Supplementary Information: Consistent greenhouse accounting identifies forests and land use as crucial determinants of climate

19 Oct 2023

Data Sources for attributing ERF and GSAT to sectors

Emissions-based effective radiative forcing (ERF), first used in IPCC AR6 [1], describes the cumulative radiative forcing of emissions since 1750. All efforts were made to assemble sector data for the entire period, however some data were extrapolated using methodology as described below.

Emission Species	Data Source	Period
CO_2	Global Carbon Budget, Friedlingstein et al., 2022 [2] Fossil Fuel & Industry LULUCF, converted to gross emissions as per Table S1, proportioned to sectors as per Table S3	 1750-2021 1750-2021
CH_4	PRIMAP data, Gütschow et al., 2023 [3] Fossil Fuel; industry; enteric fermentation; manure management; waste; other FAOSTAT Agricultural emissions Fire emissions Stern & Kaufman 1996 [4] Methodology for extrapolating data back to 1750, based on human population	 1750-2021 1961-2021 1990-2021 1750-1960/1989
N_2O	PRIMAP data, Gütschow et al., 2023 [3] Fossil Fuel; industry; enteric fermentation; manure management; waste; other GFED4 fire database, Van der Werf et al., 2017 [5] Downloaded 10 Oct 2023 from https://www.geo.vu.nl/~gwerf/GFED/GFED4/tables/; Data extrapolated using Stern & Kaufman methodology [4]	 1750-2021 1997-2021
SO2, halocarbons, NOx, NMVOC + CO, OC, BC & NH_4.	CEDS emissions data v_2021_04_21, [6,7] downloaded 3 July 2023 from https://gmd.copernicus.org/articles/11/369/2018/gmd-11-369-2018-supplement.zip GFED4 fire database, Van der Werf et al., 2017 [5] Downloaded 10 Oct 2023 from https://www.geo.vu.nl/~gwerf/GFED/GFED4/tables/; Data extrapolated using Stern & Kaufman methodology [4]	1750-2019 1997-2021

Table S1: Historic emissions data sources

CO_2 to sector attribution

1750-2021 LULUCF data were taken from PRIMAP data, converted to gross as per Table S2, then proportioned to sectors as per Table S4, S5 and S6.

Fire emissions to sector attribution

The PRIMAP data set includes comprehensive data for fossil fuel/industry and agriculture (from FAO and other sources) but does not include comprehensive land use emissions, notably emissions from anthropogenic fires. This limitation is clearly described in the PRIMAP documentation. Fires can be a major source of land use emissions, therefore additional fire data is required, as noted below.

CO2 fire data: 1750-2021 LULUCF data, including fire emissions, are derived from PRIMAP net LULUCF emissions, converted to gross as per Table S2, then proportioned to sectors as per Table S3.

CH4 & N2O fire data: Fire data are from FAO (1990-2021), extrapolated back to 1750 using Stern & Kaufman methodology. Sector attribution for fire data is as follows: Animal agriculture (grassland and savannah fires 96%, deforestation fires (tropical and peat) proportions from Table S3 (56%)); and Agriculture (deforestation fires (tropical and peat) proportions from Table S3 (20%)). For fire emission prior to 1990, relative contributions of deforestation, savanna and other fire types were taken from the 1990-2021 average. Forestry fire emissions are from the GFED4 fire database (van der Werf et al., 2017).

Fire data for other emission species (SO_2, halocarbons, NOx, NMVOC + CO, OC, BC & NH_4.): The GFED4 fire database (van der Werf et al., 2017), for the period 1997-2022 was used, extrapolated to 1750 based on the Stern and Kaufmann 1996 methodology, based on human population.

In modelling ERF, NMVOC and CO values have been given a combined value, weighted according to the warming contribution of each. From AR6 Table 7.SM.3, ozone's contribution to ozone ERF 1850-2014, W m–2 (Stevenson et al., 2013 ; Thornhill et al., 2021b), with the precursors having the following warming: CO (+0.07 ± 0.06) and NMVOC (+0.04 ± 0.04), therefore to combine their warming, CO values are scaled by 7 and NMVOC values scaled by 4 to make up the combined ERF.

Estimating Gross Anthropogenic Land Use, Land Use Change and Forestry (LULUCF) CO_2 Emissions

While we are advocating that the artificial distinction between intact and managed land is no longer useful, we do need to estimate gross anthropogenic CO_2 emissions for this study, since most historic datasets of LULUCF CO_2 are net emissions on managed land. Table S2 examines LULUCF estimates and how the gross/net conversion factor of 3.5 as used in this study is determined. Arneth et al., 2017 [8] states that net land use emissions rather than gross understates emissions by a factor of 3-4, confirming the value used here, and Xu et al., 2021 [9] estimate gross LULUCF emissions for 2000-2019 using bookkeeping and remote sensing data, that agrees within 5% of the GCB data used here, when converted using the net to gross factor of 3.5. Note that this conversion factor only applies to CO_2 because all other gases are fully quantified, again highlighting the inconsistent way we deal with land use CO_2 emissions. Also, see Sensitivity Analysis below, where the value of 3.5 used here is tested against values of +/- 15%.

LULUCF Net and Gross CO_2 Emissions			
	Net Emissions	Gross Emissions	Ratio/Comments
Houghton & Castanho, 2023 [10]	3.5 $GtCO_2$/yr	12.4 $GtCO_2$/yr	2011-2020 Gross to Net ratio 3.5 (used in this study)
Houghton & Nassikas 2017 [11]	4.07 Gt CO_2/yr	Up to 20.2 Gt CO_2/yr	2006-2015 average Wood harvest gross = 4x net.
Jia et al., 2019 [12], IPCC Land Climate Interactions, section 2.3.1	5.5 Gt CO_2/yr (Le Quere et al., 2018)	20.2 Gt CO_2/yr (Houghton & Nassikas, 2017)	Gross to Net ratio 3.7

Friedlingstein et al., 2022 [2] (Global Carbon Budget 2022)	4.8 Gt CO_2/yr		
Obermeier et al., 2021 [13]	4.5 Gt CO_2/yr, plus 2.9 Gt CO_2/yr loss of additional sink capacity (LASC)		Forest sink is growing by the amount of LASC due to CO2 fertilisation
Xu et al., 2021 [9]		17.0 Gt CO_2/yr	If GCB net emissions of 4.8Gt CO_2 is used, ratio of gross to net is 3.5
Gasser et al., 2020 [14]	4.99 Gt CO_2/yr		
Arneth et al., 2017 [8]		3 to 4 times net emissions	Gross emissions estimated at 3-4 times net.

Table S2: Derivation of LULUCF net to gross conversion ratio

Despite the recent advances, estimates of gross and net land use emissions have considerable uncertainties, therefore the gross/net conversion factor chosen here should be seen as indicative only, but are thought to be very conservative, for reasons given in *2.1 Errors and Accuracy*.

LULUCF CO_2 Emissions Attribution to Sector

The IPCC LULUCF category contains an array of emission sources due to anthropogenic activities, predominantly deforestation and degradation, and fluxes due to forest management such as wood harvest, and also includes peatland drainage and open fires. All these activities vary substantially from year to year, therefore a multi-year mean is often used. Grazing management and cropland soil carbon loss is not included in LULUCF by convention [12]. LULUCF also includes sinks, almost exclusively from vegetation regrowth, but since we are dealing with gross land emissions, these are accounted separately.

Gross land use CO_2 emissions from 2007-2016 have been estimated at 12.4Gt CO_2/yr, a factor of 3.5 greater than conventionally accounted net emissions of 3.5 Gt CO_2/yr [10] (see discussion and table S2 above). We use this factor to convert net LULUC emissions to gross emissions. This estimate is considered very conservative, for reasons given in the text, therefore this factor may be a significant underestimate. Jia et al., 2019 [12] provides a comprehensive summary of LULUCF emission estimation methods and accuracies. Houghton and Nassikas 2018 [15] and others as referenced provide the following LULUCF CO_2 emission breakdown shown in Table S3.

Open fire emissions as given in van der Werf 2017 (from deforestation, pasture maintenance, peat and crop stubble fires) [5] are attributed according to fire type: tropical deforestation and degradation, savanna pasture maintenance and peat fires are attributed to animal agriculture; agricultural waste burning is allocated half to animal and half to other agriculture; and boreal and temperate forest fires are considered natural. Together, this is considered to be a conservative estimate of anthropogenic fire emissions, because 96% of fires are deliberately ignited [16]: most savannah fires, almost all rainforest fires, and all deforestation and peat fires are deliberately lit [17].

Attribution in Table S3 is considered conservative because only 84% of LULUCF CO_2 emissions have been attributed to chosen sectors. It would seem that most of the remaining 16% could be attributed to some form of agriculture or forestry because only 1-2% of ice-free land is built-up or mining [12], but studies of this breakdown are few and uncertain. A comprehensive study of historic land use may remove some of this uncertainty.

LULUCF CO_2 Attribution to Emission Source		
Deforestation	77% of gross LULUCF [15]	
Degradation	10%of gross LULUCF, of which: [15] Timber harvest Wood Fuel	 53% 30%
Fire	13% of gross LULUCF[15], 96% deliberately lit [16] of which [5]: 4% wildfire naturally ignited	 62% savanna pasture maintenance 25% deforestation 3% crop residue 10% other
Deforestation Attribution		
Agriculture	88-99% of deforestation [18,19], of which [19]	50% cropland 39% grazing
Crop Attribution		
Crop produce by dry weight [20]	24% Human food 53% Animal feed 12% Fibre & Biofuel 11% Waste	

LULUCF Sector Attribution	Deforestation	Degradation	Fire	Total
Animal Agriculture	46%		9%	56%
Other Agriculture	18%		2%	20%
Forestry & Woodfuel		8%		8%
Other				16%
Total				100%

Table S3: Attribution of LULUCF CO_2 Emission to Sources

Emissions Attribution to Sectors

Average Yearly Emissions 1750-2021							
	Fossil Fuel & Industry	Animal Agriculture	Other Agriculture	Forestry	Waste	Other	Built-up Land
CO_2 (Gt, 1750-2021)[2,15,21] (a)	1737 [2] (1750-2021 total)	1952 [2] (1750-2021 total)	697 [21] (1750-2021 total)	279 (1750-2021 total)		558 (1750-2021 total)	
Methane (Mt, 2000-2017 average) (b)	32.19	45.80 [5,6,22]	5.42	0.05	14.0	0.03	

N2O (kt, 1980-2016 average) (b)	439.9	1174 [22]	821	7.5	91.1	271	
SO2 (kt, 1970-2014 average) (b)	37621	498	56.3	240	31.7	783	
NOx (Mk, 1970-2014 average) (b)	26398	1061	359	4.4	310	43.7	
NMVOC (kt, 1970-2014 average) (b)	38396	5522	1022	29	429	1703	
CO (kt, 1970-2014 average) (b)	238312	73925	15091	1593	2542	28849	
NMVOC+CO (scaled AR6 Table 7.SM.3)	1821766	539561	109730	11264	19507	208757	
Halocarbons (solely FF & Industry) (b)	100%						
Organic C (kt, 1970-2014 average) (b)	5971	3099	460	80	193	2033	
Black Carbon (kt, 1970-2014 average) (b)	2153	402	91	8.9	30	122	
Ammonia (kt, 1970-2014 average) (b)	1708	9688	2280	22.7	40.6	486	2
Carbon Opportunity Cost Gt/year[2,23–26]	0	26 [15,24]	16 [25]	3.9 [14]	0	0	2 [26]

Table S4 ; Attribution of Emission Species to sectors

Notes: (a) Global Carbon Budget 2022; Jia et al., 2019, section 2.3.1.3; AR6 2021 Gulev et al., 2021, Canadell et al., 2021 Tables 5.2, 5.3

(b) Data on SLCFs from Hoesly et al., 2018; Van der Werf et al., 2017 (for fire emissions); AR6 2021 Gulev et al., 2021, Canadell et al., 2021 Tables 5.2 &5.3; Global CH4 Budget; Global N2O Budget

Emission Sector Proportions							
	Fossil Fuel & Industry	Animal Agriculture	Other Agriculture	Forestry	Waste	Other	Built-up Land
CO_2	0.33	0.37	0.12	0.05	0.00	0.11	
Methane	0.33	0.47	0.16	0.00	0.14	0.00	
N_2O	0.16	0.42	0.18	0.00	0.03	0.10	
SO_2	0.96	0.01	0.03	0.01	0.00	0.02	
NOx	0.94	0.04	0.02	0.00	0.01	0.00	
NMVOC+CO	0.67	0.39	0.05	0.01	0.01	0.08	
Halocarbons	1.00						
Organic C	0.50	0.26	0.05		0.02	0.02	

Black Carbon	0.77	0.14	0.04		0.01	0.01	
Ammonia	0.12	0.68	0.11	0.00	0.00	0.00	
Carbon Opportunity Cost	0.00	0.54	0.33	0.08	0.00	0.00	0.04

Table S5: Attribution of Sector Proportions to Emission Species (simple proportions from Table S4)

Attribution of Effective Radiative Forcing (ERF) and Global Surface Air Temperature (GSAT) to Sectors

Emissions-based ERF (AR6 Figure 6.12b) is new to IPCC AR6 [1]. Abundance-based ERFs were given in AR5 and are described in AR6 6.SM.1 and 6.SM.2, and Table 7.8, but the newly-developed emissions-based ERFs, as described in AR6 6.SM.1 more accurately model aerosol–cloud interactions attributed to the emitted compounds. Due to the non-linear chemical and physical processes described above relating emissions to ERF, and the additional non-linear relations between ERF and GSAT, these emissions-based estimates of GSAT responses strongly depend on the methodology applied to estimate ERF and GSAT (AR6 Supplementary Material 6.SM.2). GSAT is calculated from the ERF time series using an impulse response function. Table S6 presents the results of applying the proposed accounting framework changes as summarised in Table 1 to emissions data from 1750 to the present.

Effective Radiative Forcing (ERF) and Global Surface Atmospheric Temperature (GSAT) by Emissions and Sector												
	Fossil Fuel & Industry		Animal Agriculture		Other Agriculture		Forestry		Waste		Other	
	ERF	GSAT	ERF	GSAT	ERF	GSAT	ERF	GSAT	ERF	GSAT	ERF	GSAT
CO_2	0.68	0.32	0.77	0.36	0.27	0.13	0.11	0.05	0.00	0.00	0.22	0.10
Methane	0.39	0.20	0.56	0.28	0.07	0.03	0.07	0.00	0.17	0.09	0.00	0.00
N2O	0.04	0.02	0.10	0.05	0.07	0.03	0.00	0.00	0.01	0.01	0.02	0.01
SO2	-0.90	-0.48	-0.01	-0.00	-0.00	-0.00	-0.01	0.00	-0.00	-0.00	-0.02	-0.00
NOx	-0.25	-0.13	-0.01	-0.01	-0.00	0.00	0.00	-0.00	-0.00	-0.00	0.00	-0.00
NMVOC+CO	0.30	0.17	0.09	0.05	0.02	0.01	0.00	0.00	0.00	0.00	0.03	0.02
Halocarbons	0.21	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Organic C	-0.11	-0.05	-0.05	-0.02	-0.01	-0.00	0.00	0.00	-0.00	-0.00	-0.04	0.02
Black Carbon	0.08	0.05	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.00
Ammonia	-0.00	-0.00	-0.02	-0.01	-0.01	-0.00	-0.00	-0.00	-0.00	-0.00	0.00	-0.00
% Net ERF & GSAT	16%	14%	51%	52%	15%	15%	4%	4%	6%	7%	8%	8%

Table S6: Attribution of Effective Radiative Forcing (ERF) and Global Surface Air Temperature (GSAT) to Sectors

Notes: (a) IPCC AR6 Section 6.4.2[1] and 6.SM.1[27], and Thornhill et al., 2021[28]

IPCC AR6 6.4.2, Fig 6.SM.1 and 6.SM.2[27]

(c) These values are emissions-based ERF as used by IPCC AR6 Working Group 1, not abundance-based ERF used until recently (and in chapter 7 AR6 WG3)

Carbon Opportunity Cost and Attribution

We define carbon opportunity cost (COC) as the potential landscape carbon storage minus actual storage. The Global Carbon Budget [2] and the IPCC Climate Change and Land report [12] use the land carbon potential value of Erb et al., 2018 [25] of 1710Gt CO_2 for total net land carbon loss. Here we have used a similar value from Walker et al., 2022 [26]. See Table S7 below.

Global Carbon Opportunity Cost		
	Potential-Actual	**Description**
Searchinger et al., 2018 (used in this study)	1700GtCO_2	Total land carbon loss
Erb et al., 2018	1710Gt CO_2	As used by Global Carbon Project
Kaplan et al., 2010	1250Gt CO_2	Includes pre-industrial, total land carbon loss
Hoesly et al., 2017	1690Gt CO_2	As used by Global Carbon Project
Walker et al., 2022	1812Gt CO_2	Total restoration potential, 513Gt CO_2 is soil carbon
Yang et al., 2021	4756 Gt CO_2 actual	79.3 Gt CO_2/yr land carbon loss
Grazing Land Carbon Opportunity Cost		
Hayek et al., (2021)	790Gt CO_2	Animal agriculture land carbon sequestration potential =26Gt CO_2/yr over 30 years
Rao et al., 2015	970Gt CO_2	grazing land forest carbon loss: 41% of grazing lands formerly forest
Searchinger et al., 2018	1035Gt CO_2	Land carbon loss on grazing lands
Bastin et al., 2019	750Gt CO_2	Forest restoration potential, excludes crops and urban areas
Walker et al., 2022 (used in this study)	825Gt CO_2	Table S8. Forest unrealised potential, excludes crops and urban areas as per Bastin et al., 2019
Cropland Carbon Opportunity Cost		
Erb et al., 2018	477Gt CO_2 = 16Gt CO_2/yr over 30 years	As used by Global Carbon Project
Walker et al., 2022 (used in this study)	490Gt CO_2	
Built-up Land Carbon Opportunity Cost		
Walker et al., 2022 (used in this study)	32Gt CO_2	

Table S7: Carbon Opportunity Cost (COC) Attribution

Sensitivity Analysis

Three sensitivity analyses were conducted to determine sensitivity to changes in emission proportions and sensitivity to changes in gross deforestation/land use emissions, as summarised below. For the first analysis, rather than 1750-present, data for this century (2000 to present) was used. This was chosen to assess the large emissions differences such as deforestation vs fossil fuel CO_2. As expected, this over-emphasised the fossil fuels/industry sector, which rose slightly in ranking, but animal agriculture remained as the leading emissions sector (see text for more discussion).

Analysis	Result
Emission proportions from recent (post-2000) sources, rather than for the entire period 1750-2014/21	Fossil fuel/industry sector rose to second in ERF ranking below animal agriculture, but animal agriculture's ERF was still 3 times higher than FF.
Lower gross/net land use emission conversion factor (15% lower, at 3.0)	Overall emissions reduced, but relative ranking of sector ERF remained the same.
Higher gross/net land use emission conversion factor (15% higher, at 4.0)	Overall emissions increased, but relative ranking of sector ERF remained the same.

Data Availability

Data Availability Statement: All data sources are publicly available as referenced. Data deposited with Zenodo, https://doi.org/10.5281/zenodo.10020269

References

1. Szopa, S.; Naik, V.; Adhikary, B.; Artaxo, P.; Bernsten, T.; Collins, W.; Fuzzi, S.; Gallardo, L.; Keindler-Sharr, A.; Klimont, Z.; et al. Short-Lived Climate Forcers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S., Pean, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J., Maycock, T., Waterfield, T., Yelekci, O., Yu, R., Zhou, B., Eds.; Cambridge University Press, Cambridge, United Kingdom and New York, USA, 2021.
2. Friedlingstein, P.; O'Sullivan, M.; Jones, M.W.; Andrew, R.M.; Gregor, L.; Hauck, J.; Le Quéré, C.; Luijkx, I.T.; Olsen, A.; Peters, G.P.; et al. Global Carbon Budget 2022. *Earth Syst. Sci. Data* **2022**, *14*, 4811–4900, doi:10.5194/essd-14-4811-2022.
3. Gütschow, J.; Pflüger, M. The PRIMAP-Hist National Historical Emissions Time Series (1750-2021) v2.4.1 2023.
4. Stern, D.I.; Kaufmann, R.K. Estimates of Global Anthropogenic Methane Emissions 1860–1993. *Chemosphere* **1996**, *33*, 159–176, doi:10.1016/0045-6535(96)00157-9.
5. van der Werf, G.R.; Randerson, J.T.; Giglio, L.; van Leeuwen, T.T.; Chen, Y.; Rogers, B.M.; Mu, M.; van Marle, M.J.E.; Morton, D.C.; Collatz, G.J.; et al. Global Fire Emissions Estimates during 1997–2016. *Earth Syst. Sci. Data* **2017**, *9*, 697–720, doi:https://doi.org/10.5194/essd-9-697-2017.
6. Hoesly, R.M.; Smith, S.J.; Feng, L.; Klimont, Z.; Janssens-Maenhout, G.; Pitkanen, T.; Seibert, J.J.; Vu, L.; Andres, R.J.; Bolt, R.M.; et al. Historical (1750–2014) Anthropogenic Emissions of Reactive Gases and Aerosols from the Community Emissions Data System (CEDS). *Geosci. Model Dev.* **2018**, *11*, 369–408, doi:10.5194/gmd-11-369-2018.

7. O'Rourke, P.R.; Smith, S.J.; Mott, A.; Ahsan, H.; McDuffie, E.E.; Crippa, M.; Klimont, Z.; McDonald, B.; Wang, S.; Nicholson, M.B.; et al. CEDS V_2021_02_05 Release Emission Data 2021.
8. Arneth, A.; Sitch, S.; Pongratz, J.; Stocker, B.D.; Ciais, P.; Poulter, B.; Bayer, A.D.; Bondeau, A.; Calle, L.; Chini, L.P.; et al. Historical Carbon Dioxide Emissions Caused by Land-Use Changes Are Possibly Larger than Assumed. *Nat. Geosci.* **2017**, *10*, 79–84, doi:https://doi.org/10.1038/ngeo2882.
9. Xu, L.; Saatchi, S.S.; Yang, Y.; Yu, Y.; Pongratz, J.; Bloom, A.A.; Bowman, K.; Worden, J.; Liu, J.; Yin, Y.; et al. Changes in Global Terrestrial Live Biomass over the 21st Century. *Sci. Adv.* **2021**, *7*, eabe9829, doi:10.1126/sciadv.abe9829.
10. Houghton, R.A.; Castanho, A. Annual Emissions of Carbon from Land Use, Land-Use Change, and Forestry from 1850 to 2020. *Earth Syst. Sci. Data* **2023**, *15*, 2025–2054, doi:10.5194/essd-15-2025-2023.
11. Houghton, R.A.; Nassikas, A.A. Global and Regional Fluxes of Carbon from Land Use and Land Cover Change 1850–2015. *Glob. Biogeochem. Cycles* **2017**, *31*, 456–472, doi:10.1002/2016GB005546.
12. Jia, G.; Shevliakova, E.; Artaxo, P.; Noblet-Ducoudre, N.; Houghton, R.; House, J.; Kitajima, K.; Lennard, C.; Popp, A.; Sirin, A.; et al. Land–Climate Interactions. In *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*; Shukla, P., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Portner, H., Roberts, D., Zhai, P., Slade, R., Connors, S., van Diemen, R., Haughey, E., Luz, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J., Eds.; Intergovernmental Panel on Climate Change, 2019.
13. Obermeier, W.A.; Nabel, J.E.M.S.; Loughran, T.; Hartung, K.; Bastos, A.; Havermann, F.; Anthoni, P.; Arneth, A.; Goll, D.S.; Lienert, S.; et al. Modelled Land Use and Land Cover Change Emissions – a Spatio-Temporal Comparison of Different Approaches. *Earth Syst. Dyn.* **2021**, *12*, 635–670, doi:10.5194/esd-12-635-2021.
14. Gasser, T.; Crepin, L.; Quilcaille, Y.; Houghton, R.A.; Ciais, P.; Obersteiner, M. Historical CO Emissions from Land Use and Land Cover Change and Their Uncertainty. *Biogeosciences* **2020**, *17*, 4075–4101, doi:10.5194/bg-17-4075-2020.
15. Houghton, R.A.; Nassikas, A.A. Negative Emissions from Stopping Deforestation and Forest Degradation, Globally. *Glob. Change Biol.* **2018**, *24*, 350–359, doi:10.1111/gcb.13876.
16. Millington, J.D.A.; Perkins, O.; Smith, C. Human Fire Use and Management: A Global Database of Anthropogenic Fire Impacts for Modelling. *Fire* **2022**, *5*, 87, doi:10.3390/fire5040087.
17. Lauk, C.; Erb, K.-H. Biomass Consumed in Anthropogenic Vegetation Fires: Global Patterns and Processes. *Ecol. Econ.* **2009**, *69*, 301–309, doi:10.1016/j.ecolecon.2009.07.003.
18. Pendrill, F.; Gardner, T.A.; Meyfroidt, P.; Persson, U.M.; Adams, J.; Azevedo, T.; Bastos Lima, M.G.; Baumann, M.; Curtis, P.G.; De Sy, V.; et al. Disentangling the Numbers behind Agriculture-Driven Tropical Deforestation. *Science* **2022**, *377*, eabm9267, doi:10.1126/science.abm9267.
19. FAO *Forest Resource Assessment 2020 Remote Sensing Survey*; FAO: Rome, 2022; ISBN 978-92-5-136147-4.
20. Smith, P.; Bustamante, M.; Ahammad, H.; Clark, H.; Dong, H.; Elsiddig, E.; Haberl, H.; Harper, R.; House, oanna; Jafari, M.; et al. Agriculture, Forestry and Other Land Use (AFOLU). In *IPCC AR5 WG3 Chapter 11 Agriculture, Forestry and Other Land Use (AFOLU)*; Cambridge University Press,: Cambridge UK and NY, 2014.
21. Gulev, S.; Thorne, P.; Ahn, J.; Dentener, F.; Domingues, C.; Gerland, S.; Gong, D.; Kaufman, D.; Nnamchi, H.; Quaas, J.; et al. Changing State of the Climate System. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press, Cambridge, United Kingdom and New York, USA, 2021.
22. Global Carbon and Other Biogeochemical Cycles and Feedbacks. In *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Canadell, Monterio, P., Costa, M., Cotrim da

Cunha, L., Cox, P., Eliseev, A., Henson, S., Ishii, M., Jaccard, S., Koven, C., Lohila, A., Patra, P., Piao, S., Rogelj, J., Syampungani, S., Zaehle, S., Zickfeld, K., Eds.; Cambridge University Press: Cambridge, 2021; pp. 673–816 ISBN 978-1-00-915788-9.

23. Searchinger, T.D.; Wirsenius, S.; Beringer, T.; Dumas, P. Assessing the Efficiency of Changes in Land Use for Mitigating Climate Change. *Nature* **2018**, *564*, 249–253, doi:10.1038/s41586-018-0757-z.
24. Hayek, M.N.; Harwatt, H.; Ripple, W.J.; Mueller, N.D. The Carbon Opportunity Cost of Animal-Sourced Food Production on Land. *Nat. Sustain.* **2021**, 1–4, doi:10.1038/s41893-020-00603-4.
25. Erb, K.-H.; Kastner, T.; Plutzar, C.; Bais, A.L.S.; Carvalhais, N.; Fetzel, T.; Gingrich, S.; Haberl, H.; Lauk, C.; Niedertscheider, M.; et al. Unexpectedly Large Impact of Forest Management and Grazing on Global Vegetation Biomass. *Nature* **2018**, *553*, 73–76, doi:10.1038/nature25138.
26. Walker, W.S.; Gorelik, S.R.; Cook-Patton, S.C.; Baccini, A.; Farina, M.K.; Solvik, K.K.; Ellis, P.W.; Sanderman, J.; Houghton, R.A.; Leavitt, S.M.; et al. The Global Potential for Increased Storage of Carbon on Land. *Proc. Natl. Acad. Sci.* **2022**, *119*, e2111312119, doi:10.1073/pnas.2111312119.
27. Szopa, S.; Naik, V.; Adhikary, B.; Artaxo, P.; Berntsen, T.; Collins, S.; Fuzzi, S.; Gallardo, L.; Kiendler-Scharr, A.; Klimont, Z.; et al. Short-Lived Climate Forcers Supplementary Material. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK and New York, 2021; pp. 817–922.
28. Thornhill, G.D.; Collins, W.J.; Kramer, R.J.; Olivié, D.; Skeie, R.B.; O'Connor, F.M.; Abraham, N.L.; Checa-Garcia, R.; Bauer, S.E.; Deushi, M.; et al. Effective Radiative Forcing from Emissions of Reactive Gases and Aerosols – a Multi-Model Comparison. *Atmospheric Chem. Phys.* **2021**, *21*, 853–874, doi:10.5194/acp-21-853-2021.