Supplementary materials to “Below zero”

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S1 Cumulative emissions and remaining carbon budget

Cumulative emissions from 1850 until 2020 amount to 652 Gt of C [9, 100]. The remaining C budget from Jan 1 2020 is set with 136 Gt of C by the sixth assessment report by IPCC [14]. Provided that any feasible transition can start at Jan 1 2023 the earliest and assuming emissions stay constant at 11 Gt/a [100] until then, cumulative emissions increase to 685 Gt. This reduces the remaining C budget to stay below 1.5 °C global heating with 50 % confidence to 103 Gt.

The minimal C emissions for the fastest possible transition amount to approximately 50 Gt (sunflower scenarios in [21]).

S2 Negative emissions in IPCC pathways

IPCC special report on 1.5 °C includes four representative groups of pathways for staying below 1.5 °C global heating [9, 36]: below 1.5 °C , 1.5 °C with low overshoot, 1.5 °C with no or limited overshoot and 1.5 °C with high overshoot. Fig. S1 shows the annual emissions for the four pathway groups. Fossil emissions continued past 2100.

As for the climate response the cumulative emissions are relevant, Fig. S2 show the same pathways as in Fig. S1 but for cumulative C emissions since 1850. Cumulative fossil emissions continue to rise at reduced rate and are overcompensated by negative emissions. Consequently, total cumulative emissions peak around 2050 (“net zero”) and decline slowly thereafter. Despite more than 200 Gt of negative C emissions, cumulative emissions do not even return to the level of 2020.

Annual and cumulative negative emissions are calculated as the difference between total and fossil emissions from the point in time onwards when annual net emissions are lower than annual fossil emissions. This is because negative emissions foreseen in IPCC pathways are predominantly land-based, i. e. first eliminating land use change emissions and then compensating fossil emissions. Cumulative net negative emissions are calculated as the difference between peak total cumulative emissions (between 2020 and 2100), and cumulative emissions in 2100; i. e. the part of negative emissions that actually reduce total cumulative emissions from the atmosphere and upper oceans. The difference between cumulative negative emissions in 2100 and net negative emissions until 2100 is what is used to compensate continued fossil emissions (see Tab. S1).

S3 Carbon stocks

Fig. S3 shows the C stocks in the Earth system. Atmosphere and hydrosphere hold both about the same amount of anthropogenic C emissions, while the total C stock in the hydrosphere is two orders of magnitude larger [44]. Coal, oil and gas resources [66] and reserves [67] are in the same order of magnitude

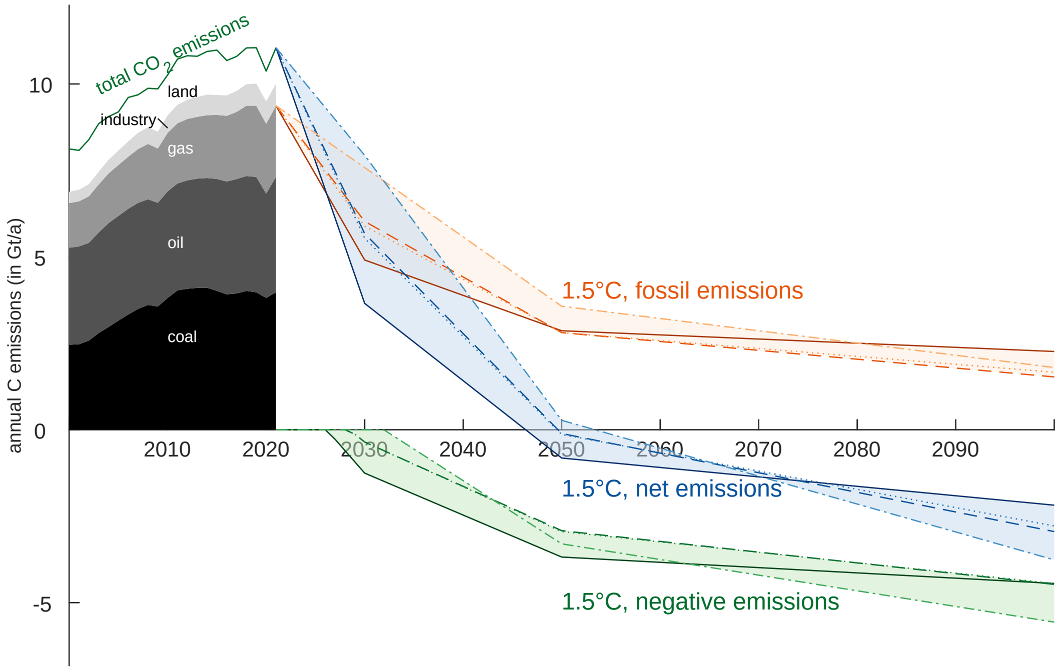

Figure S1: Total (blue), fossil (orange) and negative (green) annual C emissions in IPCC pathways aiming at limiting global heating to 1.5 °C ("Below 1.5 °C ", solid lines; "1.5 °C with low overshoot", dashed lines; "1.5 °C with no or limited overshoot", dotted lines; and "1.5 °C with high overshoot", dot-dashed lines) [9, 36]. Historic data (before 2018) is taken from [57] and separated for coal, oil, gas, industry and land use.

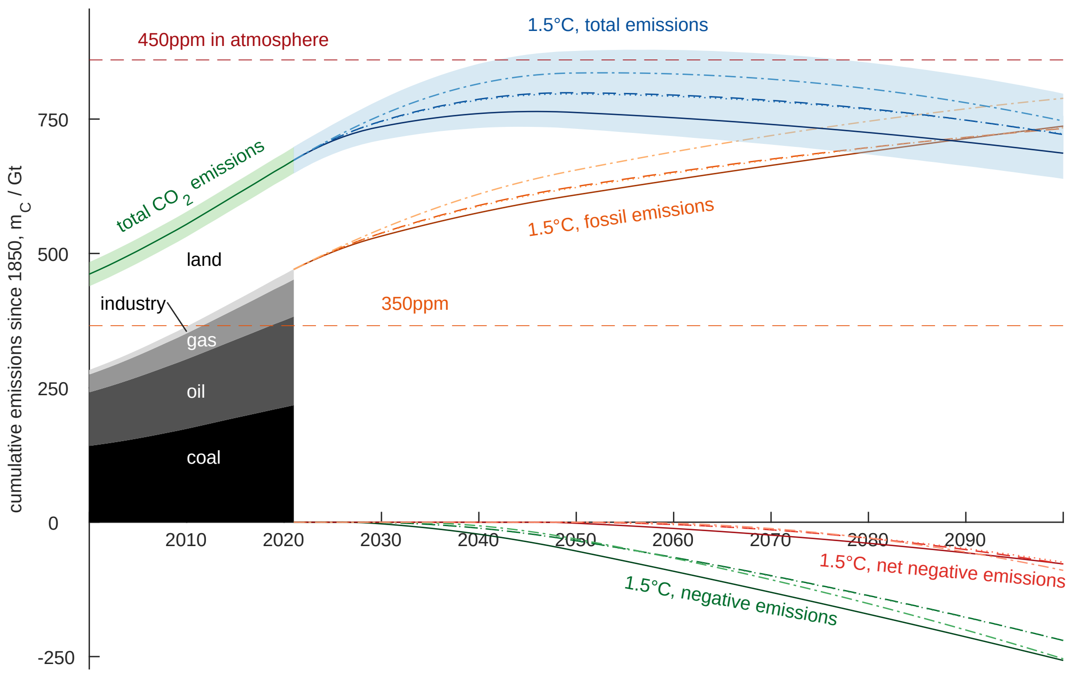

Figure S2: Total (blue), fossil (orange), negative (green) and net negative (red) cumulative C emissions in IPCC pathways aiming at limiting global heating to 1.5 °C ("Below 1.5 °C ", solid lines; "1.5 °C with low overshoot", dashed lines; "1.5 °C with no or limited overshoot", dotted lines; and "1.5 °C with high overshoot", dot-dashed lines) [9, 36]. Shaded area for total C emissions shows the 99 % confidence interval [9].

Table S1: Overview of cumulative carbon emissions in IPCC scenario groups targeting 1.5 °C . Cumulative emissions are counted from 1850 onwards, if not otherwise specified. Minimum and maximum values are rounded to nearest 10 Gt.

Cumulative carbon emissions in Gt	Below 1.5 °C	1.5 °C low-OS	1.5 °C with no/limited OS	1.5 °C high-OS	min	max
negative emissions in 2100	-257	-220	-220	-254	-220	-260
fossil emissions in 2100	737	733	734	789	730	790
fossil emissions from 2020 to 2100	267	262	264	319	260	320
total emissions in 2100	686	721	722	746	690	750
peak total emissions	764	799	796	836	760	840
net negative emissions until 2100	-78	-78	-73	-89	-70	-90
negative emissions compensating continued fossil emissions until 2100	-179	-142	-147	-164	-140	-180

to C stock in the hydrosphere and exceed all remaining C of the Earth system. The biosphere holds in living biomass about as much C as cumulative emissions since 1850 [44, 58], and is indirectly responsible for C in soil, permafrost and sediments (one order of magnitude larger than C in living biomass) [44]. C stocks in the technosphere (i. e. fossil fuel bunkers [67], plastic, wood and paper [42, 43], cultivated biomass and livestock, humans [58]) are one order of magnitude smaller than C in living biomass and about as much as C that needs to be minimally emitted for a full transition [9, 21].

S4 DAC limit

The C-flux from DAC is ultimately limited by the availability of excess energy. The removal of CO_2 through DAC is energy intensive bpth for high and low temperature processes. In electric energy, i. e. providing thermal energy requirements of these processes with electricity (and in the case of low temperature DAC with a heat pump), the energy demand is about $0.73\,\mathrm{TWa/Gt}$ of removed C [21, 73, 77, 82, 101, 102]. Solar PV can provide a maximum of 21 TW of electric energy output to society on the surface of the existing built environment [61]. Assuming a constant societal power demand, 6 TW are necessary to replace current fossil energy use [9, 103, 104], leaving a maximum of 15 TW for DAC. This power can remove a maximum C-flux of $20.5\,\mathrm{Gt/a}$.

S5 Negative emission potentials

Tab. S2 shows an overview of NET potentials reported in literature.

Table S2: Negative emission potentials from literature sources used in this study.

	C-flux / Gt / a		Cumulative C storage potential / Gt		residence time / a		time to saturation / a		Source
	min	max	min	max	min	max	min	max	
Afforestation	0.12	2.73	17	300			6	2500	This study
	0.12	1.48	17	147			11	1225	[53]
	0.14	0.98							[48]
		1.10							[54]
	0.82	2.73							[55]
	1.60	2.43							[52]
	0.14	0.98	100	300	80		102	2198	[56]
Biochar in soils	0.00016	2	100	500					This study
	1.20	3.15	500	540			159	450	[53]
	0.14	0.55			10	100			[48]
	0.70	1.30							[46]
	0.08	0.30							[55]
	0.14	0.55	100	200	100		183	1466	[56]
BECCS	0.00016	2	84	3000			42	18750000	This study
	1.80	11.60	500	3000			43	1667	[53]
	0.14	1.36							[48]
		3.30							[54]
Wood construction		0.60	2	20					This study
	0.15	1.36	2	20		100	1	133	[45]
		0.60							[60]
Soil carbon sequestration	0.00016	2							This study
	0.55	1.36							[48]
	0.70	1.30							[46]
	0.55	1.36	20	100	20		15	183	[56]
DACCS		20.00	84	3000					This study
limited by upscaling and costs	0.14	1.36							[48]
limited by upscaling and costs		3.30							[54]
		inf							[75]
saline formations			84						[93]
geological storage options			500	3000					[75]

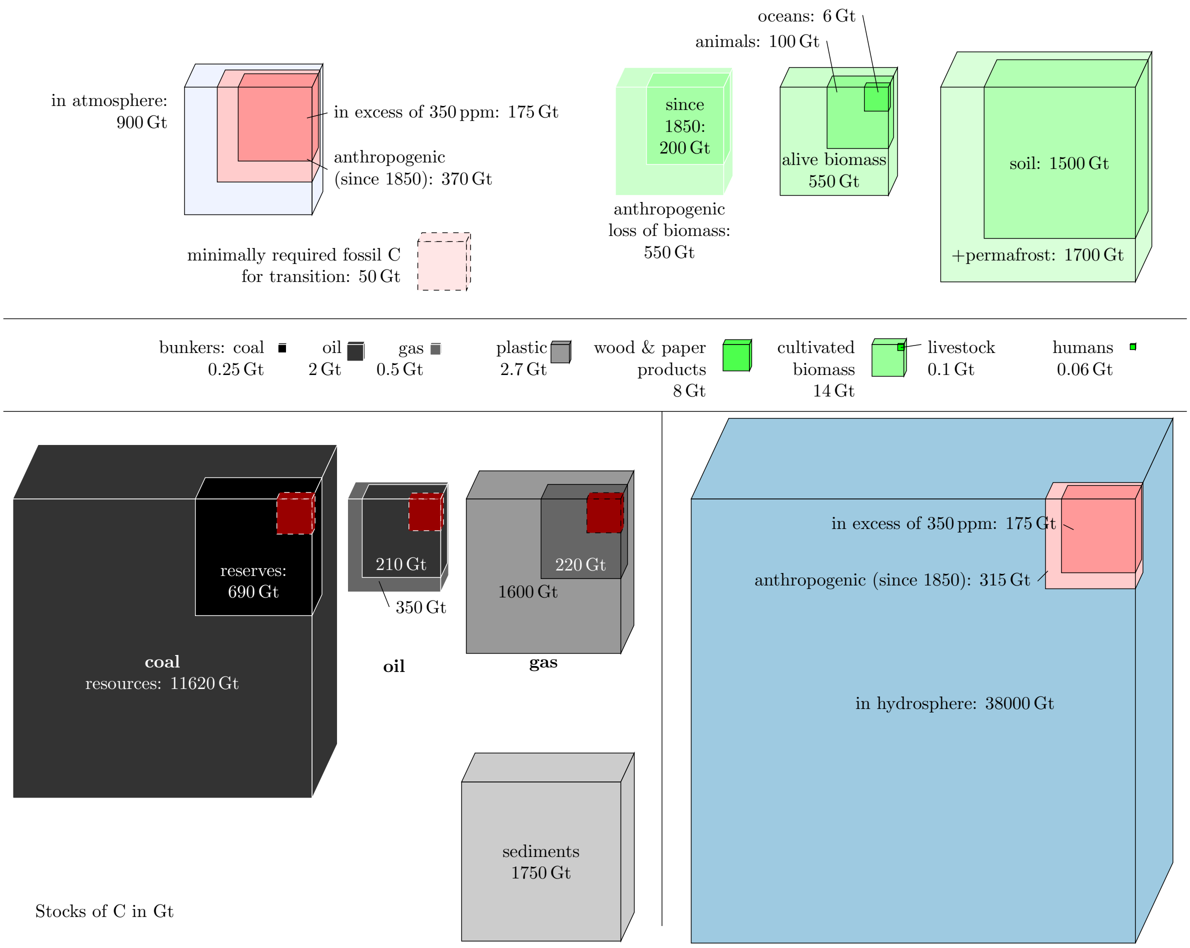

Figure S3: Carbon stocks in the Earth system and human disturbance. Data from [21, 42–44, 58, 67]. Note, the anthropogenic emissions are contained roughly half in the atmosphere and half in the hydrosphere. Negative emissions out of the atmosphere release emissions contained in the hydrosphere back to the atmosphere.

Additional references

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