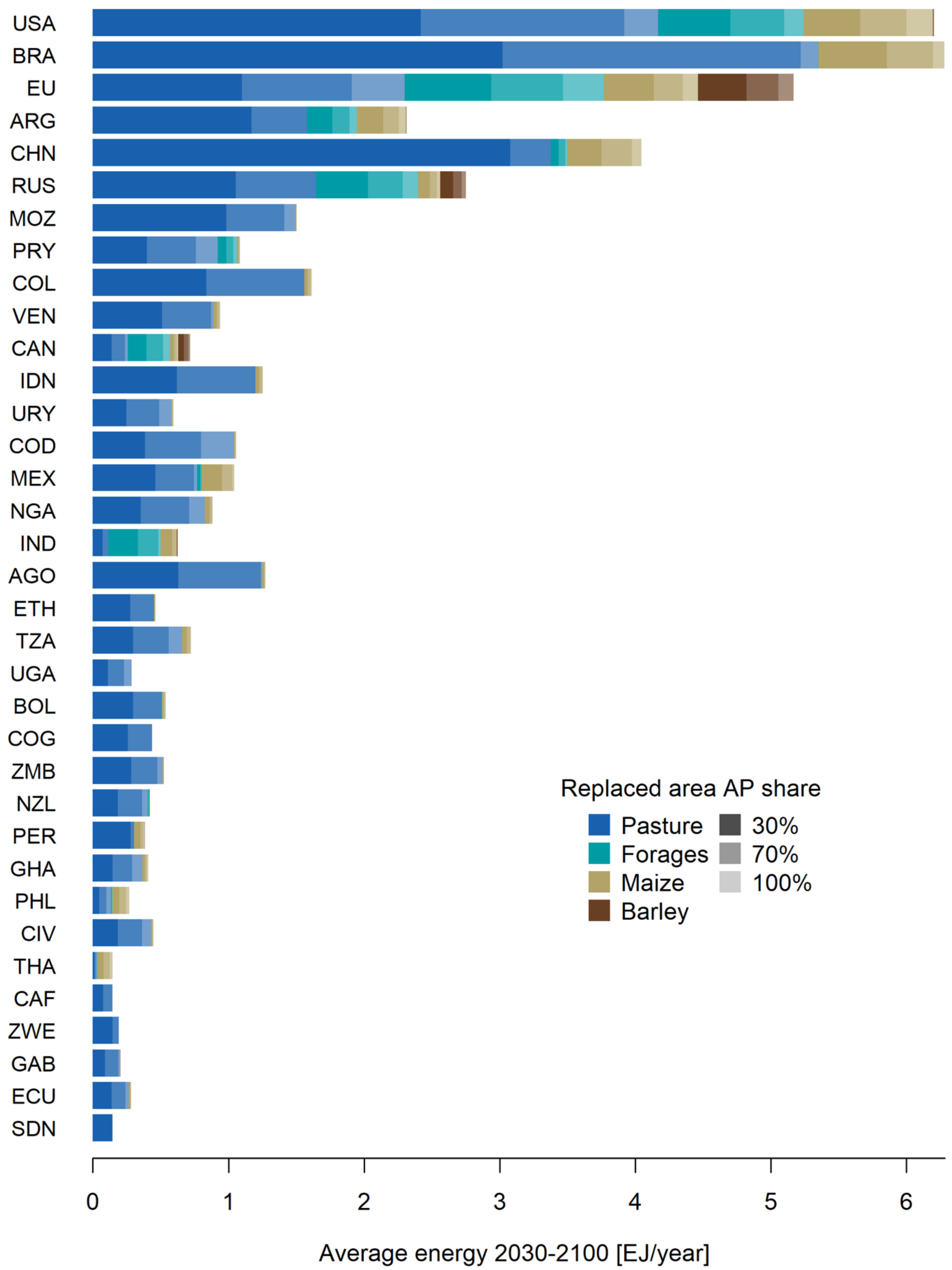

Figure S2. Energy potential for BECCS electricity of countries (only Europe as a whole) when maximizing negative emissions at three levels of alternative protein (AP) adoption. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

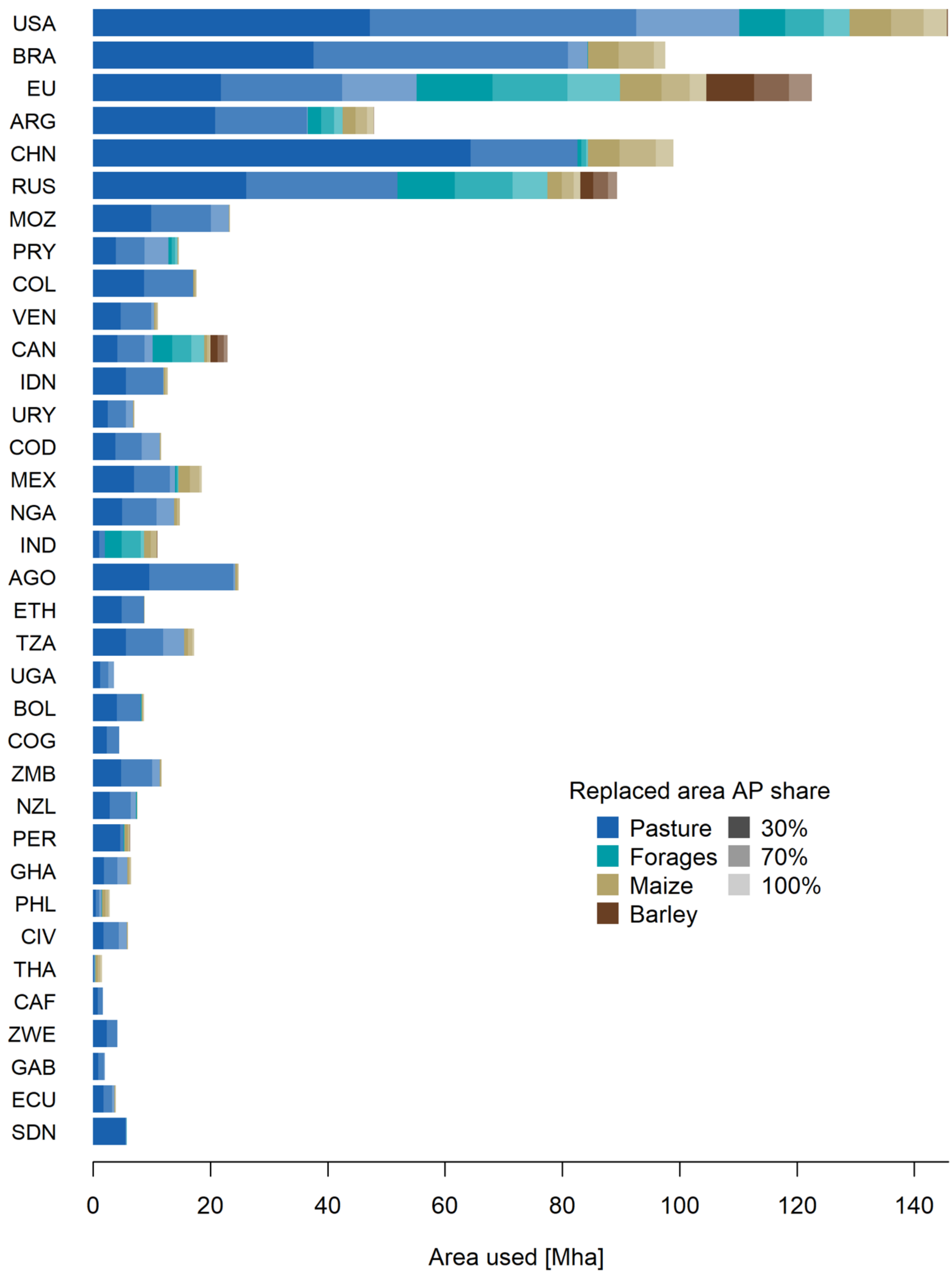

Figure S3. Area used for BECCS electricity of countries (only Europe as a whole) when maximizing negative emissions at three levels of alternative protein (AP) adoption. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

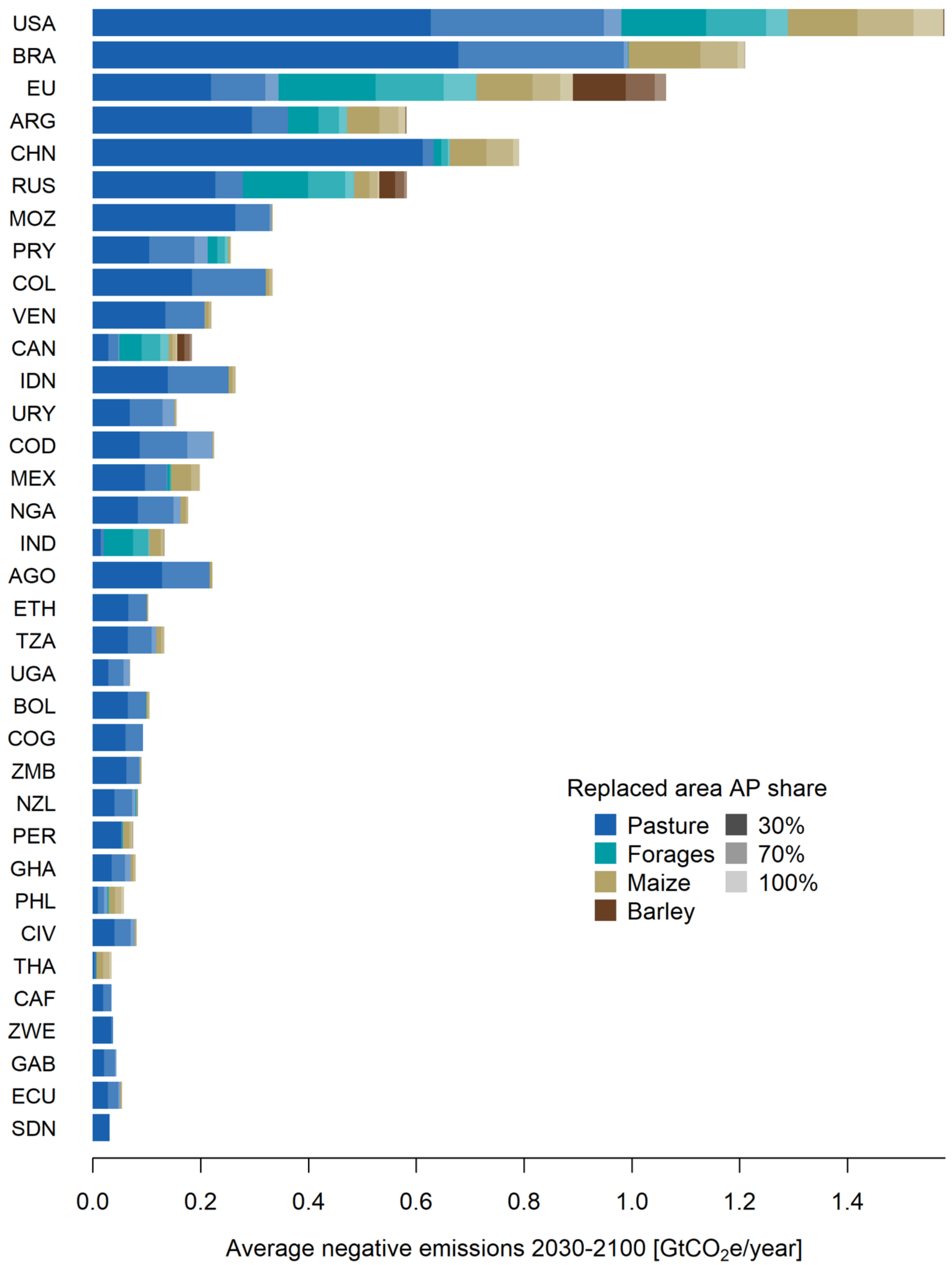

Figure S4. Negative emission potential of countries (only Europe as a whole) at three levels of alternative protein (AP) adoption for BECCS hydrogen. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

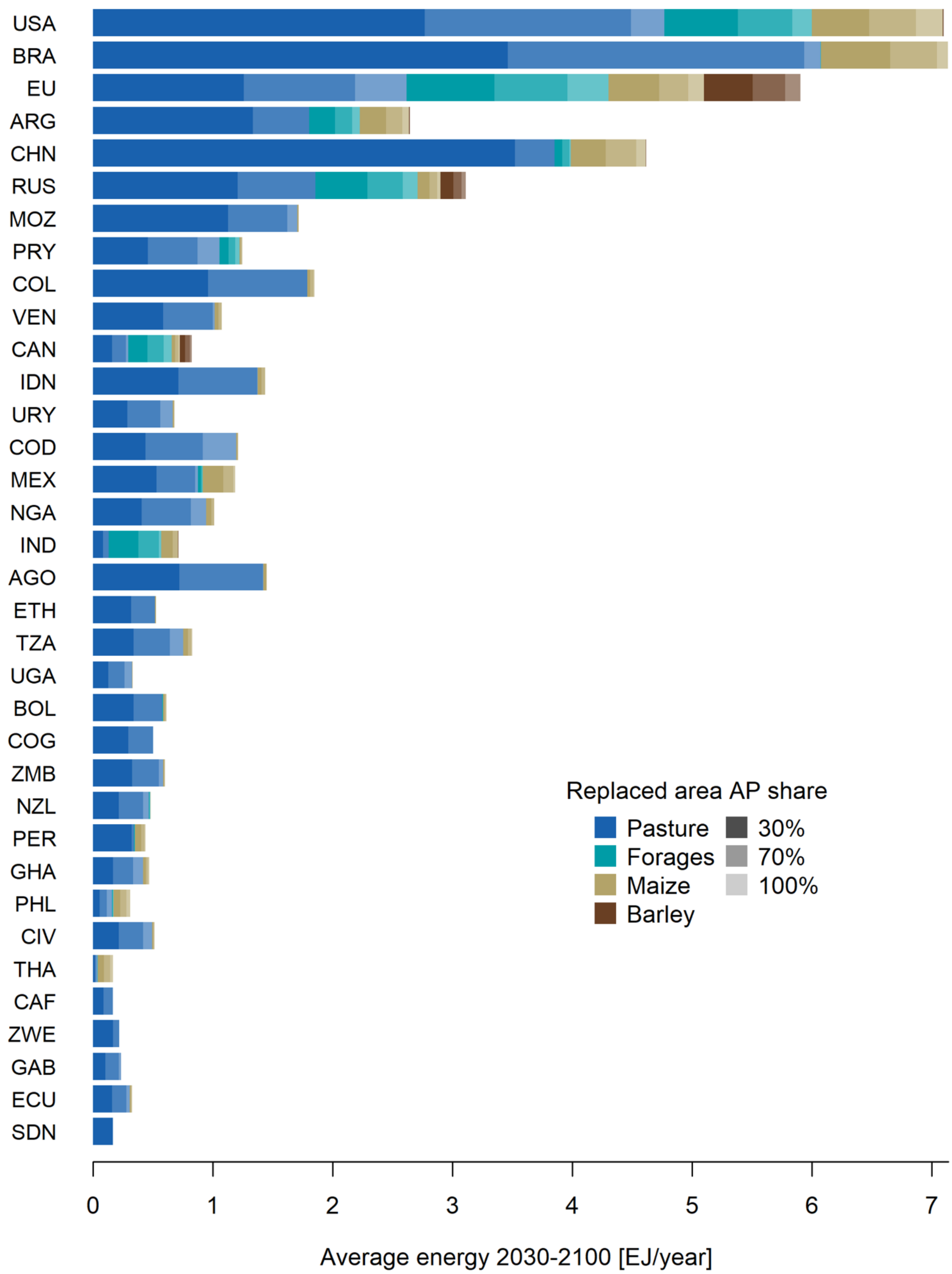

Figure S5. Energy potential for BECCS hydrogen of countries (only Europe as a whole) when maximizing negative emissions at three levels of alternative protein (AP) adoption. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

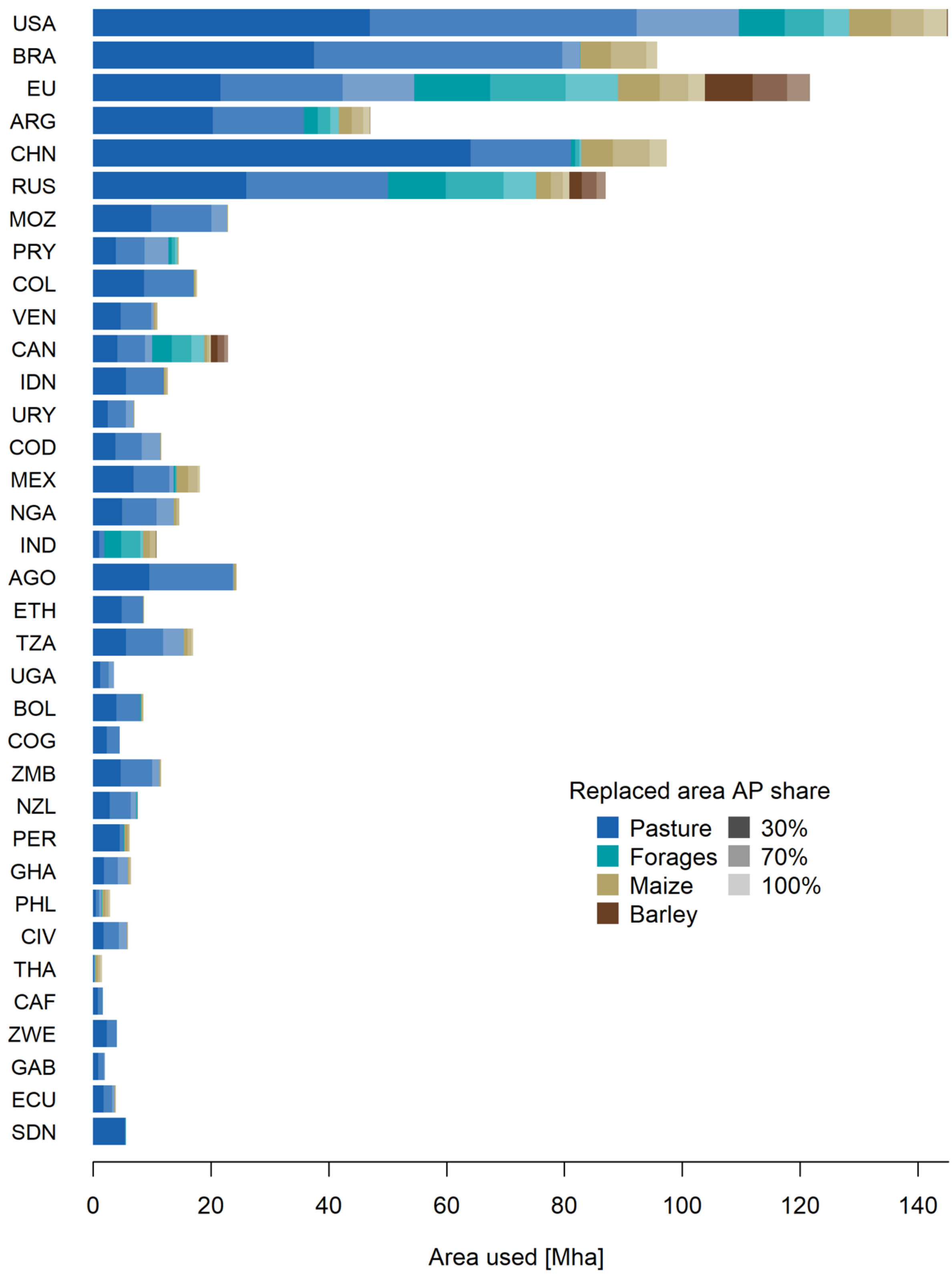

Figure S6. Area used for BECCS hydrogen of countries (only Europe as a whole) when maximizing negative emissions at three levels of alternative protein (AP) adoption. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

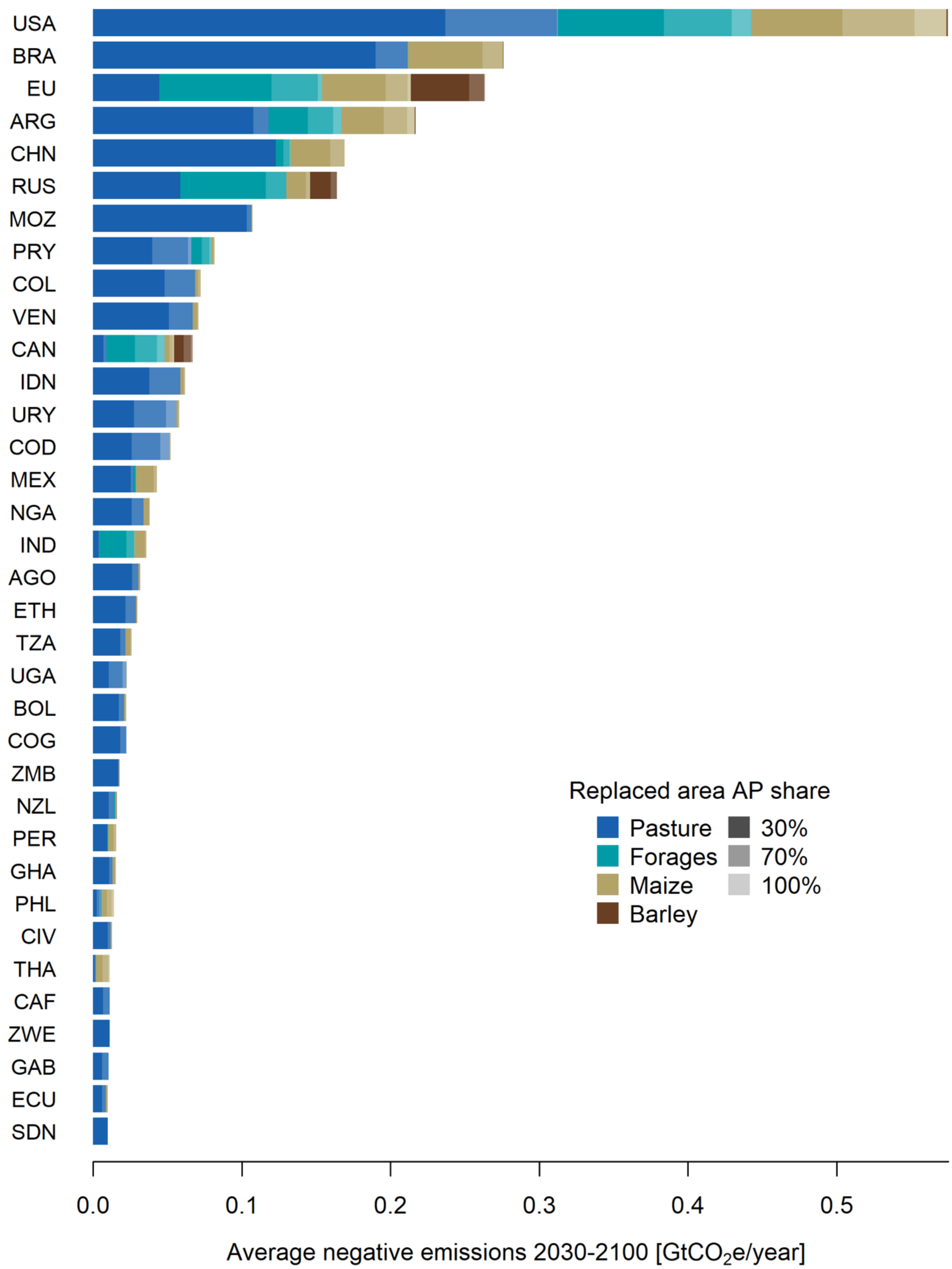

Figure S7. Negative emission potential of countries (only Europe as a whole) at three levels of alternative protein (AP) adoption for BECCS FT diesel. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

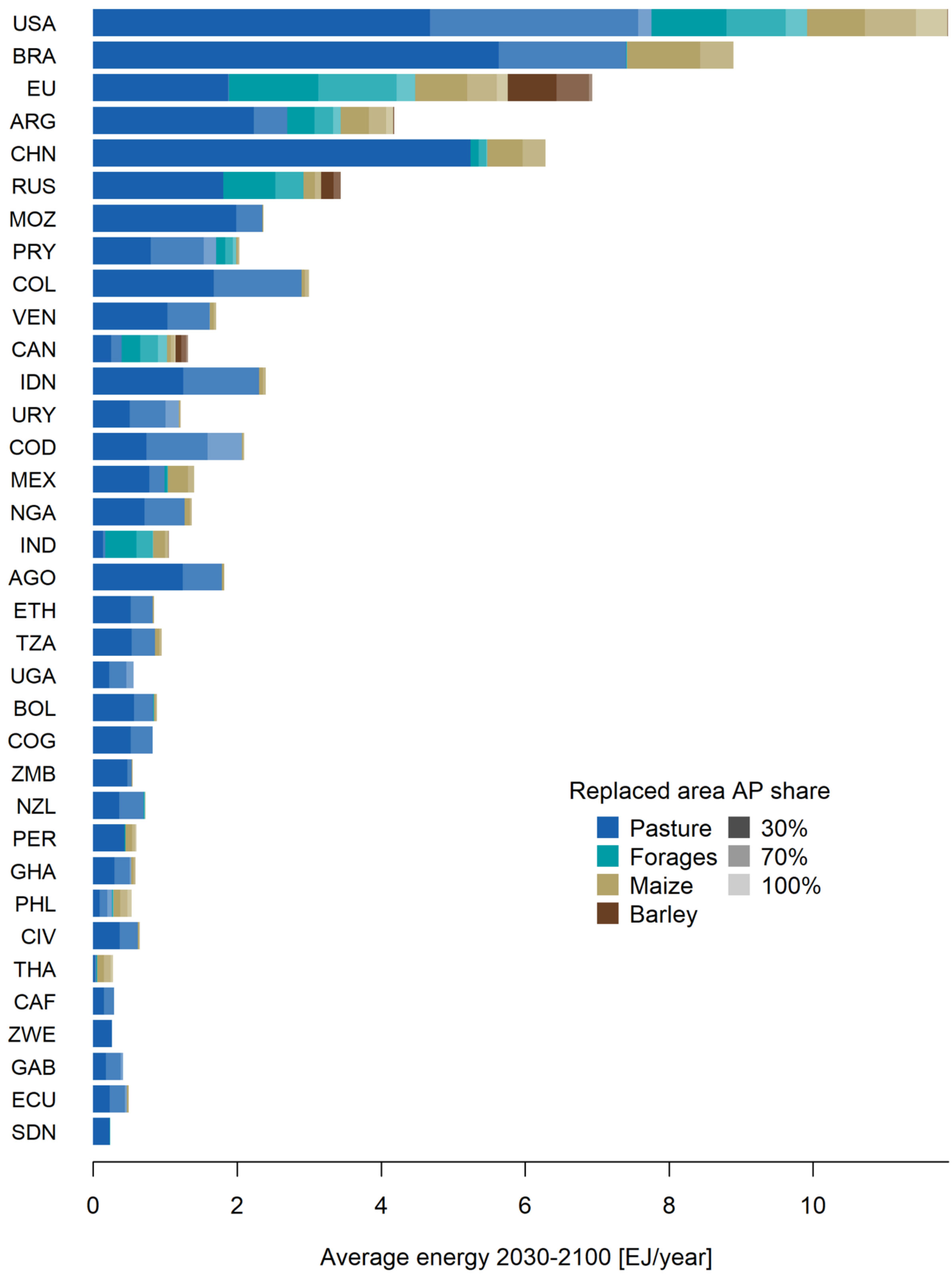

Figure S8. Energy potential for BECCS FT diesel of countries (only Europe as a whole) when maximizing negative emissions at three levels of alternative protein (AP) adoption. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

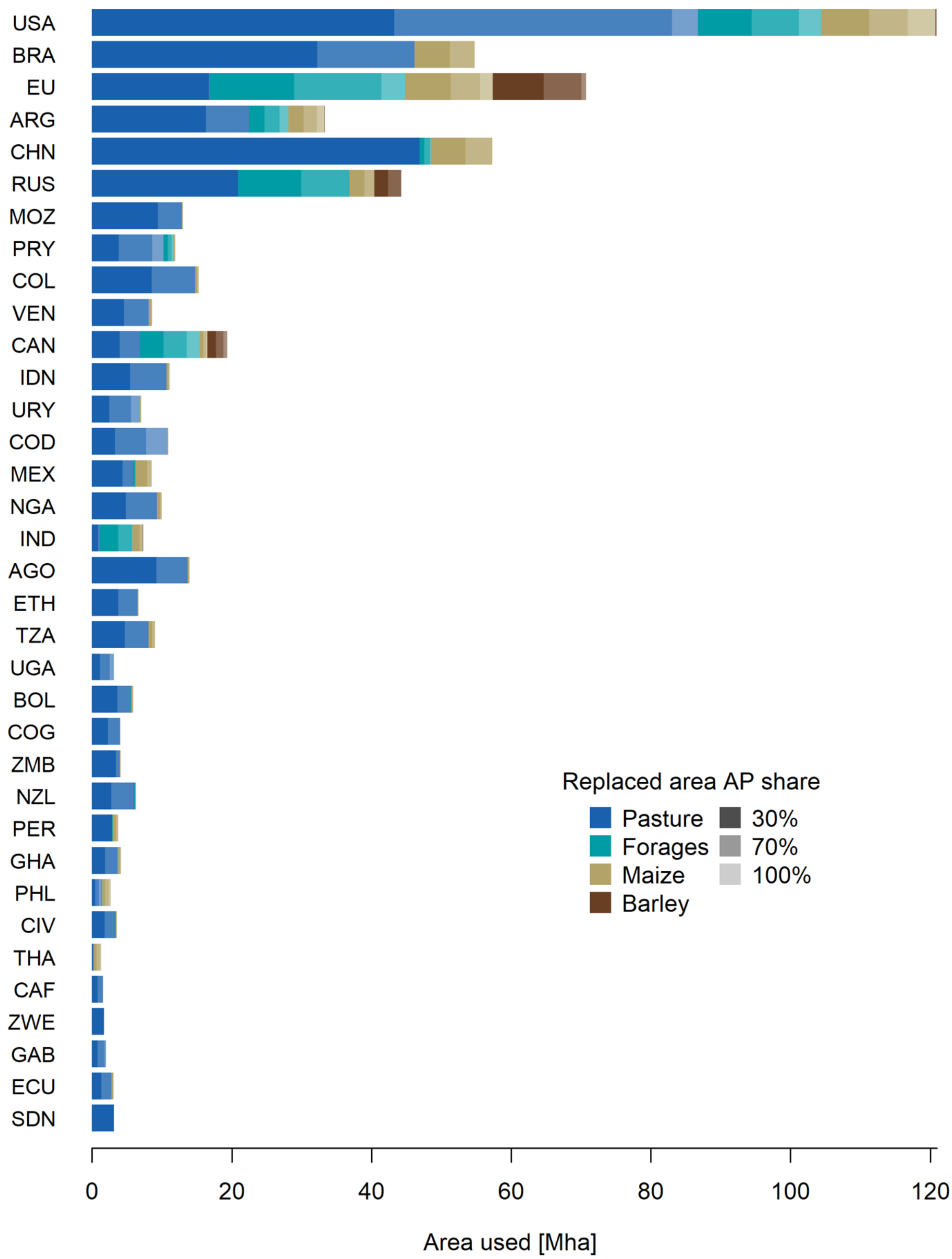

Figure S9. Area used for BECCS FT diesel of countries (only Europe as a whole) when maximizing negative emissions at three levels of alternative protein (AP) adoption. *The evaluation period is 60 years (average), from 2030 to 2100 with 20 years of ramp-up time. Related to Figure 1.*

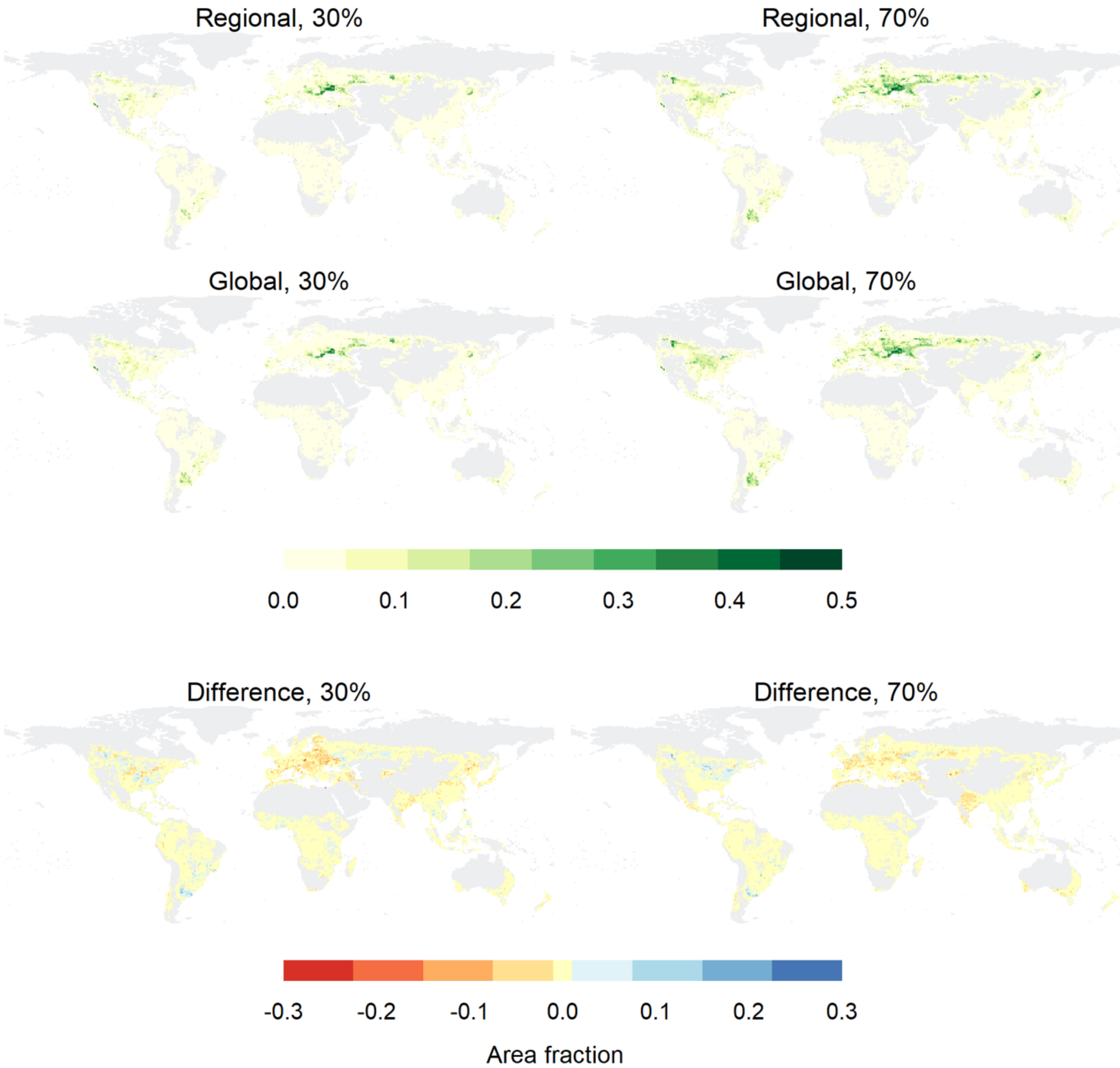

Figure S10. Feed crop areas where bioenergy crops for BECCS electricity could achieve negative emissions. *Replacement levels of animal products include 30% and 70%. Areas for bioenergy crops were optimized at the global and regional level (by country, considering only Europe as a whole) to maximize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

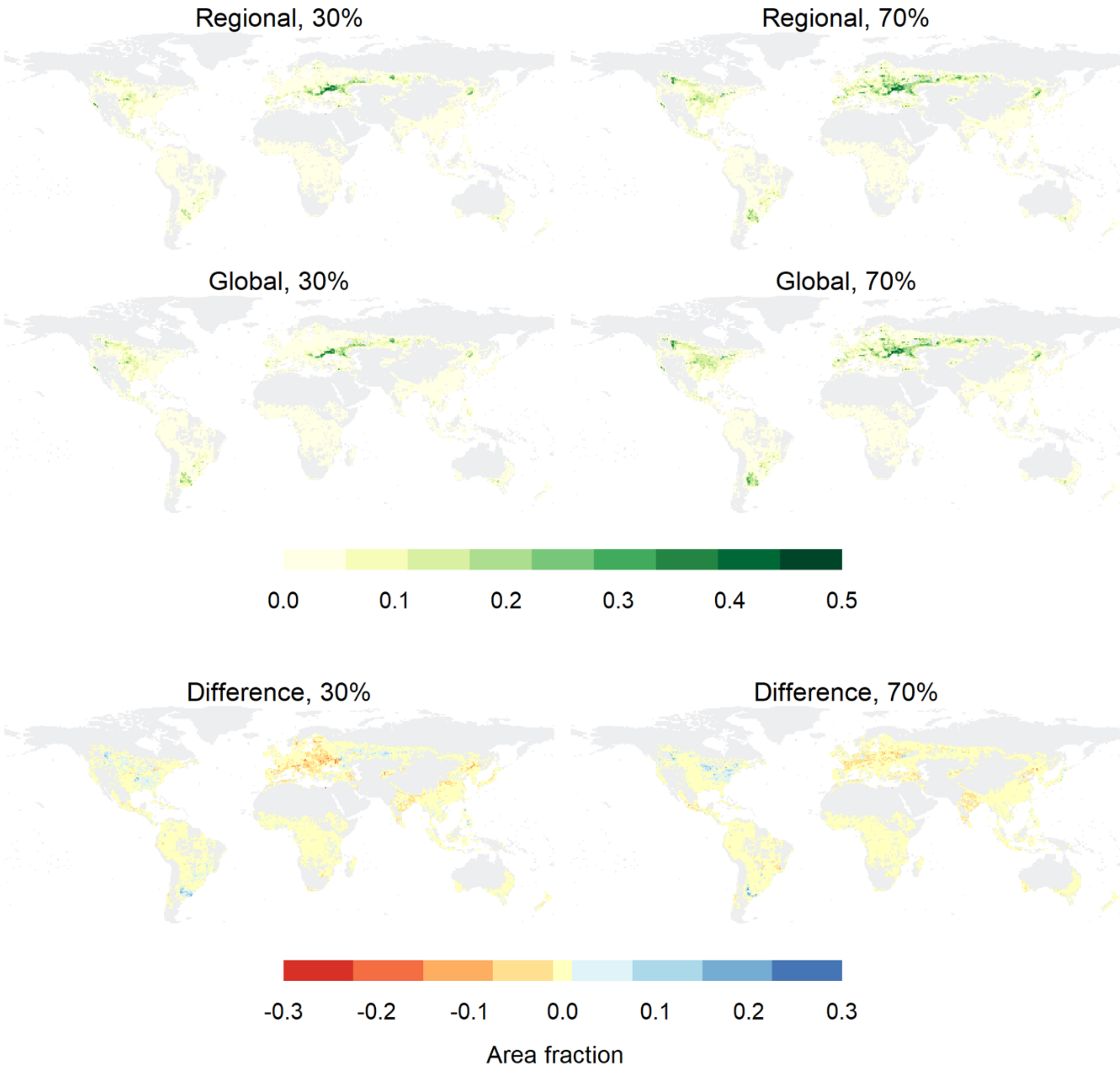

Figure S11. Feed crop areas where bioenergy crops for BECCS FT-diesel could achieve negative emissions. *Replacement levels of animal products include 30% and 70%. Areas for bioenergy crops were optimized at the global and regional level (by country, considering only Europe as a whole) to maximize negative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

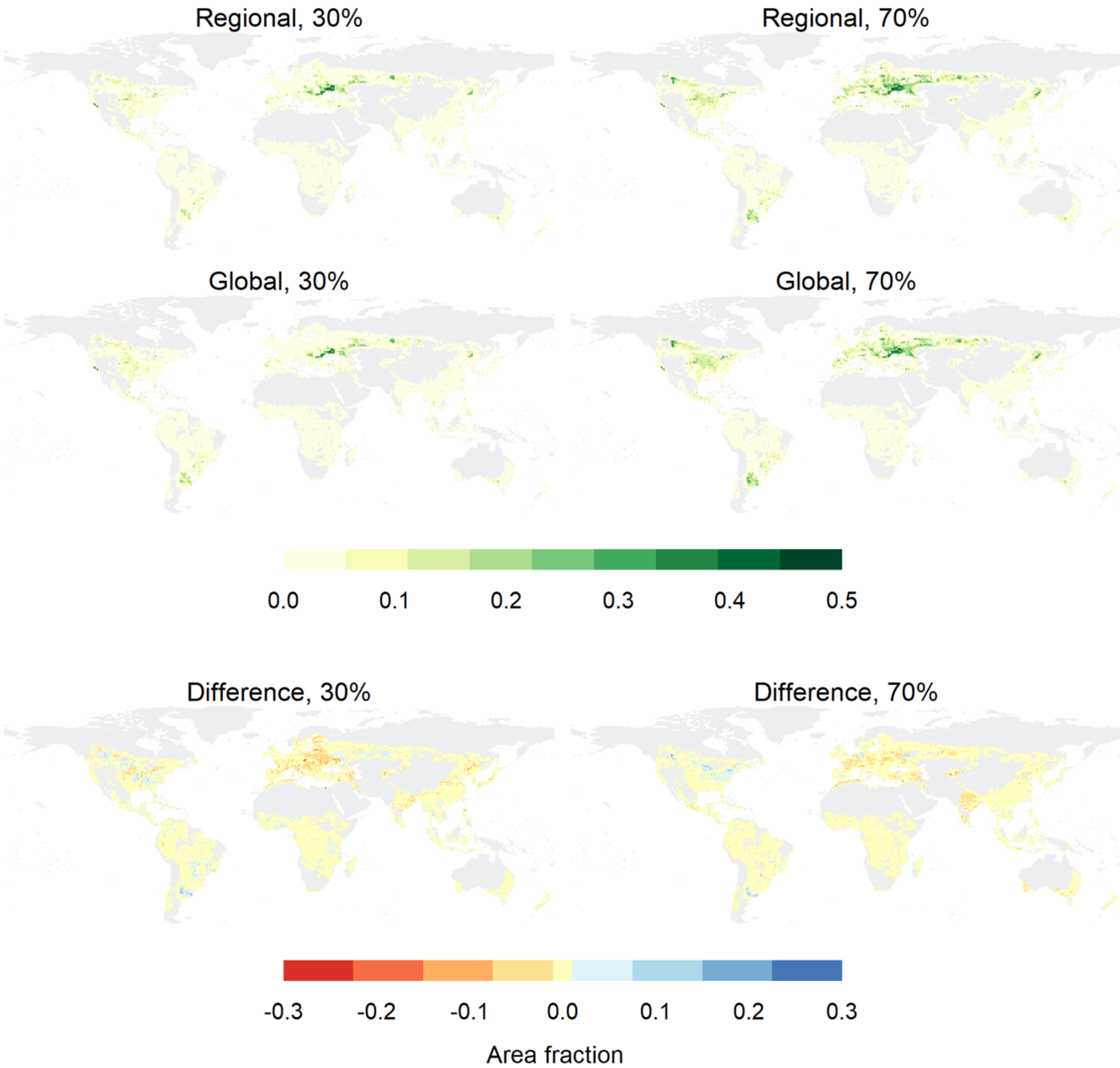

Figure S12. Feed crop areas where bioenergy crops for BECCS hydrogen could achieve negative emissions. *Replacement levels of animal products include 30% and 70%. Areas for bioenergy crops were optimized at the global and regional level (by country, considering only Europe as a whole) to maximize negative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

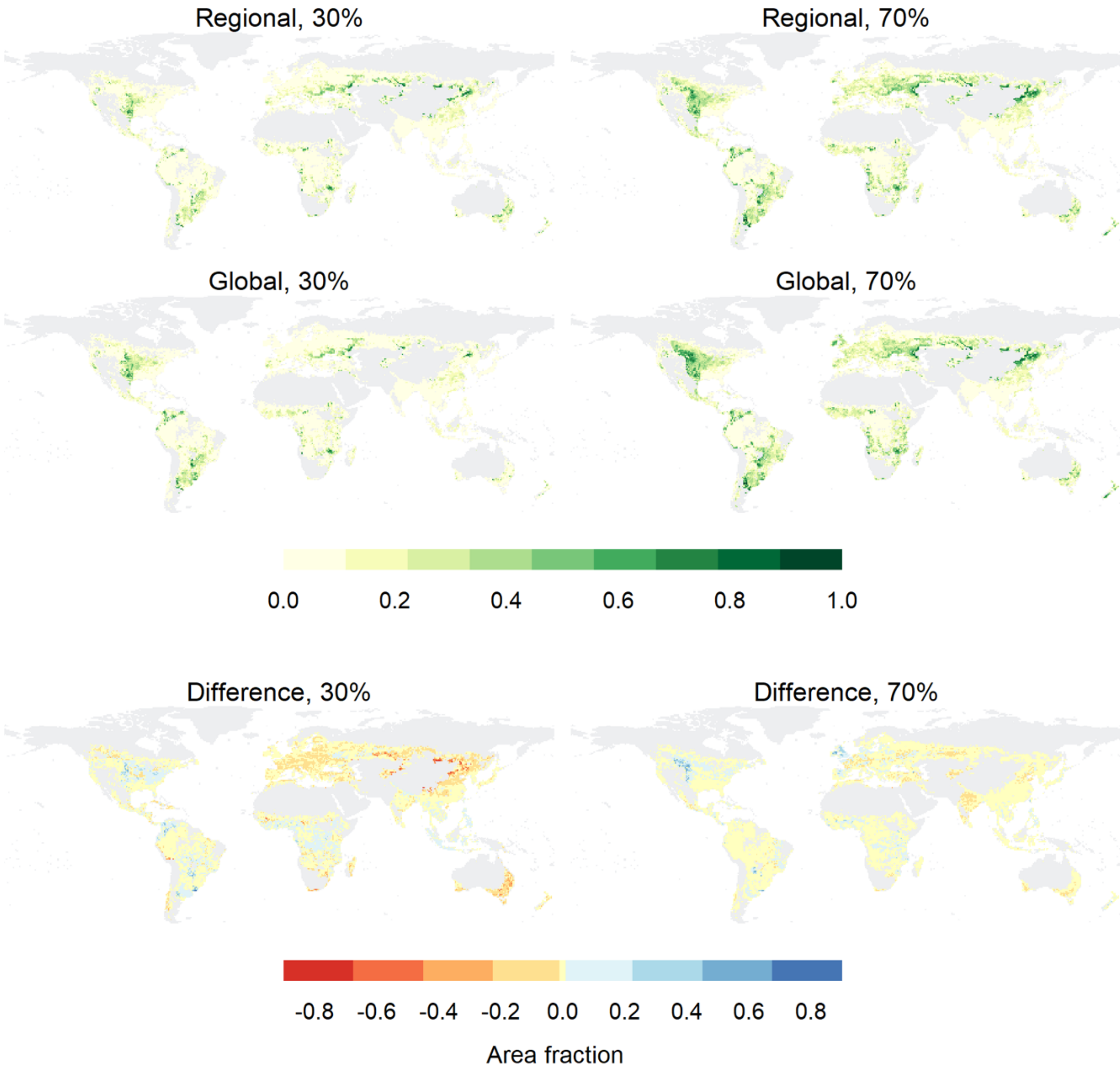

Figure S13. Feed crop and pasture areas where bioenergy crops for BECCS electricity could achieve negative emissions. *Replacement levels of animal products include 30% and 70%. Areas for bioenergy crops were optimized at the global and regional level (by country, considering only Europe as a whole)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

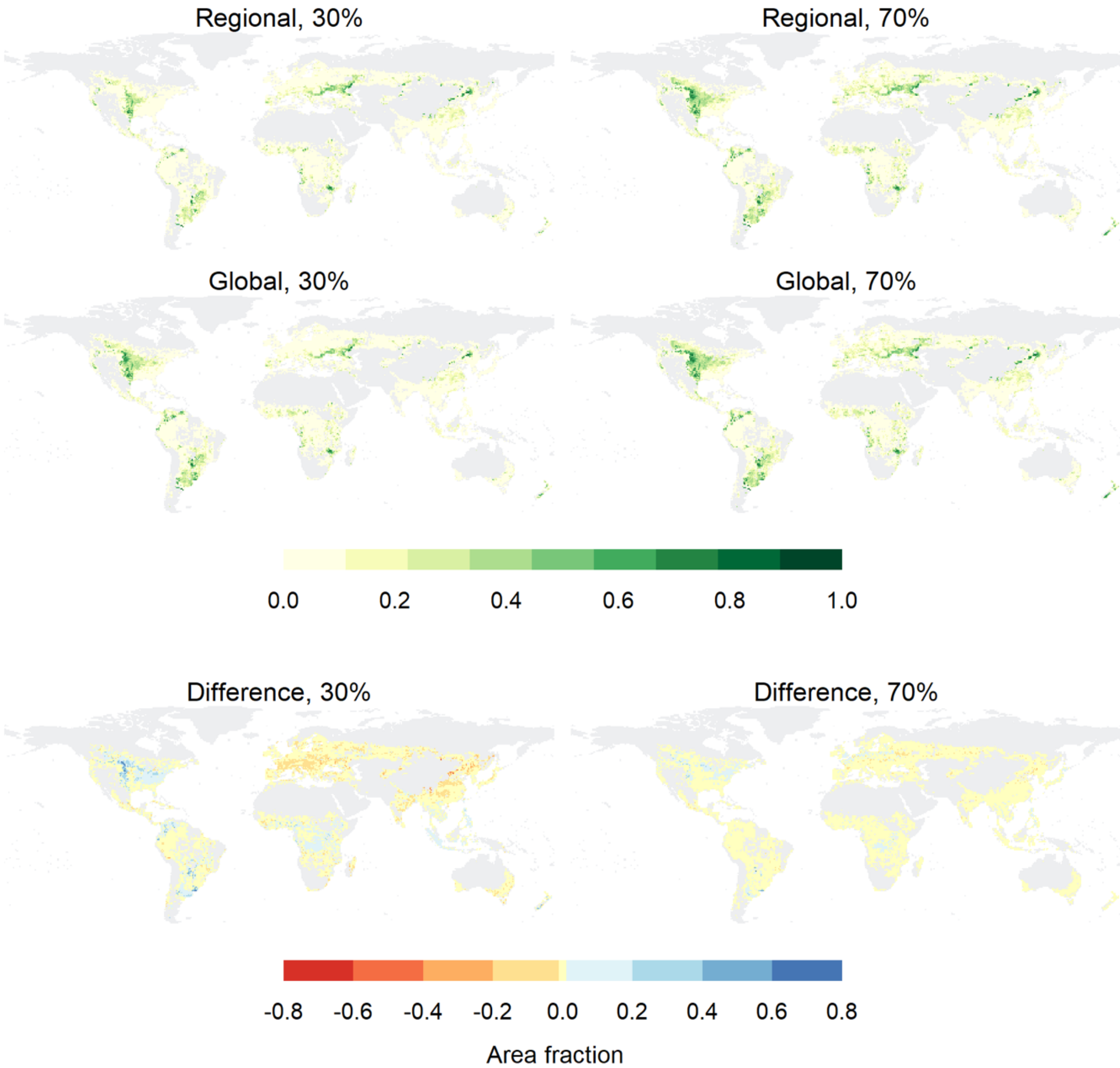

Figure S14. Feed crop and pasture areas where bioenergy crops for BECCS FT-diesel could achieve negative emissions. *Replacement levels of animal products include 30% and 70%. Areas for bioenergy crops were optimized at the global and regional level (by country, considering only Europe as a whole) to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

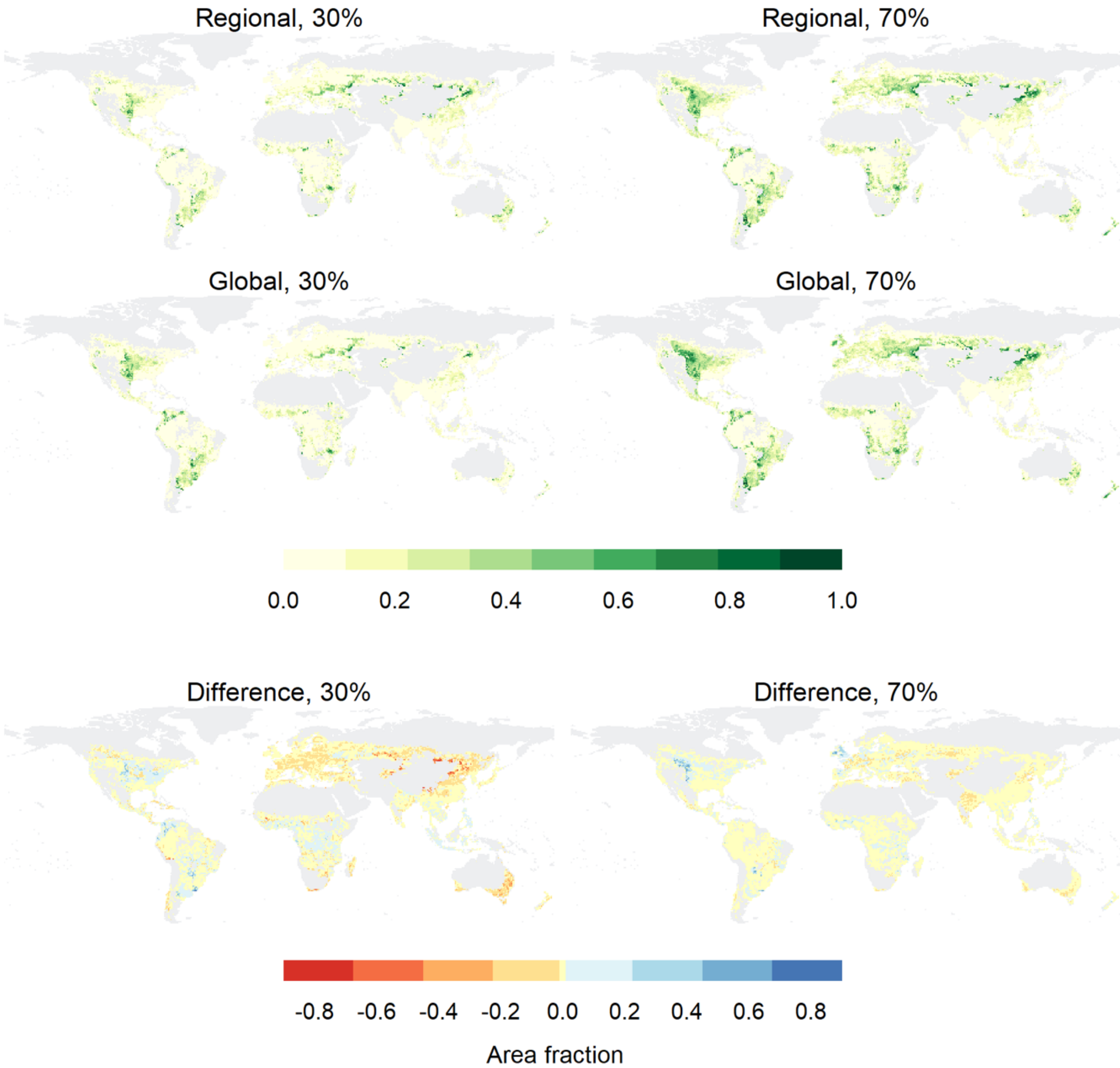

Figure S15. Feed crop and pasture areas where bioenergy crops for BECCS hydrogen could achieve negative emissions. *Replacement levels of animal products include 30% and 70%. Areas for bioenergy crops were optimized at the global and regional level (by country, considering only Europe as a whole) to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

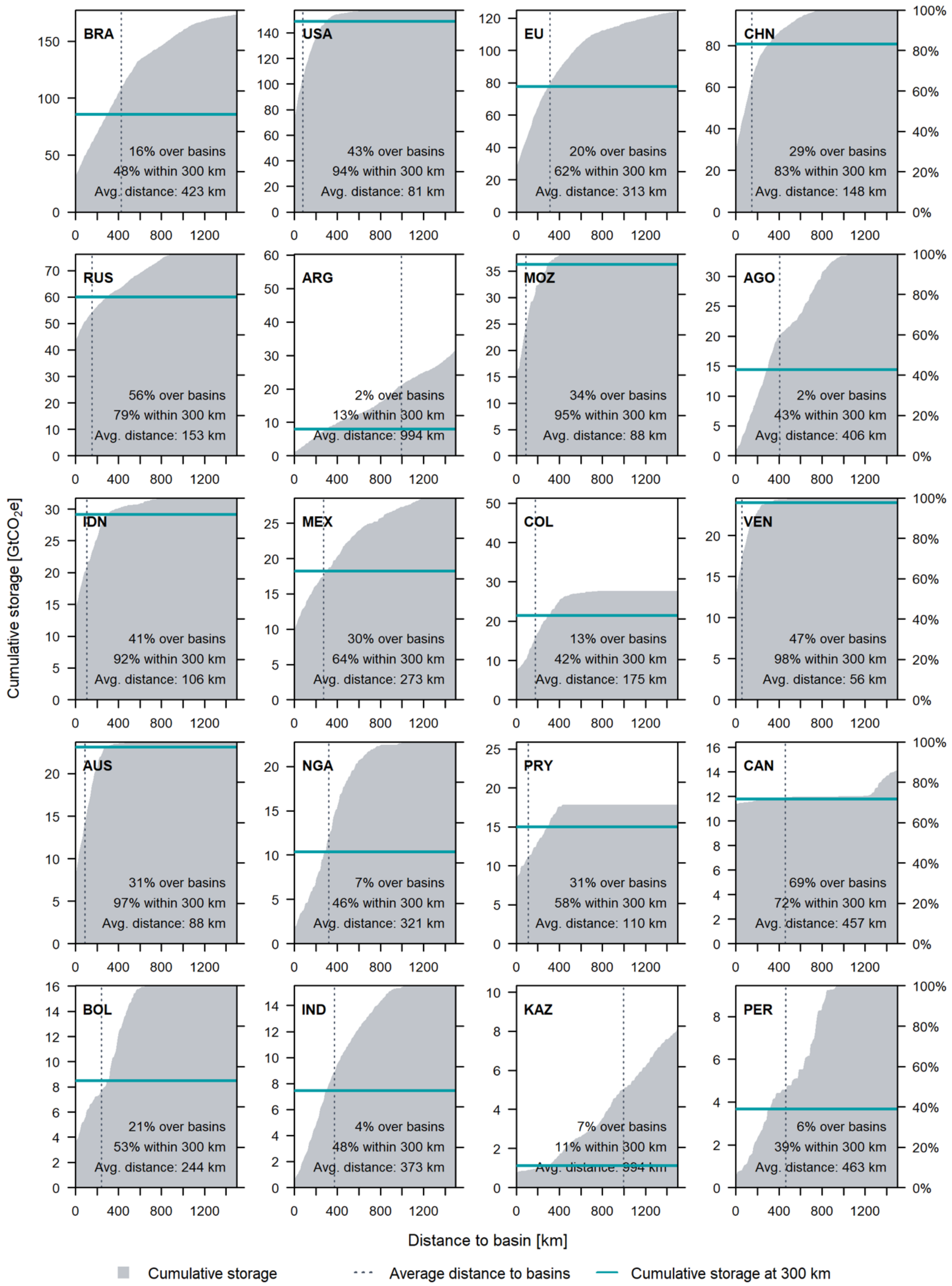

Figure S16. Source-sink distance between bioenergy crops and CO_2 storage sites for electricity production through BECCS. *Negative emissions are the difference between the net carbon removal from BECCS and the forgone carbon stock through natural regrowth. BECCS potential is the average of 4 climate models and natural regrowth is the average of estimations based on 7 potential natural vegetation maps. The evaluation period is 2030-2100 with 20 years of ramp-up time (Figure 4a). Related to Figure 3.*

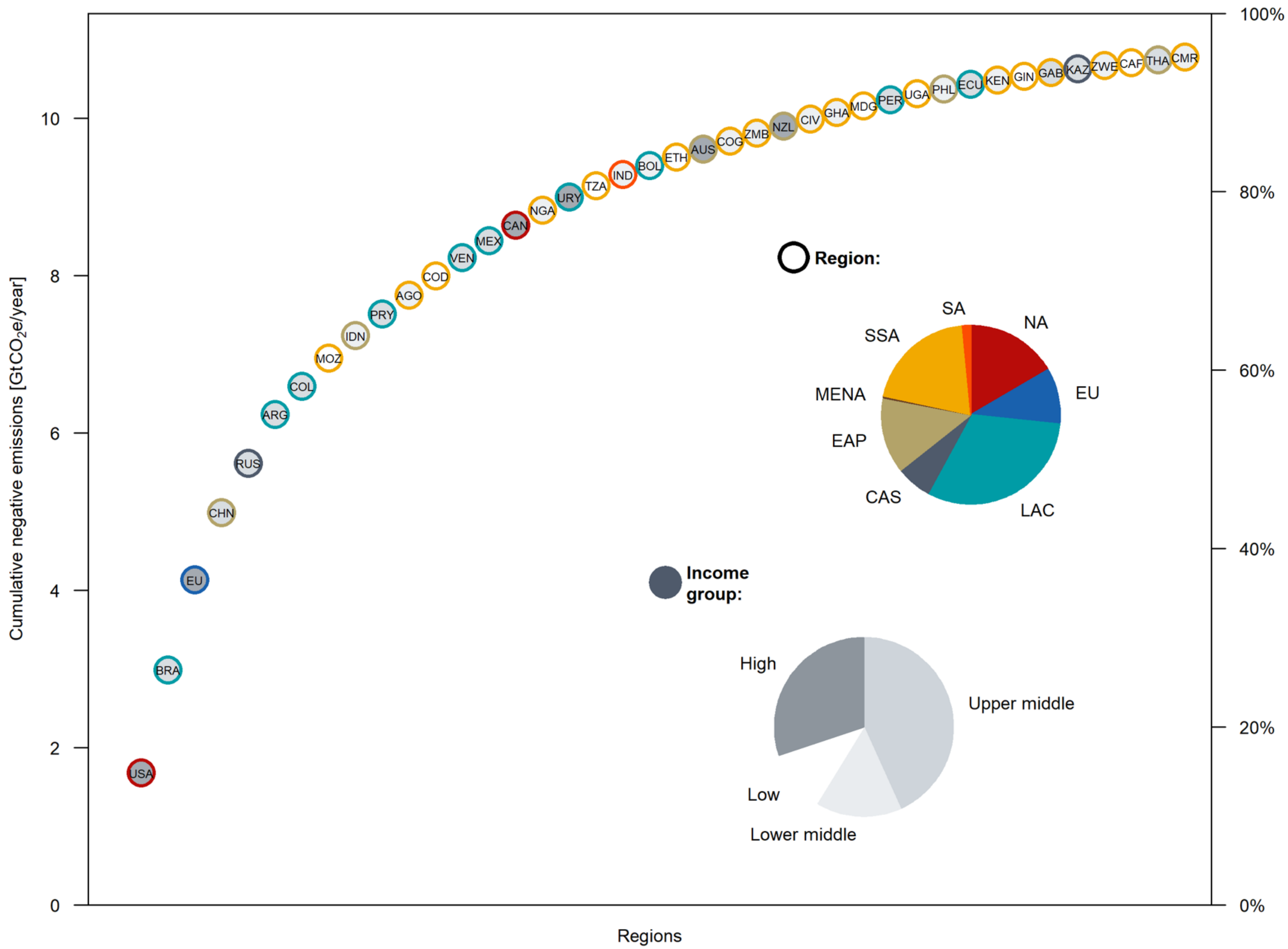

Figure S17. Negative emissions through BECCS electricity by country and country group. *Main plot shows cumulative negative emissions of countries (only Europe as a whole) with the highest potentials. Inset plots indicate breakdown by region and income group. The evaluation period is 2030-2100 with 20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

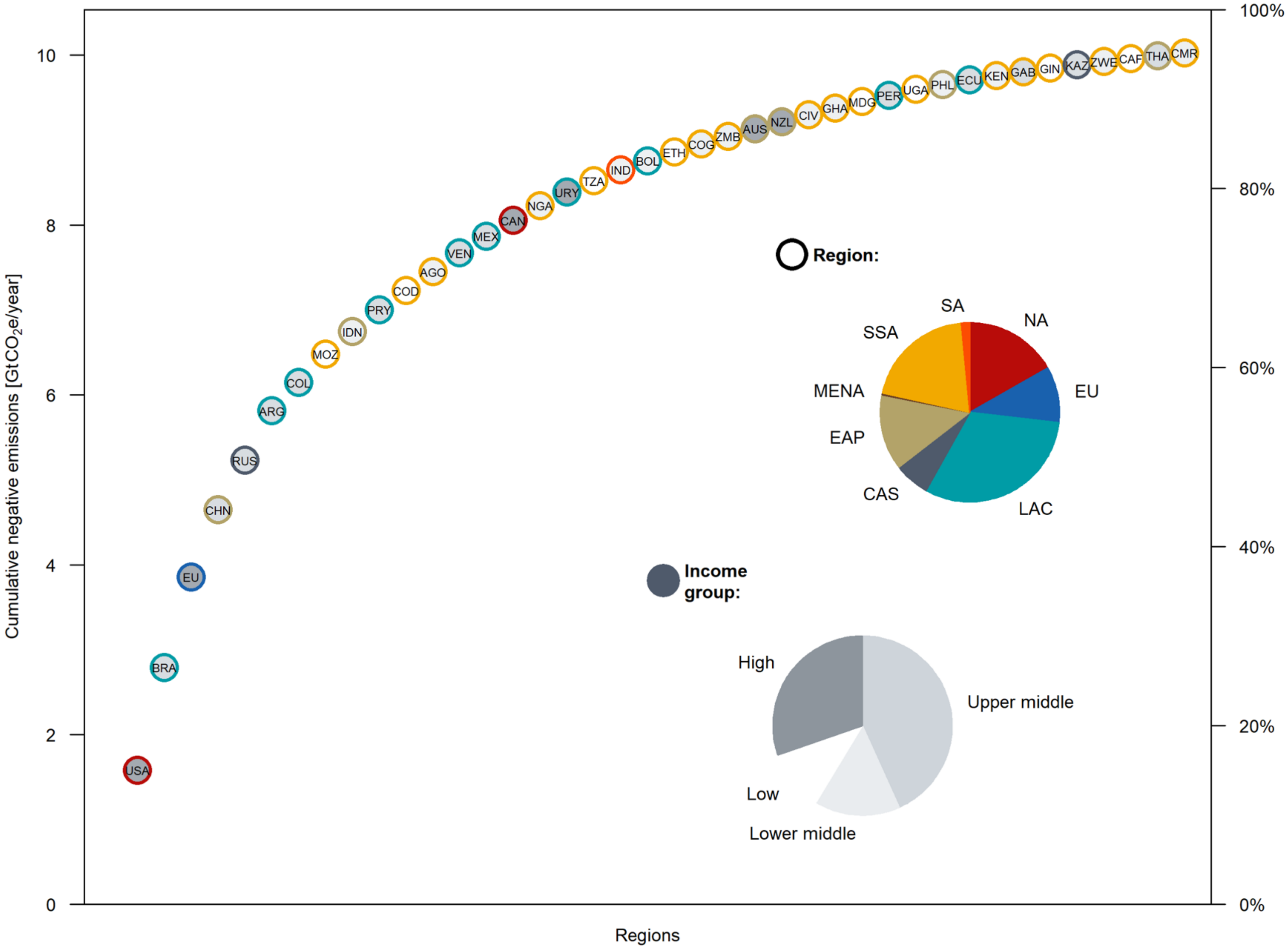

Figure S18. Negative emissions through BECCS hydrogen by country and country group. *Main plot shows cumulative negative emissions of countries (only Europe as a whole) with the highest potentials. Inset plots indicate breakdown by region and income group. The evaluation period is 2030-2100 with 20 years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

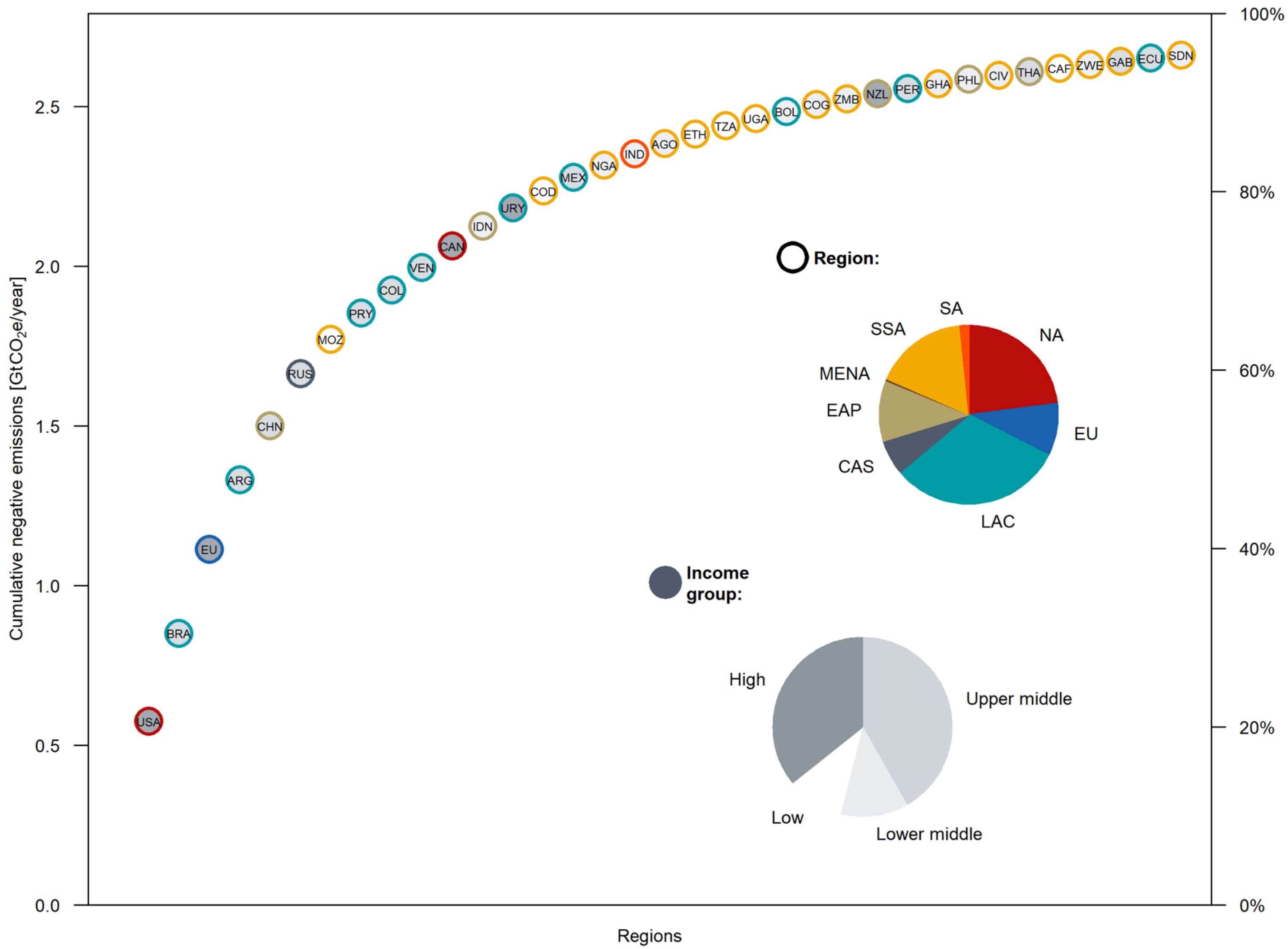

Figure S19. Negative emissions through BECCS FT diesel by country and country group. *Main plot shows cumulative negative emissions of countries (only Europe as a whole) with the highest potentials. Inset plots indicate breakdown by region and income group. The evaluation period is 2030-2100 with 20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

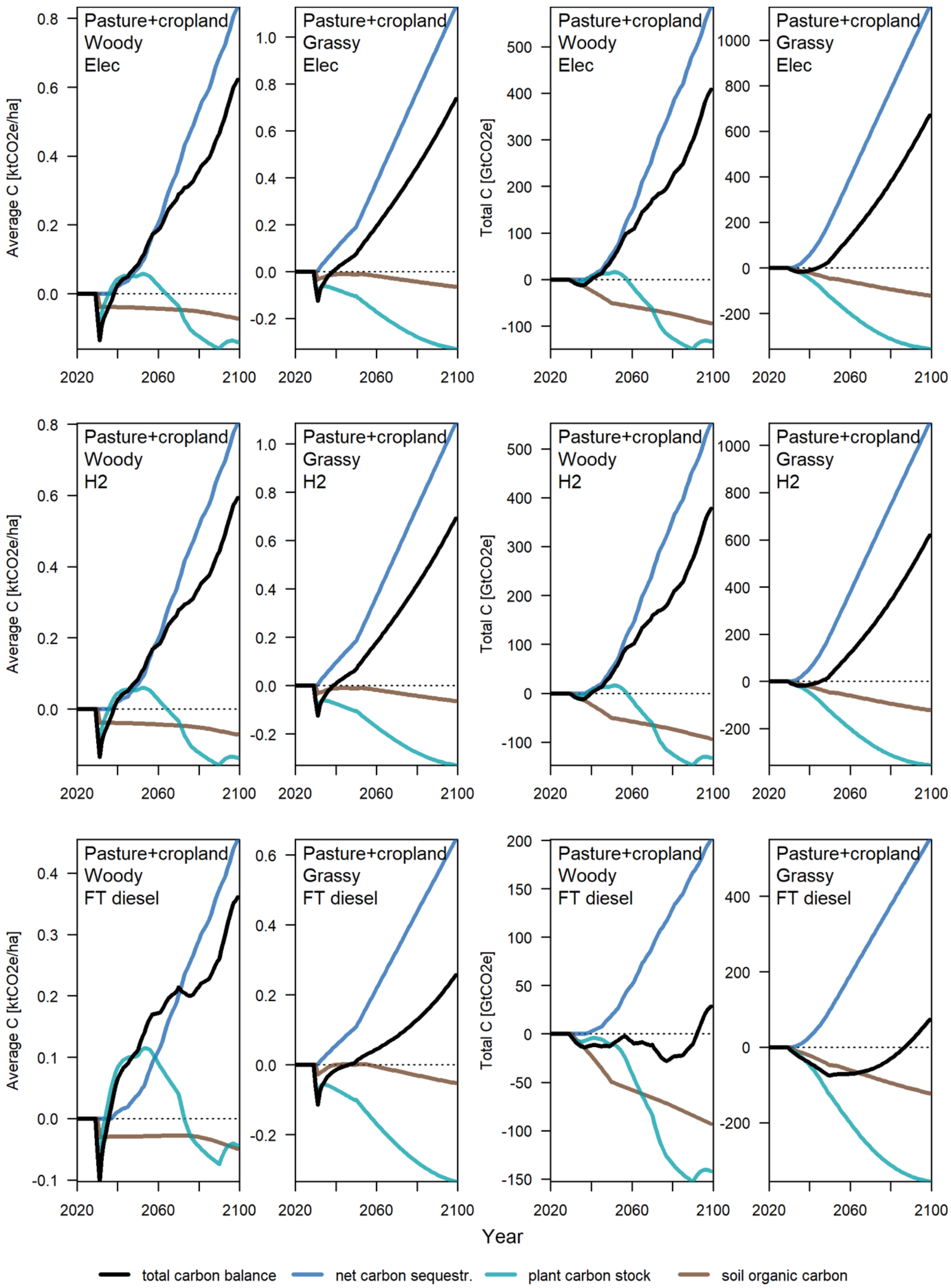

Figure S20. Global carbon balance for all areas in the Replace scenario (pasture and feed cropland). *Average (left half) and total (right half). Total carbon balance represents net negative emissions, equal to the sum of all flows: BECCS net carbon sequestration and plant and soil stocks. Stocks represent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

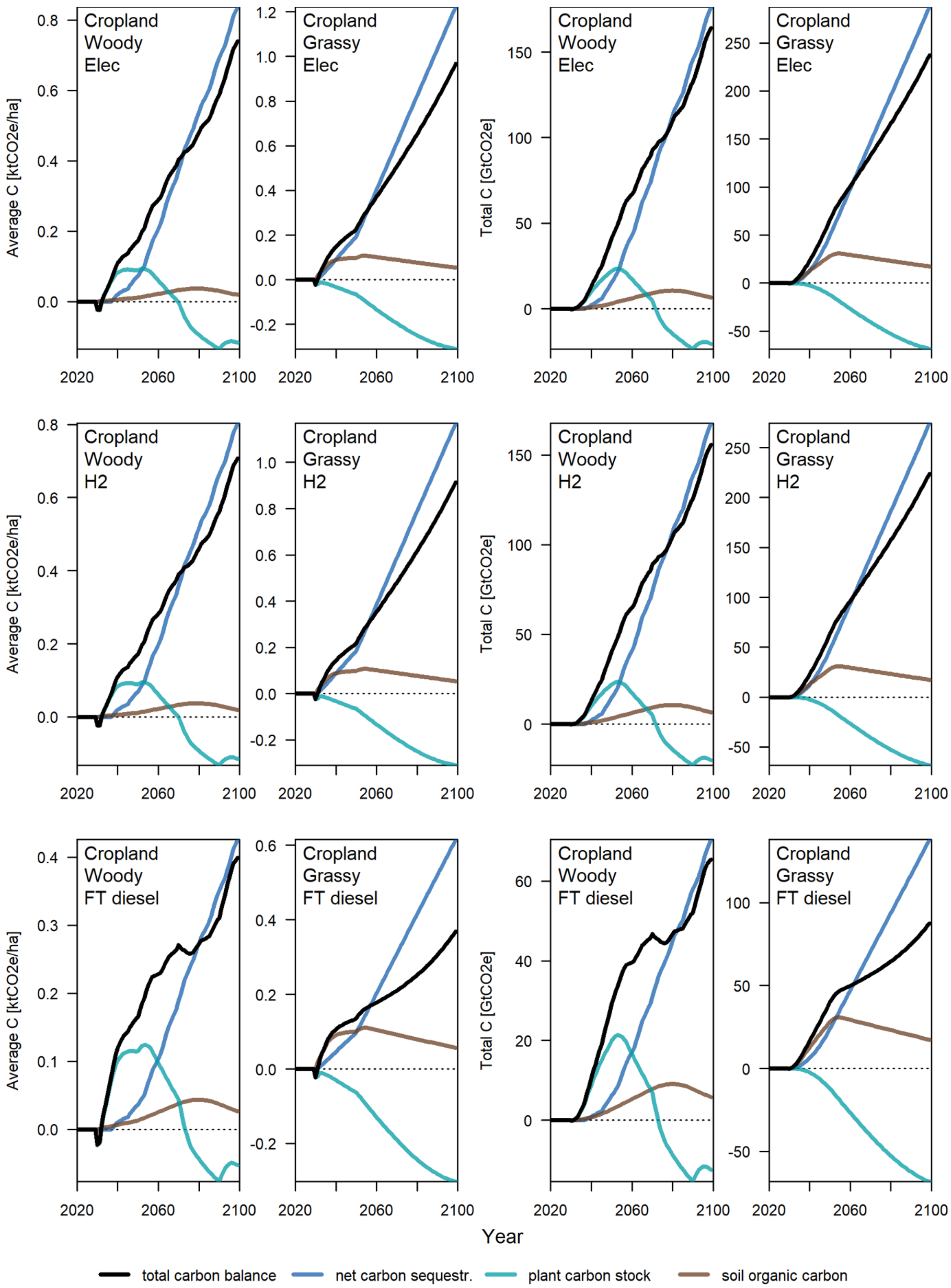

Figure S21. Global carbon balance for feed cropland in the Replace scenario. *Average (left half) and total (right half). Total carbon balance represents net negative emissions, equal to the sum of all flows: BECCS net carbon sequestration and plant and soil stocks. Stocks represent BECCS minus natural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

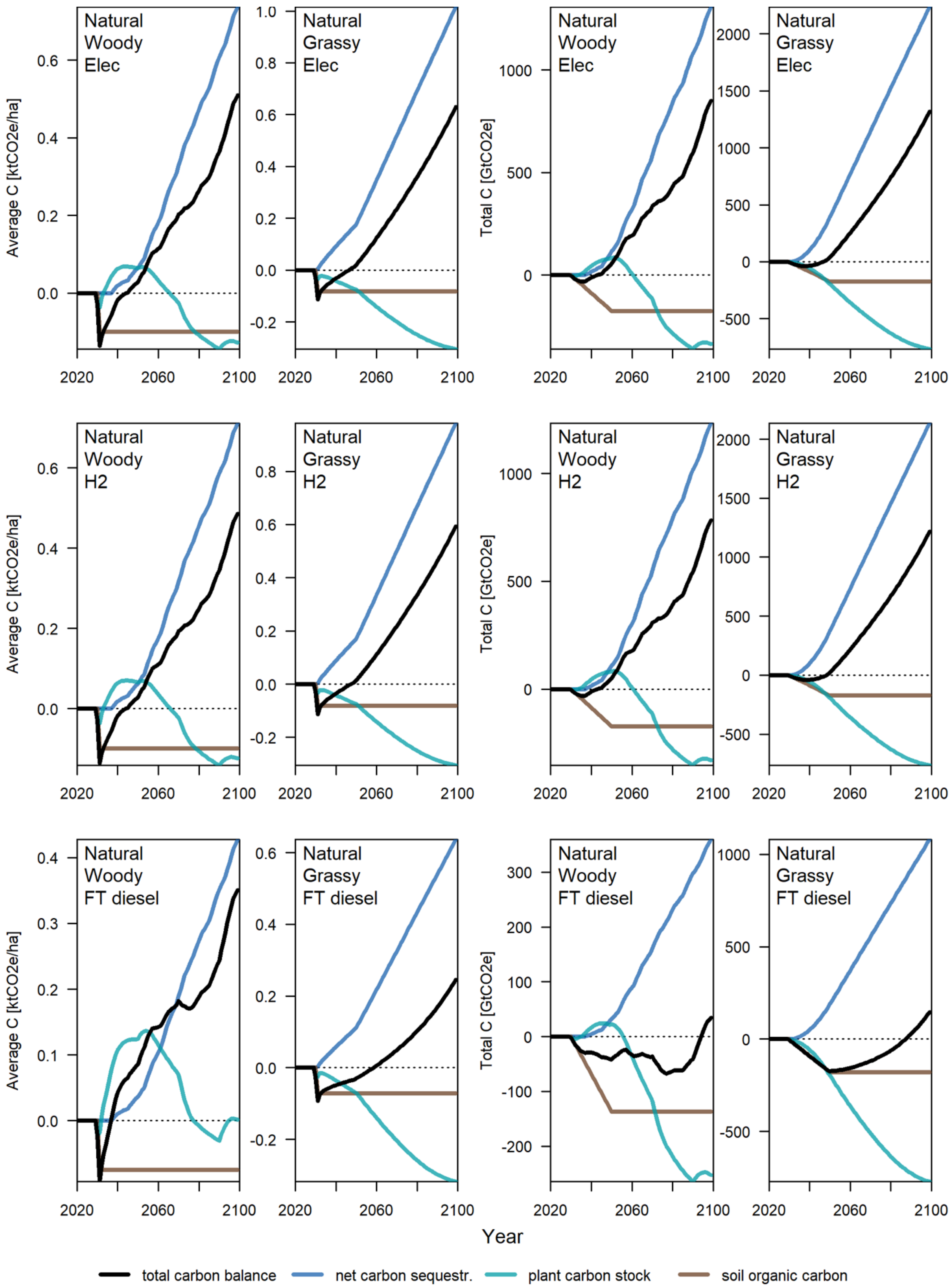

Figure S22. Global carbon balance for all areas in the Expand scenario (natural areas, excluding areas with the highest conservation value). *Average (left half) and total (right half). Total carbon balance represents net negative emissions, equal to the sum of all flows: BECCS net carbon sequestration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

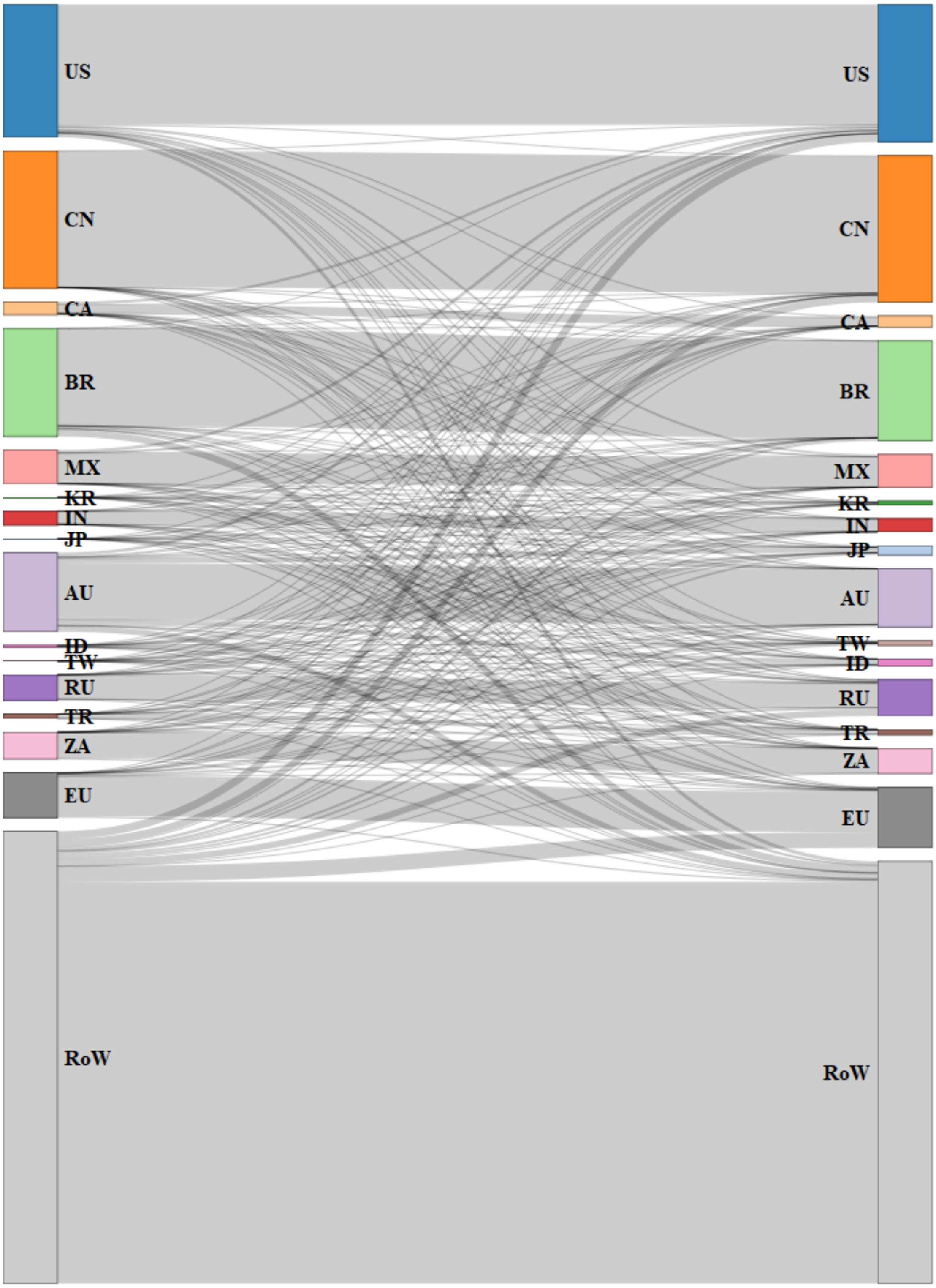

Figure S23. Land-use impacts (pasture and cropland) from the consumption of animal products in different regions. *The left side represents the production and the right side the consumption. RoW stands for Rest of the World. Related to Discussion.*

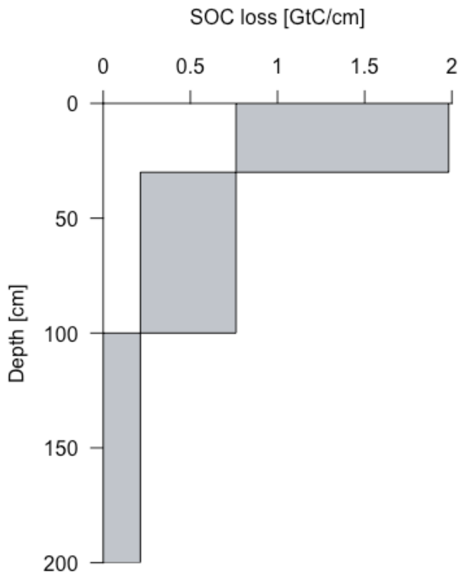

Figure S24. Soil organic carbon (SOC) loss profile. *Related to experimental procedures. Figure modified from reference.*[1]

Supplemental tables

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

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

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

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

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

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

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

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

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

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

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

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

Transitions to bioenergy crops (woody or grassy)

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

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

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

Supplemental references

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