

**The contributions of animal agriculture
and major fossil-fuel-based industries
to global warming**

Martin Müller
BBA, Cert.H.E. Natural Sciences
Email: m.mueller@industryfootprint.org
Web: <https://landwirtschaft.jetzt>
11 April 2021

PrePrint

Table of Contents

1. Introduction.....	4
2. Material and methods.....	5
3. Theory/calculation	6
3.1. Global warming potentials of GHGs.....	6
3.2. Aerosol cooling.....	12
3.3. Heating potentials of fossil fuels considering GWPins of methane	14
3.4. Opportunity costs for unused carbon sinks	15
3.5. Deforestation.....	17
3.6. Capture fisheries and aquaculture.....	18
3.7. Pre-production, processing and post-production	19
4. Results	20
4.1. Today's methane emissions have more immediate significance than today's CO ₂ emissions 20	
4.2. Animal agriculture is the biggest cause of global warming.....	20
5. Conclusions.....	23
6. Discussion.....	24
7. Appendix.....	25
A) Comparison of different studies/reports on the role of animal agriculture / livestock farming in climate change	25
B) Calculation of contributions of animal agriculture (AA) and fossil fuel based industries to climate change as assumed by FAO and IPCC (supporting Fig. 4).....	26
8. Acknowledgments.....	27
9. References.....	28
10. Funding.....	30

Table of Tables

Table 1: RF of anthropogenic WMGHG in 2020	7
Table 2: Interim results of annual contributions of major GHGs to RF in 2020 (4 s.f.)	10
Table 3: Calculation of GWP_{ins} for CH_4 and N_2O using Radiative Efficiency (RE) averaged over the last 10 years	11
Table 4: Calculation of the 2011 annual contributions of major aerosols to ERF based on GWP_{10} (4 s.f.)	13
Table 5: Calculation of relative climate heating potentials of the major fossil fuel sources (3 s.f.) ...	15
Table 6: Calculation of annual opportunity costs in terms of CO_2 emissions per year for unused carbon sinks of the current agriculture system vs. a fully plant-based system (4 s.f.)	16
Table 7: Calculation of annual CO_2 emissions from deforestation for animal agriculture (3 s.f.)	17
Table 8: Determination of most harmful industries to climate heating (3 s.f.)	22

Table of Figures

Fig. 1: RF in 2011 as depicted in IPCC's Fifth Assessment Report (AR5) and values of anthropogenic forcing	6
Fig. 2: GWPs calculated by IPCC AR5 for $H=20$ and $H=100$	8
Fig. 3: Relative significance of GHGs, for the current composition of the atmosphere and the RFs (a.), for a one-time pulse and stretching over 100 years (b.) and for the current emissions and immediate heating effects (c.)	20
Fig. 4: Previously assumed major causes of global warming vs. actual major causes after revaluation	23
Fig. 5: Comparison of different studies on the role of animal agriculture / livestock farming in global warming	25
Fig. 6: Calculation of contributions of animal agriculture and fossil-fuel-based industries to climate change as assumed by FAO and IPCC (supporting Fig. 4)	26

1. Introduction

The problem of climate heating is attracting more and more attention within politics and wider society. The fossil fuel industry is generally seen as the main cause and focus for action. Scientists too present burning fossil fuels, be it for energy production, heating or transportation, as central to the greenhouse effect, and thus reducing fossil fuel consumption is promoted as almost the only solution.

This assumption is based on authoritative reports from official bodies like the Intergovernmental Panel on Climate Change (IPCC). Most derivative studies and literature refer to reports by the IPCC and do not question the major statements thereof.

By investigating the greenhouse gas (GHG) emissions of fossil-fuel-combusting industries on the one hand, and animal agriculture¹ on the other, it is shown here that conclusions of the causes for climate heating made by scientists are often based on technically correct but irrelevant calculations, omission of physical effects, negligence of opportunity costs and imprecisely allocated inputs.

¹ Animal agriculture sometimes is understood to consist of livestock farming, aquaculture and capture fisheries. Here, the term “animal agriculture”, includes livestock farming and aquaculture, while capture fisheries is excluded (for details see chapter 3.6).

2. Material and methods

The research for this paper focused on the analysis of the major reports and studies on the contributions of animal agriculture and fossil-fuel-based industries to global warming as well as reviews of used input data, models and calculation models.

As for animal agriculture, reports, studies and input data were mainly from the Food and Agriculture Organisation (FAO), the Worldwatch Institute (WWI), the Intergovernmental Panel on Climate Change (IPCC) and the Global Change Data Lab (Our World in Data). Regarding the fossil-fuel-based industries major reports, studies and input data analyzed were from the IPCC, the International Energy Agency (IEA) and the Global Change Data Lab.

Most of the data used for the calculations are primary data, i.e. measured data. Some more complex input data are from studies that are referred to.

All used input data and calculation methods are directly referenced in detail at the appropriate positions in the text. All calculations can be reproduced in the Excel sheets which are part of the supplementary file to this paper.

The resulting mathematical model is also migrated to a website which allows the input of latest data and simulation of different scenarios: <https://www.industryfootprint.org/>.

3. Theory/calculation

3.1. Global warming potentials of GHGs

The human-induced greenhouse effect is caused by hundreds of different GHGs and a few aerosols. It is directly measured with sensors in the atmosphere, but also simulated in laboratories and mathematical models [1]. The effect can be expressed as anthropogenic Radiative Forcing (RF), which is the additional energy per second trapped in the atmosphere by GHGs and aerosols emitted due to human activities. According to NOAA/ESRL's Global Monitoring Division, the uncertainties of the models are of about 10%². Fig. 1 shows the RF in 2011 due to changes in the atmosphere compared to pre-industrial levels in 1750 [2].

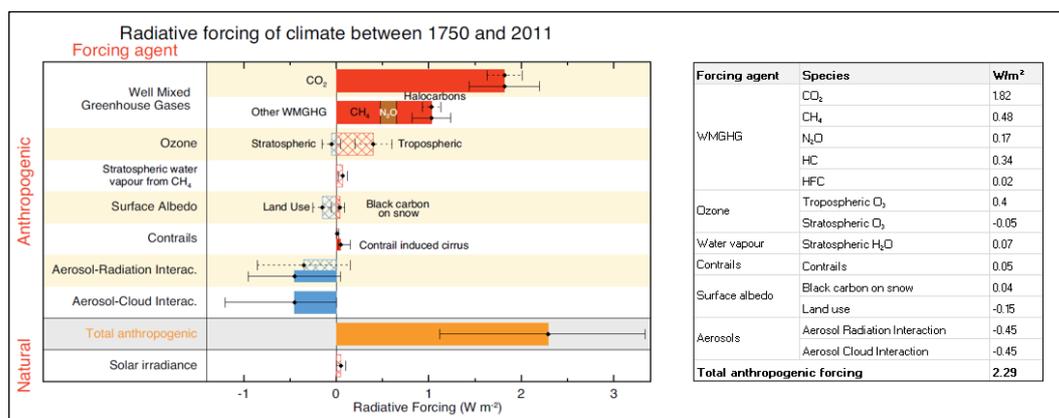


Fig. 1: RF in 2011 as depicted in IPCC's Fifth Assessment Report (AR5) and values of anthropogenic forcing

It is essential to take into account that the RF indeed **does** reflect the effect of the *human-caused composition of forcing agents in the atmosphere*, which is the result of all human-caused emissions and their absorption and decay since 1750. Yet, the RF **does not** reflect the greenhouse effect due to *current GHG emissions and aerosols*.

The 2020 RF values for anthropogenic 'Well-Mixed Greenhouse Gases (WMGHGs)' are presented in Table 1, being determined as follows:

(1) The 2020 mole fractions of CO₂ are retrieved from NOAA/ESRL³. The RF⁴ is calculated using the expressions based on radiative transfer models [3].

² Global Monitoring Laboratory (GML) of the National Oceanic and Atmospheric Administration (USA)

³ Data is taken from <https://www.esrl.noaa.gov/gmd/ccgg/trends>; another data hub is <https://gaw.kishou.go.jp>

⁴ $RF = \alpha \ln(C/C_0)$, where $\alpha = 5.35$, $C_0 = 278 \text{ ppm}$ and C is global mean atmospheric concentration of CO₂ in 2020

(2) The 2020 mole fractions of CH₄ retrieved from NOAA/ESRL. The direct RF⁵ is calculated using the expressions based on radiative transfer models [3]. The current concentration of methane alone has RF of 0.519 W m⁻². However, since methane has indirect effects on other GHGs, the actual RF of methane is almost twice as high, which is 1.013 W m⁻²:

- CH₄ has indirect effects to tropospheric and stratospheric ozone which is estimated to be additional 50% to the direct effect [4].
- CH₄ changes stratospheric H₂O being about 15% of the direct effect [4].
- CH₄ interacts with sulphate and degrades this cooling aerosol, which accounts for a further 30% forcing above the direct effect [5].
- CH₄ finally decomposes to CO₂. Since the amounts are small, the forcing effects (< 1%) are not specifically integrated in the models.
- Experiments showed that increases in global methane emissions cause significant decrease in hydroxyl, leading to a negative feedback loop for CH₄ decomposition and thus increasing CH₄ potency [5]. Due to uncertainties regarding the magnitude of the effect they are not include here.

(3) The 2020 mole fractions of N₂O are retrieved from NOAA/ESRL. The direct RF⁶ is calculated using the expressions based on radiative transfer models [3].

(4) The 2018 RF values of other WMGHGs (CFC12, CFC11, 15-minor)⁷ are retrieved from NOAA/ESRL⁸ and is extrapolate to 2020, based on the 10yr average rate of change (+0.41% yr⁻¹).

No.	WMGHG		Forcing	
			Factor	(W m ⁻²)
(1)	CO ₂			2.116
(2)	CH ₄			1.013
		abundant		0.519
		increase in tropospheric and stratospheric ozone	0.50	0.260
		increase in stratospheric H ₂ O	0.15	0.078
		decrease in sulfate	0.30	0.156
(3)	N ₂ O			0.206
(4)	HC/HFC			0.349

Table 1: RF of anthropogenic WMGHG in 2020

Considering the atmospheric composition of anthropogenic WMGHGs in 2020, CO₂ contributes to global heating by 57%, CH₄ by 28%, N₂O by 6% and Halocarbons (HC) and Hydrofluorocarbons (HCF) by 9%.

⁵ $RF = \beta \times (M^{\frac{1}{2}} - M_0^{\frac{1}{2}}) - [f(M, N_0) - f(M_0, N_0)]$, where $\beta = 0.036$, $M_0 = 722$ ppb, $N_0 = 270$ ppb, and M is global mean atmospheric concentration of CH₄ in 2020, $f(M, N) = 0.47 \times \ln[1 + 2.01 \times 10^{-5} (M \times N)^{0.75} + 5.31 \times 10^{-15} M \times (M \times N)^{1.52}]$

⁶ $RF = \epsilon \times (N^{\frac{1}{2}} - N_0^{\frac{1}{2}}) - [f(M_0, N) - f(M_0, N_0)]$, where $\epsilon = 0.12$, $M_0 = 722$ ppb, $N_0 = 270$ ppb, and N is global mean atmospheric concentration of N₂O in 2020, $f(M, N) = 0.47 \times \ln[1 + 2.01 \times 10^{-5} (M \times N)^{0.75} + 5.31 \times 10^{-15} M \times (M \times N)^{1.52}]$

⁷ Other WMGHGs are mainly chlorofluorocarbons e.g. used as refrigerants, solvents in dry cleaning, propellants in spray cans and blowing agents for expanded plastic products. Production and use has significantly decreased over decades, however, due to their very long lifetime they still play a significant role as forcing agents. Halons were developed for the extinguishing of electrical fires.

⁸ www.esrl.noaa.gov/gmd/aggi/aggi.html

This consideration does not provide answers to the contribution of current emissions to global heating since all gases have different lifetimes in the atmosphere and were emitted to different extents in the past. To overcome this issue the IPCC introduced the concept of Global Warming Potentials (GWP) for different GHGs in relation to CO₂ [6]. The GWPs are calculated as follows:

$$GWP_i(H) = \frac{\int_0^H RF_i(t) dt}{\int_0^H RF_{CO_2}(t) dt}.$$

With this method the effect of a one-time pulse of GHG *i*, leading to *RF_i* is integrated over *H* years and related to the integration of the effect of a one-time pulse of CO₂ leading to *RF_{CO2}* [39].

With GWPs it can be calculated how much more energy a one-time pulse of a certain mass of gas traps in the atmosphere relative to the same mass of CO₂ over a defined period.

Since decays of different isolated GHGs are well known it is straightforward to calculate GWPs for different periods. The IPCC provided some GWPs for random periods as shown in Fig. 2 [7].

	Lifetime (years)		GWP ₂₀	GWP ₁₀₀
CH ₄ ^a	12.4 ^a	No cc fb	84	28
		With cc fb	86	34
HFC-134a	13.4	No cc fb	3710	1300
		With cc fb	3790	1550
CFC-11	45.0	No cc fb	6900	4660
		With cc fb	7020	5350
N ₂ O	121.0 ^a	No cc fb	264	265
		With cc fb	268	298
CF ₄	50,000.0	No cc fb	4880	6630
		With cc fb	4950	7350

Fig. 2: GWPs calculated by IPCC AR5 for H=20 and H=100 ⁹

In all IPCC reports and diagrams for all GHGs and aerosols, the period of 100 years was chosen to calculate the GWP. Most citations and follow-up papers and studies, as well as nearly all press releases and articles, are based on GWPs calculated for a period of 100 years. Even national and supra-national decisions and declarations of intent (e.g. the Paris climate agreement) primarily use GWPs calculated for 100 year periods.

However, there is no single argument to choose a period of 100 years or any other period. The IPCC itself states in its Fifth Assessment Report (AR5) [8]:

“The GWP has become the default metric for transferring emissions of different gases to a common scale; often called ‘CO₂ equivalent emissions’ (e.g., Shine, 2009). It has usually been integrated over 20, 100 or 500 years consistent with Houghton et al. (1990). Note, however that Houghton et al. presented these time horizons as ‘candidates for discussion [that] should not be considered as having any special significance’. The GWP for a time horizon of 100 years was later adopted as a metric to implement the multi-gas approach embedded in the United Nations Framework Convention on Climate Change (UNFCCC) and made operational in the 1997 Kyoto Protocol. The choice of time horizon has a strong effect on the GWP values — and thus also on the calculated contributions of CO₂ equivalent emissions by component, sector or nation. There is no scientific argument for selecting 100 years compared with other choices (Fuglestedt et al., 2003; Shine, 2009).”

⁹ Most studies and reports use GWP₁₀₀ without climate carbon feedbacks (cc fb). Climate carbon feedbacks (warming-induced release of CO₂ from the land biosphere and ocean) inflate the GWPs of non-CO₂ GHGs by about 20% for long-term considerations. Since the focus in this analysis is on instantaneous RF, climate carbon feedbacks are not included in the calculations.

Calculating the total effect of a one-time pulse of GHGs over a certain time horizon may give interesting answers to hypothetical situations, e.g. TCOs¹⁰ for economic views. However, GHGs are emitted constantly, balancing out depletions and decays, or leading to decreasing or increasing concentrations in the atmosphere and resulting in the RF that are observed today.

Therefore, the question to answer is: how much do currently emitted GHGs contribute to current climate heating?

To answer this question, it is best to use directly observed data and apply straightforward calculations, as follows:

(1) The RFs of the human-caused concentrations of GHGs in the atmosphere are known from the calculations above. The focus here and in the following investigations is on the three main gases emitted by animal agriculture and the fossil fuel industries. Other gases such as HCs and HFCs are emitted by manufacturing processes and product use, but emissions have been significantly and steadily reduced in recent decades.

(2) The abundance-based relative importance of each of the three major GHGs is calculated.

(3) The human-caused rise of major GHG levels in the atmosphere are retrieved from NOAA/ESRL, implicitly factoring in depletions and decays.¹¹

(4) The human-caused amount of GHGs being in the atmosphere at present is calculated.¹²

(5) The RFs for unit masses of GHGs are calculated.

(6) The instantaneous GWP_{ins}, being effective in the present and not being stretched over a period is calculated.¹³

(7) The annually emitted amounts of GHGs are retrieved from the 2019 IPCC report [9].

(8) The annual contribution of each GHG to the overall RF is calculated.¹⁴

(9) The emission-based relative importance of each of the three major GHGs is calculated.

¹⁰ Total Cost of Ownership: financial estimate to determine the direct and indirect costs of a product or system

¹¹ Data is retrieved from <https://www.esrl.noaa.gov/gmd/ccgg/trends>; another data hub is <https://gaw.kishou.go.jp>

¹² The total mean mass of the atmosphere m_{atmos} without water vapour is 5.1352×10^{18} kg [34]. Abundance increases (ABI) are given in table 2, No. 3. Molar masses M of all gasses are calculated from standard atomic masses. The average molar mass of air (M_{air}) in the atmosphere is 28.9656 g mol_{air}⁻¹ (4 d.p.) [35]. The total mass increases of CH₄, CO₂ and N₂O in the atmosphere are calculated as follows: $m_{GHG_{1750-2020}} = m_{atmos} \times ABI_{GHG} \times M_{GHG} \times M_{air}^{-1}$.

¹³ $GWP_{CH_4} = (RF_{CH_4} \text{ Gt}^{-1}) \times (RF_{CO_2} \text{ Gt}^{-1})^{-1}$, $GWP_{N_2O} = (RF_{N_2O} \text{ Gt}^{-1}) \times (RF_{CO_2} \text{ Gt}^{-1})^{-1}$

¹⁴ (Emissions (Gt) Yr⁻¹) × (RF (W m⁻²) Gt⁻¹)

No.	Value/Calculation	GHG	CH ₄	CO ₂	N ₂ O
(1)	RF (W m ⁻²)		1.013	2.116	0.2061
(2)	Share		30%	64%	6%
(3)	Rise (ppm)		1.155	134.9	0.0632
(4)	Amount (Gt)		3.285	1053	0.493
(5)	RF ((W m ⁻²) Gt ⁻¹)		0.3083	0.002011	0.4180
(6)	GWP _{ins}		153.3	1	207.9
(7)	Emissions (Gt Yr ⁻¹)		0.362	39.1	0.0106
(8)	Annual Contr. to ERF (W m ⁻²)		0.1116	0.07862	0.004431
(9)	Share		57.3%	40.4%	2.3%

Table 2: Interim results of annual contributions of major GHGs to RF in 2020 (4 s.f.)

Interim results (1):

- Ref. (No. 2) and (No. 9): Considering the yearly emitted amount of methane rather than its current abundance in the atmosphere almost doubles its significance as a GHG. This is a result of its short lifetime of about 12.4 years. The significance of CO₂ drops by a third and that of N₂O by two thirds which can be explained by the long lifetimes of > 200 and 121 years respectively. The contributions of very long-lived GHGs like HCs and HCFs to current emission-based RF are very low due to low and declining emissions. Their contributions to current abundance-based RF are mostly caused by past emissions.
- Ref. (No. 6): The GWP of methane used by IPCC, throughout scientific world and media is 28 on a 100 year time horizon. Without integration over time, however, the instantaneous GWP_{ins} of methane is 153. It emerges that it is higher than the initial GWP₀ of ~120 according to models used by the IPCC. This is due to the findings of Shindell et al., that a rise in global methane emissions showed decreases in sulphate particles, playing a crucial role in the depletion of methane [5].

With the above calculations certain GWP_{ins} of CH₄ and N₂O relative to CO₂ are obtained. With the method used, however, current Radiative Efficiencies per unit mass increase (RE/M)¹⁵ due to current band saturations¹⁶ in the atmosphere were not taken into account. Instead, REs averaged over concentration changes between the years 1750 and 2020 were put into relation.

To determine the GWP_{ins} for current GHG saturation levels recent RF changes must be put in relation to recent abundance changes.¹⁷

(1) The atmospheric concentrations (AC) of all GHGs are retrieved from NOAA/ESRL.

(2) All RFs are calculated (see footnotes 4,5,6).

(3) The respective molar masses M are known.

¹⁵ RE/M is the radiative forcing per unit mass increase (where M is the molar mass of the agent) in atmospheric abundance of a defined forcing agent [10].

¹⁶ RE/M decrease with increased band saturations of defined forcing agent. This is reflected in the models to calculate RFs (see footnotes 4,5,6).

¹⁷ In order to balance out inaccuracies in annual concentrations a period of 10 years was chosen to average the values.

(4) The Radiative Efficiencies per molar mass increase averaged over the period 1750 – 2020 are calculated,

$$RE/M_{[GHG]270} = ((RF_{2020} - RF_{1750}) \times (AC_{2020} - AC_{1750})^{-1}) \times M_{GHG}^{-1},$$

and following the GWP_{ins} of CH₄ as its RE/M in relation to that of CO₂. The GWP_{ins} of N₂O is to be calculated differently in order to consider CH₄ reductions in the atmosphere due to increased N₂O abundance [4]. The RE/M_{N2O} is to be corrected by the following expression:

$$1 - 0.36 \times ((RF_{2020} - RF_{1750}) \times (AC_{2020} - AC_{1750})^{-1})_{N2O}^{-1}.$$

(5) The Radiative Efficiencies per molar mass increase averaged over the period 2010 – 2020 are calculated,

$$RE/M_{[GHG]10} = ((RF_{2020} - RF_{2010}) \times (AC_{2020} - AC_{2010})^{-1}) \times M_{GHG}^{-1}$$

and following the GWP_{ins} of CH₄ as its RE/M in relation to that of CO₂. The GWP_{ins} of N₂O is to be calculated differently in order to consider CH₄ reductions in the atmosphere due to increased N₂O abundance [4]. The RE/M_{N2O} is to be corrected by the following expression:

$$1 - 0.36 \times ((RF_{2020} - RF_{2010}) \times (AC_{2020} - AC_{2010})^{-1})_{N2O}^{-1}.$$

(6) The changes in the Radiative Efficiencies per molar mass increase between the averages of the period 2010 – 2020 to the averages of the period 1750 – 2020 are calculated.

No.	GHG Value/Calculation	CH ₄		CO ₂		N ₂ O	
		Value	Unit	Value	Unit	Value	Unit
(1)	Abundance (AB) in 1750	0.722	ppm	278.0	ppm	0.2700	ppm
	Abundance (AB) in 2010	1.799	ppm	388.6	ppm	0.3231	ppm
	Abundance in 2020	1.877	ppm	412.9	ppm	0.3332	ppm
(2)	RF in 1750	0	W m ⁻²	0	W m ⁻²	0	W m ⁻²
	RF in 2010	0.9569	W m ⁻²	1.792	W m ⁻²	0.1746	W m ⁻²
	RF in 2020	1.013	W m ⁻²	2.116	W m ⁻²	0.2061	W m ⁻²
(3)	Molar mass	16.04	g mol ⁻¹	44.009	g mol ⁻¹	44.01	g mol ⁻¹
(4)	RE/M 1750-2020	0.05465	((W m ⁻² ppm ⁻¹) / (g mol ⁻¹) ⁻¹)	0.0003565	((W m ⁻² ppm ⁻¹) / (g mol ⁻¹) ⁻¹)	0.07411	((W m ⁻² ppm ⁻¹) / (g mol ⁻¹) ⁻¹)
	GWP _{ins} (1750-2020)	153.3		1		187.8	
(5)	RE/M 2010-2020	0.04444	((W m ⁻² ppm ⁻¹) / (g mol ⁻¹) ⁻¹)	0.0003034	(W m ⁻² ppm ⁻¹) / (g mol ⁻¹)	0.07091	((W m ⁻² ppm ⁻¹) / (g mol ⁻¹) ⁻¹)
	GWP _{ins} (2010-2020)	146.4		1		214.5	
(6)	RE/M change	-19%		-15%		-4%	

Table 3: Calculation of GWP_{ins} for CH₄ and N₂O using Radiative Efficiency per molar mass increase (RE/M) averaged over the last 10 years

Interim results (2):

- Compared to the first calculation method, the GWP_{ins} of CH₄ and N₂O change slightly:
 - the GWP_{ins} of CH₄ drops to about 146 from 153

- the GWP_{ins} of N_2O increases to 214 from 188.
- The reasons for the changes in the GWPs are the different REs in the different periods and the integration of indirect effects for N_2O :
 - The RE of CH_4 (period 2010 – 2020 vs. period 1750 – 2020) drops more than that of CO_2 (19% vs. 15%). This is because of a higher saturation effect of CH_4 compared to that of CO_2 .
 - The RE of N_2O (period 2010 – 2020 vs. period 1750 – 2020) drops less than that of CO_2 (4% vs. 15%). This is because of a lower saturation effect of N_2O compared to that of CO_2 .
 - Increased N_2O abundance lead to a reduction of CH_4 in the atmosphere (-36 molecules per +100 molecules N_2O) [4].

The GWP_{ins} (146.4) for the period 2010 – 2020 are used in all following calculations.

3.2. Aerosol cooling

In addition to heat-trapping gases, other anthropogenic emissions can impact the climate by scattering and absorbing shortwave and longwave radiation and/or by enforcing cloud albedo. These aerosols almost entirely originate from fuel combustion and biomass burning and thus are strongly related to fossil- and biofuel-caused CO_2 emissions.

Radiative forcing of aerosols can be caused by

- aerosol–radiation interaction (ARI), also denoted as direct aerosol effect
- aerosol–cloud interaction (ACI), also denoted as cloud albedo effect

As indicated in Fig. 1, in 2011 atmospheric composition of aerosols both ARI and ACI had cooling effects of 0.45 W m^{-2} each. Analog to GHGs above, these figures represent the effect of all human-caused emissions since 1750, but not the effect due to emissions.

Unlike the major GHGs, there are no data of averaged global atmospheric concentrations of aerosols¹⁸, so that it is not possible to calculate instantaneous GWPs as done above. The best available data are 2011 model-based GWPs of the five major aerosols for one-time pulses and radiative forcing periods of 10 years [11], the following calculations can be done:

(1) There are estimates of the yearly emissions of major aerosols [12].

(2.1) There are estimates of GWPs over 10 years [11]. These only relate to ARI, not to ACI.

(2.2) The $RF \text{ Gt}^{-1}$ for each aerosol (ARI), using the $RF \text{ Gt}^{-1}$ of CO_2 ($0.002012 \text{ W m}^{-2}$) as determined in table 2 is calculated.

(2.3) The annual contribution of each aerosol to ERF is calculated and summed up to get the total ARI. The ACI can be calculated using factor 1.125 [13].

(3.1, 3.2, 3.3) The same can be calculated for GWPs over 100 years.

¹⁸ Aerosols are only strongly emitted at hotspots and are very short-lived, so that they do not mix uniformly in the atmosphere. It is therefore difficult to measure them and determine mean values.

No.	Aerosol	Black Carbon (BC)	Organic Carbon (OC)	SO ₂ (H ₂ SO ₄)	NO _x	CO	Total (ARI)	Total (ARI&ACI)
	Value/Calculation							
(1)	Emissions (Gt Yr ⁻¹)	0.005310	0.01360	0.1270	0.03720	0.8930		
(2.1)	GWP ₁₀	4349	-438.5	-253.5	134.2	8.600		
(2.2)	RF ₁₀ ((W m ⁻²) Gt ⁻¹)	8.751	-0.8823	-0.5101	0.2700	0.01730		
(2.3)	RF ₁₀ (W m ⁻²)	0.04647	-0.01200	-0.06478	0.01004	0.01545	-0.004813	-0.01023
(3.1)	GWP ₁₀₀	658.6	-66.4	-38.4	-10.8	1.9		
(3.2)	RF ₁₀₀ ((W m ⁻²) Gt ⁻¹)	1.325	-0.1336	-0.07726	-0.02173	0.003823		
(3.3)	RF ₁₀₀ (W m ⁻²)	0.007037	-0.001817	-0.00981	-0.0008084	0.003414	-0.001987	-0.004223
(4)	Lifetimes (years)	0.01923	0.0001142	1.5	0.0004338	0.3333		

Table 4: Calculation of the 2011 annual contributions of major aerosols to ERF based on GWP₁₀ (4 s.f.)

Interim results:

- Unlike the significant cooling effect of 0.9 W m⁻² (ARI & ACI combined), representing a 31% cooling to the RF of the three main atmospheric GHGs CH₄, CO₂ and N₂O in 2011¹⁹, the effect with perspective to emitted GHGs seems to be much smaller. If ARI & ACI with GWP₁₀ are put into relation with the RF contributions of emitted GHGs in 2011, they only lead to a cooling of about 5%²⁰. There are at least two explanations:
 - First, this relation cannot really be made since the RF of emitted GHGs and the RF of aerosols integrated over 10 years are not comparable. Data for the RF of currently emitted aerosols are not (yet) available (due to a lack of data for atmospheric concentrations), but as aerosols follow exponential decay, it is possible that their RF would have higher cooling effects.
 - Second, this big discrepancy between the cooling of aerosols existent in the atmosphere and aerosols emitted emerges from the short lifetime of the strongest heating aerosol, Black Carbon (BC), in contrast to the much longer lifetime of the strongest cooling aerosol, SO₂, which decomposes to sulphate (H₂SO₄). It seems that the strong cooling net effects of aerosols are legacies of huge past emissions of SO₂.
- While there is confidence in the overall net cooling effect of aerosols of 0.9 W m⁻² due to atmospheric composition [14], there are high uncertainties regarding emission based aerosol effects. This is because there is no data of globally averaged aerosol concentrations and because of a lack of understanding of highly complex decomposing and feedback processes.
- Even though it is likely that there is significant cooling due to currently emitted aerosols, these effects are not included in the overall calculations due to the high uncertainties on their magnitudes. If this were done, however, the impact of fossil-fuel-based industries on climate heating would be further weakened because of their role as the major cause for all aerosols.

¹⁹ By using factor 1.95 as calculated in 3.1, indirect effects of CH₄ lead to a 2011 RF of 0.936 W m⁻². Therefore the calculation is (-0.9 W m⁻²) / (2.926 W m⁻²).

²⁰ The calculation is: (-0.01023 W m⁻²) / (0.1116 W m⁻² + 0.07867 W m⁻² + 0.004434 W m⁻²).

3.3. Heating potentials of fossil fuels considering GWP_{ins} of methane

Significant amounts of CH₄ are emitted from all major fossil fuel energy sources. CH₄ is released through exploitation, processing, transport and combustion of coal, oil and gas. While reasons (fugitive and vented emissions and emissions resulting from incomplete combustion, i.e. flaring) vary heavily among energy sources and the amount of energy production per energy source is different, overall methane emitted by coal, oil and gas is almost shared equally.

Using data on energy extracted by coal, oil and gas mining, data on emissions and the GWP_{ins} of methane, the rise in heating potentials of fossil fuels compared to the prevalent assumptions can be determined:

(1) The global energy production²¹ in terms of TPES²² (overall production excluding stock changes and bunkers) can be retrieved International Energy Agency using the energy balance from 2017 [32].²³

(2) The GWP₁₀₀ as used by IPCC is 28, the GWP_{ins} as calculated in chapter 3.1 is about 146.

(3) The methane emissions of coal, oil and gas is estimated to be about 40 Mt each [32].

(4) The CO₂eq of the methane emissions is calculated.

(5) The CO₂ emissions by energy source can be retrieved from International Energy Agency [32].

(6) The total CO₂eq emissions is calculated per energy source.

(7) The climate effective emissions per energy unit is calculated

- for considerations with a GWP of methane being stretched over 100 years

- for considerations with an instantaneous GWP of methane.

(8) Based on the results of No. (7), it can be determined how the consideration of methane with GWP_{ins} increases the emissions of CO₂eq per energy unit in contrast to when GWP₁₀₀ is applied.

(9) Based on the results of No. (7), the output of coal and gas emissions per unit of energy can be put in relation to that of oil emissions (aerosol cooling effects are not considered here).

²¹ Energy production is the used term in the energy balances of the fossil fuel mining industry and refers to the energy contained in oil, coal and gas extracted from the ground.

²² TPES: Total Primary Energy Supply

²³ It is to be noted that this is the energy supply of each source and not the energy consumption. Energy consumption is much lower due to energy losses along the exploitation chain and different energy efficiencies (e.g. power plants, combustion engines).

No.	Energy Source Category	Coal		Oil		Gas	
		GWP ₁₀₀	GWP _{ins}	GWP ₁₀₀	GWP _{ins}	GWP ₁₀₀	GWP _{ins}
(1)	Energy production (PWh)	44.1		51.7		36.1	
(2)	GWP	GWP ₁₀₀	GWP _{ins}	GWP ₁₀₀	GWP _{ins}	GWP ₁₀₀	GWP _{ins}
(3)	Emissions ((Gt CH ₄) yr ⁻¹)	0.04	0.04	0.04	0.04	0.04	0.04
(4)	Emissions ((Gt CO ₂ eq) yr ⁻¹)	1.12	5.86	1.11	5.80	1.11	5.80
(5)	Emissions ((Gt CO ₂) yr ⁻¹)	14.5	14.5	11.4	11.4	6.74	6.74
(6)	TOTAL (CH ₄ + CO ₂)	15.6	20.4	12.5	17.2	7.85	12.5
(7)	Gt CO ₂ eq (PWh (kg kWh ⁻¹)) ⁻¹	0.354	0.462	0.241	0.332	0.217	0.347
(8)	Rise in heating potential		30%		38%		60%
(9)	GHG efficiency relative to oil	1.47	1.39	1	1	0.90	1.05

Table 5: Calculation of relative climate heating potentials of the major fossil fuel sources (3 s.f.)

Interim results:

- CO₂eq emissions per energy unit is by far worst for coal in all scenarios. Using GWP_{ins} in the calculations reveals that the ratio is best for oil with 332 g Wh⁻¹. This is different to previous assumptions, where gas is seen to be most GHG efficient.
- Using GWP_{ins} for methane increases the heating potentials for coal by 30%, for oil by 38% and for gas by 60%. The different increases occur because the total amount of CO₂ emissions are highest for coal, followed by oil, and are lowest for gas.
- Previous assumptions are, that the combustion of gas is about 20% more GHG efficient than oil and about 40% compared to coal [32]. Applying GWP_{ins} shows, that gas is about 5% less GHG efficient than oil.

3.4. Opportunity costs for unused carbon sinks

Almost all studies, including all IPCC reports consider land use by animal agriculture as a given and constant fact. If at all, land use is only taken into account regarding changes compared to former years. It is scientific consensus that food production through animals requires multiples of resources compared to plant-based alternatives and thus is highly inefficient. Around 83% of agricultural land is used for meat, aquaculture, eggs and dairy (animal feed and grazing) but it provides only 18% of food calories and 37% of protein for human consumption [15]. Plant-based nutrition is both healthiest and least contributory to climate heating [16]. Animal products are not necessary for human nutrition and health. On the contrary, they are causes for certain health conditions, including ischemic heart disease, type 2 diabetes, hypertension, certain types of cancer and obesity [17]. Therefore, land used for animal agriculture could be freed extensively. Without needless animal agriculture global farmland use could be reduced by more than 76% [15].

Land used for animal agriculture then represents opportunity costs, i.e. costs for unused alternatives, e.g. for carbon sinks.

The opportunity costs (in terms of CO₂ emissions per year) for unused carbon sinks of the current agriculture system vs. a plant-based system can be determined as follows:

- (1) The global agricultural land can be retrieved from FAO [18].
- (2) The area of land used for animal agriculture is about 83% of the overall agricultural land [15].
- (3) The area of land freed up by eliminating animal agriculture and switching to a fully plant-based food system is 76% of the land used for animal agriculture [15].
- (4) The area of land that can be reforested²⁴ and the total sequestration potential per year can be calculated [19],[20].²⁵
- (5) The difference between No. 3 and No. 4 is the area of land that can turn back into grassland. The sequestration potential of grassland per square meter per year [21],[22]²⁶ and the overall sequestration potential of grasslands can be calculated.

Finally the total sequestration potential per year is calculated.

No.	(Potential) land use	Area	Sequestration Potential / m ²	Sequestration Potential
		M km ²	(CO ₂ (kg m ⁻²)) yr ⁻¹	(CO ₂ (Gt)) yr ⁻¹
(1)	Agricultural land	51.00		
(2)	Land use for animal agriculture	42.33		
(3)	Land freed up with plant-based food system	32.17		
(4)	thereof qualified for forests	2.848	1.493	4.252
(5)	thereof qualified for grasslands	29.32	0.2455	7.199
Total sequestration potential				11.45

Table 6: Calculation of annual opportunity costs in terms of CO₂ emissions per year for unused carbon sinks of the current agriculture system vs. a fully plant-based system (4 s.f.)

Interim results:

- Animal products for human consumption are not necessary. On the contrary, their production and intake have huge disadvantages for the environment, human health and animal wellbeing. Even though the environmental damage goes far beyond GHGs, only the opportunity costs in terms of missed CO₂ sinks are explored here.
Switching to a plant-based food system releases an area of more than 32 million square kilometres. A smaller part can be reforested and a bigger part can transform back to grassland.
- The result of about 11.45 Gt CO₂ calculated here as sequestration potential is close to the result obtained by a different calculation method used by Goodland and Anhang of the Worldwatch Institute in 2009 [23]. In their study they summed up CO₂ exhaled by grazing livestock (8.8 Gt CO₂) and the CO₂ sinks missed due to land use for grazing and feeding (2.7 Gt CO₂). The argumentation of the FAO that respiration by livestock is offset by photosynthesis is true,

²⁴ According to Bronsen et al., a total of 6.78 M km² of land could be reforested of which to date 42% is grazing land.

²⁵ According to Bronsen et al., a total of 10.124 (Gt CO₂) yr⁻¹ could be sequestered by reforested land, of which to date 42% is grazing land.

²⁶ According to Michael Abberton et al., and Janssens, I. A. et al., the mean grassland sequestration for carbon is 67 (g m⁻²) y⁻¹, so that the CO₂ sequestration potential is: 0.067 (kg m⁻²) y⁻¹ × 44.01 g mol⁻¹ × (12.01 g mol⁻¹)⁻¹.

however respiration accounts for net opportunity costs, since without livestock CO₂ sequestered by photosynthesis is permanently stored in the soil.

- According to Hayek et al. (2020) the carbon opportunity costs of animal-sourced food production on land over 30 years are 332–547 Gt CO₂ which is equivalent to 11.1-18.2 Gt CO₂ per year [40].

3.5. Deforestation

Animal agriculture requires the vast majority of agricultural land. In order to balance crop failures caused by climate change, soil degradation and biodiversity loss, and to increase the production of animal products, further land is needed every year and made available by deforestation.

Deforestation for animal agriculture is often mentioned in IPCC reports or in studies by the Food and Agriculture Organization (FAO), but is usually not fully taken into account or imprecisely assigned (see appendix).

The CO₂ emitted per year by burning forests for animal agriculture is calculated as follows:

(1) The total CO₂ emission reduction potential resulting from ending deforestation can be retrieved from the IPCC Special Report on climate change [24].

(2) The portion for commercial crop production for animal agriculture is calculated [25], [26].²⁷

(3) The portion for commercial cattle ranching can be retrieved from The UNFCCC [26].

(4) The portion for small scale animal agriculture is calculated [15], [26].²⁸

Finally the total annual CO₂ emission reduction potential achievable by stopping deforestation for animal agriculture is calculated.

No.	Deforestation	Portion	(CO ₂ (Gt)) yr ⁻¹
(1)	Overall reduction potential from ending deforestation		5.20
(2)	therof with commercial crops for livestock	6.60%	0.343
(3)	therof with commercial cattle ranching	12.0%	0.624
(4)	therof with small scale animal agriculture	34.9%	1.81
Reduction potential from ending deforestation for animal agriculture		53.5%	2.78

Table 7: Calculation of annual CO₂ emissions from deforestation for animal agriculture (3 s.f.)

²⁷ According to UNFCCC United Nations Framework Convention on Climate Change, 2007, about 20% of all deforestation is due to commercial crop production. According to United Nations Food and Agricultural Organization, 2006, about 33% of overall crop production is for livestock feed. Therefore, it was projected that commercial crop production for animal agriculture accounts for at least 6.6% of deforestation.

²⁸ According to UNFCCC United Nations Framework Convention on Climate Change, 2007, about 42% of all deforestation is due to small scale agriculture. According to Poore et al., 2018, about 83% of overall agricultural land is for animal agriculture. Therefore, it was projected that small scale agriculture (animal feed and grazing land) accounts for about 34.9% of deforestation.

Interim results:

- According to the World Bank, at the average global forests have decreased by 0.051 M km² per year over the last 30 years [27]. The major cause for deforestation has been and is animal agriculture. More than half of global deforestation is for additional grazing land and land to grow additional animal feed.²⁹
- Annually about 2.8 Gt of CO₂ is released to the atmosphere due to deforestation for animal agriculture. This number is a little bit higher than the 2.4 Gt CO₂ as calculated by the 2006 study from FAO [28]. A reason might be that FAO excluded Argentina because of lack of data.

3.6. Capture fisheries and aquaculture

In some studies and reports only livestock is considered for the GHG emissions in animal agriculture (see appendix). However, 39% of meat production today comes from the fishing industry. In 2015 meat from livestock accounted for 324 M tons and seafood production for 210 M tons. Aquaculture has been growing exponentially from 2 M tons in 1960 to 106 M tons in 2015, now being even bigger than capture fisheries (94 M tons) [18].

Similar to land animals, marine animals exhale CO₂ and produce excretions becoming GHG effective. CO₂ and GHG effective excretions produced by wild marine animals originate from ocean plant intake (mostly algae) at the very beginning of the food chain and thus are CO₂ neutral. As for aquaculture, however, a certain portion produced by animals comes from cultivated plants (wheat, soybean, maize, rapeseed oil, palm oil). These CO₂ and GHG effective excretions are GHG net sources and need to be attributed to animal agriculture. An alternate way to determine these GHGs is to calculate the carbon sinks of the land needed for plant-based aqua feed. This is (at least partially) considered in the factor of 0.83 used in 3.4; No. 2, representing the portion of land used for animal agriculture. About 5 percentage points of this factor can be attributed to aquaculture.³⁰

Aquafeed consists of fish meal, fish oil and plants, with the proportion of vegetable aquafeed estimated at 30-70% [29]. The estimates are rough and of wide range, but seem to be considerably higher than those included in the calculations.

It is worth mentioning that due to high costs of animal aquafeed and ocean overfishing a shift to plant-based aquafeed is currently taking place.

As for marine animals it might be that their withdrawal and consumption are not CO₂ neutral since without such withdrawal dead ocean plants and dead marine animals would sink to the bottom of the sea and such carbon would be permanently removed from the carbon cycle. Since this vague assumption is not backed by any reliable data and studies, such CO₂ is not included in the calculations of this analysis.

²⁹ Deforestation for growing crops for aquaculture feed is not included in the calculations due to lack of reliable data. In the approximate calculations these CO₂ emissions are relatively low.

³⁰ According to Poore, J., Nemecek, T., 2018, livestock and aquaculture requires 83% of agricultural land [15], while according to United Nations Food and Agricultural Organization, 2006, livestock alone requires 78 % of agricultural land [36].

3.7. Pre-production, processing and post-production

Some studies and reports include GHG emissions from pre-production, processing and post production of products. This would require a Life-Cycle-Analysis (LCA) of all products of all sectors. Although some estimates are available for some industries³¹ due to high uncertainties and in order to be consistent across all sectors such data is not included in the calculations of this analysis.

³¹ LCA for agricultural products would include energy (e.g., grain drying, heating in greenhouses), transport (e.g., international trade), industry (e.g., synthesis of inorganic fertilisers, manufacturing of farm inputs) and post-production (e.g., agri-food processing). Pre- to post-production for the whole agricultural sector (excluding fishery) is estimated at 2.6-5.2 Gt CO₂ [9]. Specific data for animal agriculture is not available. A conservative LCA for aquaculture results in 0.36 Gt CO₂ (with footprints of capture fishery: (1t CO₂) x (1t fish)⁻¹, aquaculture: (2.5t CO₂) x (1 t fish)⁻¹ [30].

4. Results

4.1. Today's methane emissions have more immediate significance than today's CO₂ emissions

While the long lived GHG CO₂ has the potential to trap much energy over a long period of time, its immediate effect is much smaller than that of CH₄. To tackle climate heating it is necessary to focus on the reduction of those GHGs that have the most impact. The instantaneous climate heating effect of CH₄ in combination with its current amount of emission makes CH₄ the GHG of most significance. In other words, cutting CH₄ emissions has more impact than cutting CO₂ emissions.

The heating effect of GHGs currently in the atmosphere is depicted in Fig. 3 (a.) The relatively high importance of CO₂ is due to its accumulation over centuries and its long lifetime. The importance of CO₂ as GHG increases heavily in calculations of IPCC when current emissions and GWPs stretched over 100 years are considered (Fig. 3 (b.)). Taking into account that emitted GHGs are effective instantaneously reverses the picture and shows that CH₄ is indeed the most significant GHG. (Fig. 3 (c.)).

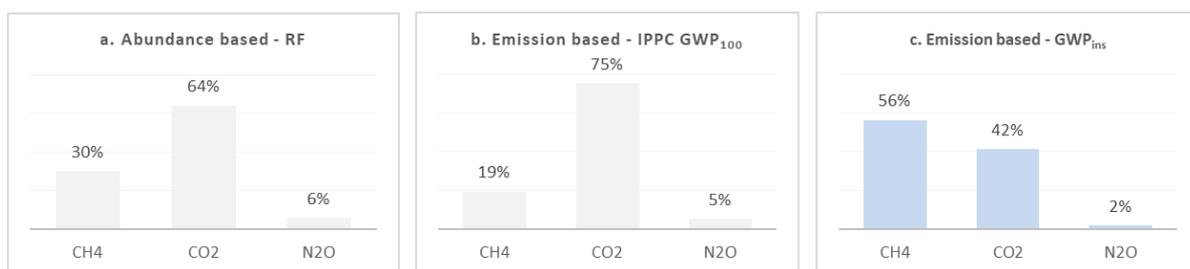


Fig. 3: Relative significance of GHGs, for the current composition of the atmosphere and the RFs (a.), for a one-time pulse and stretching over 100 years (b.) and for the current emissions and immediate heating effects (c.)

4.2. Animal agriculture is the biggest cause of global warming

In chapter 3 the instantaneous GWPs of methane and N₂O, the aerosol cooling, unused potential carbon sinks and often imprecisely allocated major sources of CO₂ were investigated. In the following final calculation only the findings with very strong data basis and high certainty of accuracy are integrated. Thus, aerosol cooling effects, not precisely known net CO₂ emissions of fisheries, CO₂ emissions from pre-production, processing and post production of products and CO₂ emissions originated by animal husbandry caused diseases are not included (see appendix).

The final calculation is as follows:

(1) The annually emitted amounts of GHGs are retrieved from the IPCC [9]³². Unused carbon sinks as calculated in chapter 3.4 are to be added as opportunity costs of animal agriculture. The ascertained total amount of CO₂ is therefore partly not emitted physically but is partly not sequestered from the atmosphere which has the same effect as emissions. Unsequestered carbon from avoidable animal agriculture contributes to the greenhouse effect, so it must be considered as part of the total emissions to which the sectors' emissions are eventually related. For simplicity

³² Average for each gas for 2007–2016; estimates are only given until 2016 as this is the latest date when comparable data are available for all gases

reasons in the following it is not further differentiated between the physical and not sequestered parts. They are called 'emissions' altogether.

(2) The immediate GWPs of all GHGs are taken from the calculations in chapter 3.1.

(3) The CO₂eq of each GHG are calculated.

(3.1) Animal agriculture accounts for 33% of global methane emissions [18] and 65% of global N₂O emissions [33]. Unused carbon sinks have been about 11.4 Gt CO₂ and animal agriculture caused deforestation emitted about 2.8 Gt CO₂ as calculated in chapters 3.4 and 3.5 respectively.³³

(3.2) The focus here is on the major fossil fuel (FF) consuming sectors, which are the energy sector³⁴ and the transportation sector³⁵. In total, fossil fuel combustion annually releases about 119 Mt CH₄ (17.4 Gt CO₂eq) through coal, oil, gas exploitation, processing and transport. Each energy source emits about one third of fossil-fuel-caused CH₄ (see chapter 3.3).

CH₄ emissions in the energy sector are determined by the TPES values 'Electricity plants', 'CHP plants' and 'Heat plants'³⁶ of the 2017 energy balance of the IEA³⁷ [32]. CH₄ emissions of the transportation sector are determined by the TPES values 'Transport'. CH₄ emissions of other sectors are determined by the remaining TPES values.

The CO₂ emissions per sector and the portions of coal, oil and gas in the energy sector are retrieved from the IEA [32].

The portions of N₂O emissions per sector are calculated according to the World Resources Institute [37]. N₂O emissions per energy source are not known (NK).

(3.3) Apart from animal agriculture (AA) and fossil-fuel-based (FF) industries, waste and cultivation of rice produce make up considerable portions of GHGs. This is due to their high emissions of methane. Waste accounts for about 9% [31] and rice cultivation for about 4% [18] of the considered total GHG emissions.

Other sectors comprise housing, industry, forestry, bio-fuels and plant-based agriculture. They make up the rest and account for about 9% of the totals.

³³ Fossil fuel based CO₂ emissions for livestock farming have been about 0.3 Gt in 2015 [32]. However, to be consistent they are not included here since only industry specific emissions across the sectors are considered.

³⁴ Electricity and external heat production (not residential heat)

³⁵ All means of transportation, incl. cars, busses, aircrafts, ships, trucks, etc.

³⁶ CHP: combined heat and power

³⁷ International Energy Agency

No.	GHG Category	CH ₄		CO ₂		N ₂ O		TOTAL	
		abs.	%	abs.	%	abs.	%	abs.	%
(1)	Emissions (Gt yr ⁻¹)	0.362		50.6		0.0106		n/a	n/a
(2)	GWP	146		1		214		n/a	n/a
(3)	Emissions ((Gt CO ₂ eq) yr ⁻¹)	53.0	100%	50.6	100%	2.27	100%	106	100%
(3.1)	Animal agriculture (AA)	17.4	32.8%	14.2	28.2%	1.48	65.0%	33.1	31%
(3.2)	Energy (FF)	7.1	13.3%	13.5	26.6%	0.081	3.6%	20.6	19%
	by coal	4.10	8%	9.8	19%	< 0.05	NK	13.9	13%
	by oil	0.31	1%	0.72	1%	< 0.05	NK	1.03	1%
	by gas	2.65	5%	2.98	6%	< 0.05	NK	5.62	5%
	Transport (FF)	3.78	7.1%	8.04	15.9%	0.0537	2.4%	11.9	11%
	Others (FF)	6.61	12.5%	11.35	22.5%	0.0788	3.5%	18.0	17%
(3.3)	Others (non AA, non FF)	18.2	34.3%	3.48	6.9%	0.582	25.6%	22.2	21%

Table 8: Determination of most harmful industries to climate heating (3 s.f.)

- Due to the high instantaneous GWP of methane, all industries that emit large amounts thereof are more important causes of climate heating than previously thought. Animal agriculture and fossil-fuel-combusting industries are by far the leading causes of methane emissions.
- Overall, animal agriculture contributes most to global warming, with a share of 31%, followed by the fossil-fuel-based energy sector with 19%. Fossil-fuel-based transportation (cars, buses, trucks, airplanes, trains, ships, etc.) is less harmful than formerly assumed. Apart from animal agriculture and fossil fuel based energy and transport, waste and the cultivation of rice are significant climate heating causes.
- It is important to note that fossil-fuel-based industries most likely have significantly lower impact on climate heating due to combustion caused aerosol cooling effects (see chapter 3.2), weighing other sectors higher. Further data gathering and research is necessary to determine aerosol concentrations in the atmosphere and determine global aerosol cooling effects.

5. Conclusions

In the course of the reassessment of the global warming potential of methane, all industries that emit large amounts thereof are found to be more important causes of climate heating than previously thought. Most methane emitting anthropogenic sources are:

- Animal agriculture: 33%
- Waste: 18%
- Fossil-fuel-based energy: 13%
- Fossil-fuel-based transportation: 7%
- Rice cultivation: 7 %

Additionally, as shown, animal agriculture becomes more damaging due to CO₂ emissions that are often not considered.

Putting all these factors together, animal agriculture doubles its relative contribution to climate change compared to previously assumed portions, while the contribution of fossil-fuel-based energy production more than halves as a proportion of the whole.

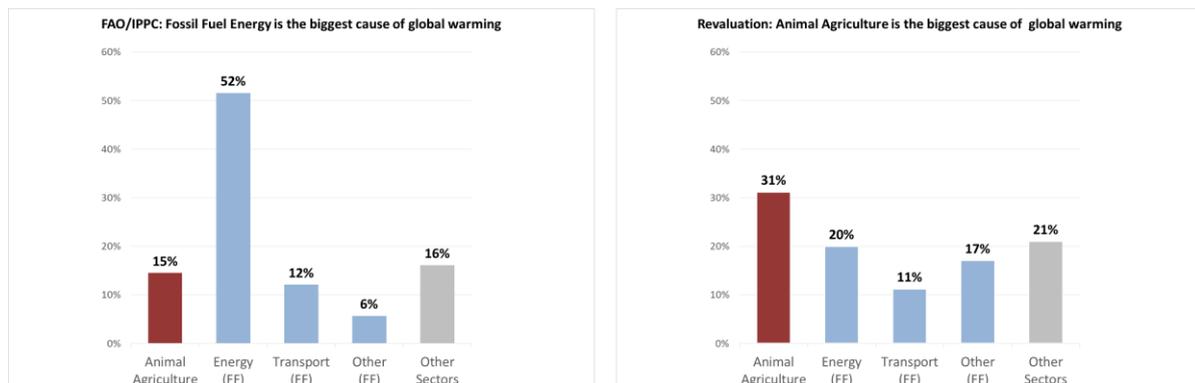


Fig. 4: Previously assumed major causes of global warming vs. actual major causes after revaluation

Strategies to mitigate climate heating should focus on the main drivers. The findings show that these are first animal agriculture, second fossil-fuel-based energy production and third fossil fuel based transportation. Since alternatives are available for all of them (plant-based nutrition, renewable energies, electrified vehicles and public transportation), politics should strongly support transitions and eventually even prohibit existing practices.

In particular, emphasis must be placed on the massive reduction of livestock and fisheries and the transition to a plant-based food system.

6. Discussion

Based on the results of this analysis, a reorientation of climate politics, the climate movement and the behaviour of each individual seems appropriate.

In particular:

- The IPCC should adjust the Global Warming Potential in their models. This necessary step would be the starting point for subsequent changes of data used and provided by private agencies, environmental associations, policy consultancies and official authorities.
- The greater importance of methane should lead to changes in the support and subsidisation of the methane emitting industries. Investments and political commitments to gas exploration, transport and combustion should be readjusted. Subsidies for animal agriculture should be massively reduced if not abolished, and the transition to a plant-based food system should be supported by political and economic incentives. Rice should be taxed higher and local alternatives should be fostered.
- The FAO and the IPCC should integrate opportunity costs for unused carbon sinks in their calculations. Moreover, the IPCC should split the agricultural sector in their considerations into plant-based agriculture and animal agriculture and should assign emissions precisely to the emitting subsectors.
- The climate movements should shift the focus away from coal to animal agriculture.
- Individuals should change to a plant-based diet.
- Further research is necessary to refine the models that determine the contributions of different industries to global warming. Such research would include the determination of instantaneous effects of cooling aerosols and the assignment to appropriate industries, the net CO₂ effects of aquaculture, the net CO₂ effects of capture fisheries and – if possible and feasible– the effects of life-cycle contributions of all products across all sectors.

7. Appendix

A) Comparison of different studies/reports on the role of animal agriculture / livestock farming in climate change

Study/Report Category	FAO 2006	World Watch Institute (WWI) 2009	FAO 2013	This Analysis 2021
Aerosol cooling effects	not considered	not considered	not considered	not integrated, more global data gathering and research is needed to determine the immediate effects (GWP ₁₀₀)
Methane emissions in animal agriculture	considered as enteric fermentation & manure management; result: 37 % of global anthropogenic emissions; factor used: GWP ₁₀₀ (23)	considered as enteric fermentation & manure management; result: 37 % of global anthropogenic emissions; factor used: GWP ₂₀ (72)	considered as enteric fermentation & manure management; result: 33 % of global anthropogenic emissions (based on 2007 IPCC data); factor used: GWP ₁₀₀ (25)	considered as enteric fermentation & manure management; result: 32.8 % of global anthropogenic emissions (based on 2017 FAOSTAT data); factor used: GWP ₁₀₀ (146)
Methane emissions in fossil fuel industries	considered as about a third of global anthropogenic emissions; factor used: GWP ₁₀₀ (23)	considered as about a third of global anthropogenic emissions; factor used: GWP ₁₀₀ (25)	considered as about a third of global anthropogenic emissions; factor used: GWP ₁₀₀ (25)	considered as 33% of global anthropogenic emissions; factor used : GWP ₁₀₀ (146)
Missed Carbon Sinks	partly considered as respiration of livestock and calculated (3.16 Gt CO ₂) but not integrated in final results; reason given is the offset by photosynthesis	yes, included as respiration of livestock and land use for grazing and feeding (11.5 Gt CO ₂)	used land for grazing and feeding is not mentioned and not integrated in final results; only average annual land-use changes are considered (0.63 Gt CO ₂)	yes, included as missed areas for afforestation and grassland (11.45 Gt CO ₂) due to livestock feed, livestock grazing and aquafeed
Deforestation	yes (2.4 Gt CO ₂)	yes (< 3 Gt CO ₂)	yes, but reduced to 0.65 Gt CO ₂ compared to the 2006 report; reasons given are different reference periods, the inclusion of only the Soybean expansion in Brazil and Argentina and different IPCC directives	yes (2.78 Gt CO ₂)
Capture fisheries	not considered	not considered	not considered	not integrated, more research is needed on whether net emissions occur and to what extent
Aquaculture	not considered	yes	not considered	partly integrated for aquafeed
Pre-Production, Processing, Post-Production	yes	yes	yes	not included, since - not reliably calculable - if included, not consistent with other industries
Animal husbandry caused diseases (zoonotic endemics/pandemics, infections with antibiotic-resistant bacteria, cardiovascular diseases, diabetes, obesity)	not considered	yes	not considered	not included, since - not reliably calculable - if included, not consistent with other industries
Overall contribution of animal agriculture to GHG emissions	18%	51%	14.5%	31%

Fig. 5: Comparison of different studies on the role of animal agriculture / livestock farming in global warming³⁸

³⁸ It is worth noting that the FAO publicly had started partnering with the International Meat Secretariat and International Dairy Federation in 2012, one year before the 2013 FAO report [38] was published.

B) Calculation of contributions of animal agriculture (AA) and fossil fuel based industries to climate change as assumed by FAO and IPCC (supporting Fig. 4)

CH ₄ in CO ₂ eq					
Gt/yr	10.136				
Sector	AA	Fossil Fuels			Others
		Energy	Transport	Other FF	
Portion	33%	35.56%	0.01%	0.07%	31.36%
Gt/yr	3.345	3.604	0.001014	0.007095	3.179
CO ₂					
Gt/yr	39.1				
Sector	AA	Fossil Fuels			Others
		Energy	Transport	Other FF	
Portion	6.08%	59.06%	16.06%	7.22%	11.58%
Gt/yr	2.377	23.09	6.279	2.823	4.528
N ₂ O in CO ₂ eq					
Gt/yr	2.809				
Sector	AA	Fossil Fuels			Others
		Energy	Transport	Others	
Portion	65%	5.74%	0.52%	4.5%	24.24%
Gt/yr	1.826	0.1612	0.01461	0.1264	0.6809

Fig. 6: Calculation of contributions of animal agriculture and fossil-fuel-based industries to climate change as assumed by FAO and IPCC (supporting Fig. 4)³⁹

³⁹ AA stands for Animal Agriculture; emission data is taken from IPCC SCCRL [9] and portions are directly retrieved from "Global Change Data Lab: Our World in Data", indirectly from data of FAO [31]

8. Acknowledgments

Special thanks goes to the main reviewer Dr. Bernd Böck for his comments on the first version of the manuscript and for further comments on a revised version. These comments were very helpful in the revisions. We would like to thank also further contributors for copy-edits on points of language and style.

9. References

- 1 Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Pp 675-688
- 2 Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis*. P 697 (Fig. 8.15)
- 3 Myhre, G., E. J. Highwood, K. P. Shine, and F. Stordal, 1998: New estimates of radiative forcing due to well mixed greenhouse gases. *Geophys. Res. Lett.*, 25, Pp. 2715–2718.
- 4 Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing Supplementary Material. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Available from www.climatechange2013.org and www.ipcc.ch. P. 8SM-17
- 5 Shindell, D.T., G. Faluvegi, D.M. Koch, G.A. Schmidt, N. Unger, and S.E. Bauer, 2009: Improved attribution of climate forcing to emissions. *Science*, 326, 716-718
- 6 Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing Supplementary Material. In: *Climate Change 2013: The Physical Science Basis*. P. 8SM-14
- 7 Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis*. P 714 (Table 8.7)
- 8 Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis*. P 711
- 9 IPCC, 2019: *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* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press. P 10
- 10 Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing Supplementary Material. In: *Climate Change 2013: The Physical Science Basis*. P. 8SM-14
- 11 Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing Supplementary Material. In: *Climate Change 2013: The Physical Science Basis*. P. 8SM-39 (Table 8.SM.17)
- 12 Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing Supplementary Material. In: *Climate Change 2013: The Physical Science Basis*. P. 8SM-41 (Table 8.SM.19)
- 13 Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing Supplementary Material. In: *Climate Change 2013: The Physical Science Basis*. P. 8SM-42
- 14 Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S.K. Satheesh, S. Sherwood, B. Stevens and X.Y. Zhang, 2013: Clouds and Aerosols. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. P 574
- 15 Poore, J., Nemecek, T., Reducing food's environmental impacts through producers and consumers, *Science*, June 2018, Vol 360, Issue 6392. Pp 987-992
- 16 Clark Michael A. et al., Multiple health and environmental impacts of foods, *PNAS*, Nov 2019, 116 (46) 23357-23362
- 17 Vesanto Melina, Winston Craig, Susan Levin, Position of the Academy of Nutrition and Dietetics: Vegetarian Diets, *Journal of the Academy of Nutrition and Dietetics*, Dec 2016, Volume 116, Issue 12. Pp 1970–1980
- 18 UN Food and Agriculture Organization, FAOSTAT, 2020, Retrieved from www.fao.org/faostat
- 19 Bronson W. Griscom et al., Natural climate solutions, *PNAS*, 2017, 114 (44) 11645-11650. P 4
- 20 Bronson W. Griscom et al., Oct. 2017, SI Appendix, Table S1

- 21** Abberton et al., Grassland carbon sequestration: management, policy, and economics, *Integrated Crop Management*, April 2009, Vol. 11–2010. P 11
- 22** Janssens, I. A. et al., The carbon budget of terrestrial ecosystems at country-scale – a European case study, *Biogeosciences*, 2005, 2. Pp 15–26
- 23** Goodland, R., Anhang, J. M., 2009, *Livestock and Climate Change: What if the key actors in climate change are pigs, chickens and cows*, World Watch, Worldwatch Institute, Washington DC, USA. Pp 10-19
- 24** IPCC, 2019: *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* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press. P 8
- 25** United Nations Food and Agricultural Organization, 2006: *Livestock's Long Shadow, Environmental Issues and Options*. Chief, Electronic Publishing Policy and Support Branch, Communication Division – FAO, Viale delle Terme di Caracalla, 00153 Rome, Italy. P xxi
- 26** UNFCCC United Nations Framework Convention on Climate Change, 2007, *Investment And Financial Flows To Address Climate Change*, Information Services of the UNFCCC secretariat, ISBN 92-9219-042-3. P 81
- 27** The World Bank, International Bank For Reconstruction And Development, 2020, Retrieved from <https://data.worldbank.org>
- 28** United Nations Food and Agricultural Organization, 2006: *Livestock's Long Shadow, Environmental Issues and Options*. Chief, Electronic Publishing Policy and Support Branch, Communication Division – FAO, Viale delle Terme di Caracalla, 00153 Rome, Italy. P 113
- 29** Rana, Krishen J. et al., United Nations Food and Agricultural Organization, 2009, *Impact of rising feed ingredient prices on aquafeeds and aquaculture production*, Rome, Italy, Pp 37-39
- 30** Boyd C.E., *Feed and Feeding Practices in Aquaculture*, 2015, Woodhead Publishing, ISBN 978-0-08-100506-4
- 31** Global Change Data Lab: *Our World in Data*, 2020, data based on FAOSTAT (FAO, 2016) for Agriculture total, Land Use sources and Forest and on the EDGAR Database (JRC/PBL, 2016) for the other sectors. Retrieved from <https://ourworldindata.org>
- 32** International Energy Agency, *Data and statistics*, 2020, Retrieved from <https://www.iea.org>
- 33** United Nations Food and Agricultural Organization, 2006: *Livestock's Long Shadow, Environmental Issues and Options*. Chief, Electronic Publishing Policy and Support Branch, Communication Division – FAO, Viale delle Terme di Caracalla, 00153 Rome, Italy. P 271
- 34** Trenberth, Kevin E., Smith, Lesley, 2004: *The Mass of the Atmosphere: A Constraint on Global Analyses*, National Center for Atmospheric Research, *Journal of Climate*, Vol. 18, Boulder, USA. P 864
- 35** Wallace, John M., Hobbs, Peter V., 2006, *Atmospheric Science, Second Edition: An Introductory Survey (International Geophysics)*, Academic Press, 2nd Edition, Cambridge, USA . P 155
- 36** United Nations Food and Agricultural Organization, 2006: *Livestock's Long Shadow, Environmental Issues and Options*. Chief, Electronic Publishing Policy and Support Branch, Communication Division – FAO, Viale delle Terme di Caracalla, 00153 Rome, Italy. P 74
- 37** World Resources Institute, *CAIT Climate Data Explorer*, 2020, Retrieved from <https://www.climatewatchdata.org>
- 38** Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G. 2013. *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization of the United Nations (FAO), Rome.
- 39** Joos, F. et al., 2013: *Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis*, *Atmos. Chem. Phys.*, 13, 2793–2825, 2013
- 40** Hayek, M., Harwatt, H., Ripple, W., Mueller Nathaniel, 2020: *The carbon opportunity cost of animal-sourced food production on land*. *Nature Sustainability*, September 2020, [Online], Retrieved from <https://doi.org/10.1038/s41893-020-00603-4>

10. Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.