Questions for Climate Scientists

Bruce Parker (bruceparker@alum.mit.edu)

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The IPCC's carbon budget is arguably the world's most important climate change metric as climate scientists have recently concluded that a global temperature increase over 1.5°C could be devastating for our civilization and the IPCC carbon budget was designed to calculate the maximum post-2019 cumulative CO2 emissions that humans could emit and still have the global temperature increase remain at or below 1.5°C. There is general agreement that the IPCC's budget calculations do not sufficiently account for natural feedbacks[1]. But there appear to be several estimates for the quantity included. For example:

- "The AR6 estimates to appropriately include the effect of all these feedbacks, remaining carbon budgets have to be reduced by 26 ± 97 GtCO2 per degree Celsius of additional warming"[2]
- Based on Table 5.29 of the AR6's *Climate Change 2021: The Physical Science Basis*, a good "planning" number for the expected emissions from natural feedbacks appears to be about 225 GTCO2 per degree C of temperature increase[3]
- Based on the data from "AR6 Scenario Explorer and Database hosted by IIASA", the expected emissions from natural feedbacks appears to between 217 and 234 GTCO2 per degree C of temperature increase[4,5]

But the UNFCC expects emissions from just permafrost to be between 150 and 200 GTCO2 for a warming of between 1.6- 1.8°C and between 220 and 300 GTCO2 for a warming of 1.9°C[6]. In addition, "if tipping points are crossed, the remaining carbon budget for limiting warming to specific targets like 1.5°C or 2°C could effectively shrink to zero"[7]. And if natural emissions exceeded the quantity of CO2 emission-equivalents included in the IPCC's carbon budget calculations by 800 GTCO2, post 2019 anthropogenic CO2 emissions of 400 GTCO2 would result in a temperature increase of 2.0°C instead of 1.5°C. So in order to plan for an appropriate response to global warming it would be very helpful if climate scientists could answer the following two questions:

1. What quantity of CO2 emission-equivalents can be expected from natural feedbacks this century?
2. What quantity of CO2 emission-equivalents from natural feedbacks are included in the IPCC's carbon budget calculations? (The answer can either be expressed in "natural emissions per degree increase in temperature" or as "natural emissions for a temperature increase target" – e.g., for 1.5°C, 2.0°C, etc.)

Once these questions are answered, the tables below can be used to estimate the post-2024 emissions budget (or deficit) for a specific temperature increase or the expected temperature increase in 2100. All of the tables were created based on the IPCC's AR6 66% probability range (post-2019 budgets of 400 GTCO2 and 1150 GTCO2 for a 1.5°C increase and a 2.0°C increase respectively).

- The values in Tables 1-3 (for the post-2024 emissions budget) are calculated based on natural emissions through 2100 that are dependent on the temperature increase per degree C – either 100, 150, or 200 GTCO2. For example, if (1) the temperature increase in 2100 is 1.5°C, (2) natural emissions through 2100 in the IPCC's budget calculations were100 GTCCO2 per degree C (for a total of 150 GTCO2), and (3) cumulative natural emissions through 2100 are 150 GTCO2, then (4) the remaining budget for a 66% chance of not exceeding 1.5°C is about 200 GTCO2 (which also equals the post-2019 GTCO2 budget of 400 – 5 years of 40 GTCO2 of anthropogenic emissions) (see Table1).

- The values in the Tables 4 and 5 (used to estimate the temperature increase in 2100) are based on the natural emissions that are expected for a specific carbon budget. For example, if the carbon budget for 1.5°C includes 200 GTCO2 of natural emissions but the emissions from natural emissions are expected to be 400 GTCO2, the temperature increase in 2100 will be about 1.64°C (see Table 4).

200 GTCO2e per 1°C Temperture Change in the IPCC Budget																				
Target Temp Incr	Cumulative Natural Emissions 2025-2100 (GTCO2e)																			
	100	150	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900
1.5°C	513	463	413	313	213	113	13	-87	-187	-287	-387	-487	-587	-687	-787	-887	-987	-1087	-1187	-1287
2.0°C	1325	1275	1225	1125	1025	925	825	725	625	525	425	325	225	125	25	-75	-175	-275	-375	-475
2.5°C	2137	2087	2037	1937	1837	1737	1637	1537	1437	1337	1237	1137	1037	937	837	737	637	537	437	337
3.0°C	2949	2899	2849	2749	2649	2549	2449	2349	2249	2149	2049	1949	1849	1749	1649	1549	1449	1349	1249	1149
	CO2 Budget/Deficit																			

Table 1

225 GTCO2e per 1°C Temperture Change in the IPCC Budget																				
Target Temp Incr	Cumulative Natural Emissions 2025-2100 (GTCO2e)																			
	100	150	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900
1.5°C	548	498	448	348	248	148	47.5	-53	-153	-253	-353	-453	-553	-653	-753	-853	-953	-1053	-1153	-1253
2.0°C	1372	1322	1272	1172	1072	972	872	772	672	572	472	372	272	172	71.5	-28.5	-129	-229	-329	-429
2.5°C	2194	2144	2094	1994	1894	1794	1694	1594	1494	1394	1294	1194	1094	994	894	794	694	594	494	394
3.0°C	3018	2968	2918	2818	2718	2618	2518	2418	2318	2218	2118	2018	1918	1818	1718	1618	1518	1418	1318	1218
	CO2 Budget/Deficit																			

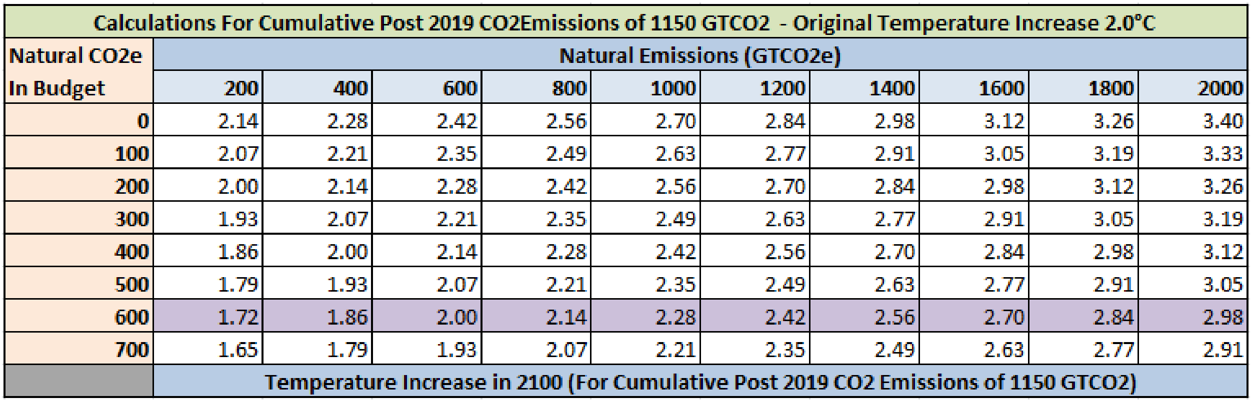
Table2

225 GTCO2e per 1°C Temperture Change in the IPCC Budget																				
Target Temp Incr	Cumulative Natural Emissions 2025-2100 (GTCO2e)																			
	100	150	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900
1.5°C	548	498	448	348	248	148	47.5	-53	-153	-253	-353	-453	-553	-653	-753	-853	-953	-1053	-1153	-1253
2.0°C	1372	1322	1272	1172	1072	972	872	772	672	572	472	372	272	172	71.5	-28.5	-129	-229	-329	-429
2.5°C	2194	2144	2094	1994	1894	1794	1694	1594	1494	1394	1294	1194	1094	994	894	794	694	594	494	394
3.0°C	3018	2968	2918	2818	2718	2618	2518	2418	2318	2218	2118	2018	1918	1818	1718	1618	1518	1418	1318	1218
	CO2 Budget/Deficit																			

Table 3

Calculations For Cumulative Post 2019 CO2Emissions of 400 GTCO2 - Original Temperature Increase 1.5°C										
Natural CO2e In Budget	Natural Emissions (GTCO2e)									
	200	400	600	800	1000	1200	1400	1600	1800	2000
0	1.64	1.78	1.92	2.06	2.20	2.34	2.48	2.62	2.76	2.90
100	1.57	1.71	1.85	1.99	2.13	2.27	2.41	2.55	2.69	2.83
200	1.50	1.64	1.78	1.92	2.06	2.20	2.34	2.48	2.62	2.76
300	1.43	1.57	1.71	1.85	1.99	2.13	2.27	2.41	2.55	2.69
400	1.36	1.50	1.64	1.78	1.92	2.06	2.20	2.34	2.48	2.62
500	1.29	1.43	1.57	1.71	1.85	1.99	2.13	2.27	2.41	2.55
600	1.22	1.36	1.50	1.64	1.78	1.92	2.06	2.20	2.34	2.48
700	1.15	1.29	1.43	1.57	1.71	1.85	1.99	2.13	2.27	2.41
	Temperature Increase in 2100 (For Cumulative Post 2019 CO2 Emissions of 400 GTCO2)									

Table 4



Calculations For Cumulative Post 2019 CO2Emissions of 1150 GTCO2 - Original Temperature Increase 2.0°C										
Natural CO2e	Natural Emissions (GTCO2e)									
In Budget	200	400	600	800	1000	1200	1400	1600	1800	2000
0	2.14	2.28	2.42	2.56	2.70	2.84	2.98	3.12	3.26	3.40
100	2.07	2.21	2.35	2.49	2.63	2.77	2.91	3.05	3.19	3.33
200	2.00	2.14	2.28	2.42	2.56	2.70	2.84	2.98	3.12	3.26
300	1.93	2.07	2.21	2.35	2.49	2.63	2.77	2.91	3.05	3.19
400	1.86	2.00	2.14	2.28	2.42	2.56	2.70	2.84	2.98	3.12
500	1.79	1.93	2.07	2.21	2.35	2.49	2.63	2.77	2.91	3.05
600	1.72	1.86	2.00	2.14	2.28	2.42	2.56	2.70	2.84	2.98
700	1.65	1.79	1.93	2.07	2.21	2.35	2.49	2.63	2.77	2.91
	Temperature Increase in 2100 (For Cumulative Post 2019 CO2 Emissions of 1150 GTCO2)									

Table 5

Footnotes

1 ChatGPT

Yes, there has been increasing criticism regarding the Intergovernmental Panel on Climate Change (IPCC)'s carbon budget calculations, particularly concerning their treatment of natural feedback mechanisms. Many climate scientists argue that the IPCC's models often underestimate or simplify the impact of natural feedbacks—such as permafrost thaw, methane release from wetlands, and reduced carbon uptake by forests and oceans—on the overall climate system.

These feedback loops can significantly amplify warming. For instance:

1. **Permafrost Thaw**: As the Arctic warms, permafrost melts, releasing trapped carbon dioxide and methane, potent greenhouse gases that can further accelerate global warming.
2. **Methane Hydrates**: Warming oceans may destabilize methane hydrates, releasing methane from ocean sediments, which also has a high warming potential.
3. **Forest Dieback**: Climate stress, especially due to droughts and heatwaves, can cause forest ecosystems, which currently act as carbon sinks, to release stored carbon into the atmosphere, further intensifying the greenhouse effect.
4. **Ocean Carbon Cycle**: The oceans, which absorb around a quarter of human CO2 emissions, may become less efficient at sequestering carbon as they warm and become more stratified, limiting nutrient circulation and biological uptake.

The IPCC's carbon budget, which estimates how much more CO2 can be emitted while still limiting global warming to certain thresholds (like 1.5°C or 2°C), may therefore be overly optimistic if these feedbacks are not adequately included. This means that we may have less "breathing room" than the official budgets suggest, necessitating even more urgent mitigation actions.

Many scientists advocate for integrating a more robust representation of these natural feedback mechanisms into climate models, which would likely lead to smaller carbon budgets and a faster timeline for needed emissions cuts.

2 **A deep dive into the IPCC's updated carbon budget numbers**
12 Aug 2021

Other Earth system feedbacks – The last piece is to account for Earth system feedbacks that would otherwise not be covered. SR1.5 assumed an additional blanket reduction of 100 GtCO$_2$ for this century for these feedbacks. This was a crude estimate and therefore not included as a central part of the remaining carbon budget numbers in SR1.5 AR6 updates this assessment entirely and includes this contribution in its main estimates.

Taking into account not only permafrost thaw, but also a host of other biogeochemical and atmospheric feedbacks, the AR6 estimates to appropriately include the effect of all these feedbacks, remaining carbon budgets have to be reduced by 26 ± 97 GtCO$_2$ per degree Celsius of additional warming.

Altogether these updates mean AR6 remaining carbon budget estimates are very similar compared to SR1.5, while they additionally include the effect of Earth system feedbacks that would otherwise not be covered.

https://www.realclimate.org/index.php/archives/2021/08/a-deep-dive-into-the-ipccs-updated-carbon-budget-numbers/

3

Global Carbon and Other Biogeochemical Cycles and Feedbacks (*Climate Change 2021: The Physical Science Basis)*

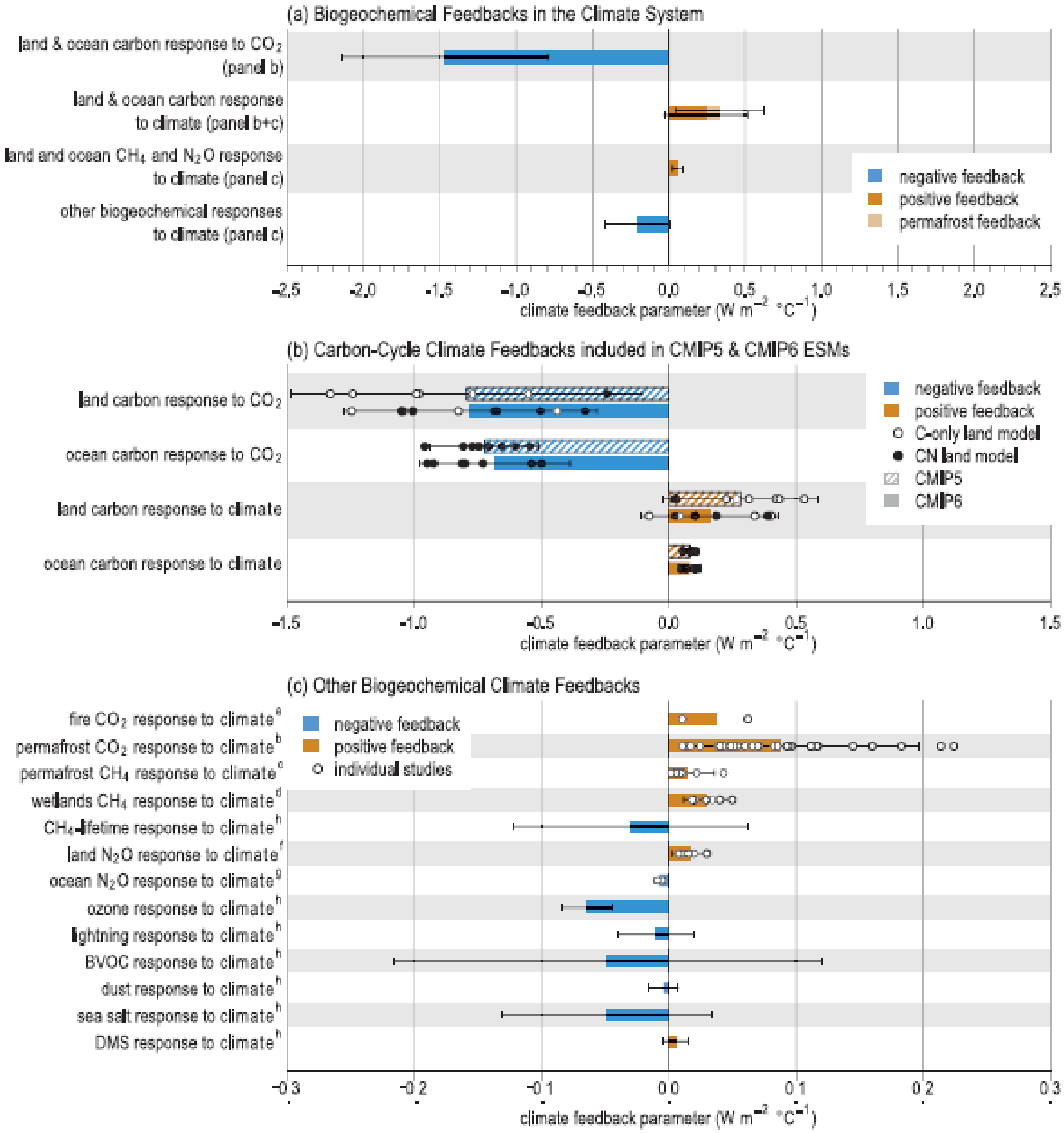


Figure 5.29 | Estimates of the biogeochemical climate feedback parameter (α). The parameter α (W m^{-2} °C^{-1}) for a feedback variable x is defined as $\alpha_x = \frac{dW}{dx}\frac{dx}{dT}$ where $\frac{dW}{dx}$ is the change in top-of-atmosphere energy balance in response to a change in x induced by a change in surface temperature (T), as in Section 7.4.1.1. **(a)** Synthesis of biogeochemical feedbacks from panels (b) and (c). Orange (blue) bars correspond to positive (negative) feedbacks increasing (decreasing) radiative forcing at the top of the atmosphere. Bars denote the mean and the error bar represents the 5–95% range of the estimates; **(b)** carbon-cycle feedbacks as estimated by coupled carbon-cycle climate models in the CMIP5 (Arora et al., 2013) and CMIP6 (Arora et al., 2020) ensembles, where dots represent single model estimates, and filled (open) circles are those estimates which do (not) include the representation of a terrestrial nitrogen cycle; **(c)** Estimates of other biogeochemical feedback mechanisms based on various modelling studies. Dots represent single estimates, and coloured bars denote the mean of these estimates with no weighting being made regarding the likelihood of any single estimate, and error bars the 5–95% range derived from these estimates. Results in panel (c) have been compiled from (a) Section 5.4.3.2 (Eliseev et al., 2014a; Harrison et al., 2018); (b) Section 5.4.3.3 (Schneider von Deimling et al., 2012; Burke et al., 2013, 2017b; Koven et al., 2015a, c; MacDougall and Knutti, 2016b; Gasser et al., 2018; Kleinen and Brovkin, 2018), where the estimates from Burke et al., 2013 have been constrained as assessed in their study (c) Section 5.4.7 (Schneider von Deimling et al., 2012, 2015; Koven et al., 2015c; Turetsky et al., 2020); (d) Section 5.4.7 (Arneth et al., 2010; Denisov et al., 2013; Shindell et al., 2013; B.D. Stocker et al., 2013; Zhang et al., 2017); (f) Section 5.4.7 (Xu-Ri et al., 2012; B.D. Stocker et al., 2013; Zaehle, 2013; Tian et al., 2019); (g) Section 5.4.7 (Martinez-Rey et al., 2015; Landolfi et al., 2017; Battaglia and Joos, 2018b). (h) Section 6.3, Table 6.9 mean and the 5–95% range the assessed feedback parameter. Further details on data sources and processing are available in the chapter data table (Table 5.SM.6).

Table 5.29 can be used to determine that the expected climate feedback factor is 0.166 W/m-2 (0.036 + 0.0870 + 0.013 + 0.03) for the three natural feedbacks (fire, permafrost, and wetlands) included in the budget analysis. The CO2 emissions that would result in that radiative forcing for two values of airborne fraction and two values for the starting atmospheric CO2 concentration are shown in the following table:

Airborne Fraction	Starting PPM	
	420	450
45	230	246
50	207	222
	CO2 Emissions for 0.166 W/m-2	

Since the airborne fraction is apt to rise this century, a good "planning" number for the expected emissions from natural feedbacks appears to be about 225 GTCO2 per degree C of temperature increase (or 130 GTCO2/0.1 W/m-2)

https://doi.org/10.1017/9781009157896.007

4 **Airborne fraction and natural emissions**

ChatGPT

The **airborne fraction** and **natural emissions** are two interrelated concepts within the carbon cycle and play key roles in determining the concentration of CO_2 in the atmosphere, thereby affecting climate change.

1. Airborne Fraction

The **airborne fraction** refers to the proportion of total CO_2 emissions (both anthropogenic and natural) that stays in the atmosphere, while the remainder is absorbed by natural carbon sinks, such as oceans, forests, and soils. On average, the airborne fraction has remained around **40-45%** in recent decades, meaning that about 55-60% of CO_2 is taken up by natural sinks. However, this fraction can vary year by year due to fluctuations in natural processes.

2. Natural Emissions

Natural emissions are the CO_2 and other greenhouse gases (e.g., methane and nitrous oxide) released from natural processes such as:

- **Plant and soil respiration**: Plants take in CO_2 during photosynthesis and release it during respiration. Soil microbes break down organic matter and release CO_2.
- **Oceans**: CO_2 is exchanged between the atmosphere and the oceans through diffusion. Warming oceans may release more CO_2 back into the atmosphere.
- **Volcanic activity**: Releases CO_2 and other gases from the Earth's interior.
- **Wetlands**: Produce methane through anaerobic decomposition of organic matter.
- **Permafrost thaw**: Releases both methane and CO_2 as frozen organic material decomposes.

These natural emissions are part of the **natural carbon cycle**, which has historically been balanced, with natural sinks absorbing an equivalent amount of CO_2 as natural emissions. However, this balance has been disrupted by human activities that emit large amounts of CO_2 from fossil fuels, deforestation, and land-use changes.

3. Interaction Between Airborne Fraction and Natural Emissions

The **airborne fraction** is influenced by the ability of natural sinks to absorb both anthropogenic and natural CO_2 emissions. Several factors determine how the airborne fraction evolves over time, especially under future climate change scenarios:

***a.** Warming-Induced Changes to Natural Emissions*

As the planet warms, natural emissions from processes like soil respiration, permafrost thaw, and ocean outgassing are expected to increase. This means that:

- **Increased soil respiration**: Higher temperatures stimulate microbial activity in soils, leading to greater CO_2 emissions. This adds to the overall pool of CO_2 in the atmosphere.
- **Permafrost thaw**: Releases significant amounts of methane and CO_2 as frozen organic matter begins to decompose in warming conditions.
- **Ocean outgassing**: Warmer waters hold less CO_2, leading to higher emissions from the ocean back into the atmosphere.

These changes in natural emissions could **increase the airborne fraction**, as natural sinks might not be able to keep up with the rising influx of CO_2 and other GHGs.

***b.** Sink Saturation and Decreased Carbon Sequestration*

As natural emissions increase, the capacity of carbon sinks to absorb CO_2 can weaken. Some of the key processes affecting this include:

- **Ocean saturation**: The ocean's ability to absorb CO_2 may decrease as it becomes saturated with carbon and as surface waters warm, reducing solubility.
- **Forest dieback**: Forests may lose their capacity to sequester carbon as they face stress from droughts, wildfires, and other climate impacts. In some cases, forests could even become net sources of CO_2.

As sinks weaken, a greater proportion of the emitted CO_2 (both from human activities and natural processes) will remain in the atmosphere, raising the airborne fraction.

***c.** Positive Feedback Loops*

The relationship between natural emissions and the airborne fraction can create positive feedback loops. For example:

- **Permafrost-carbon feedback**: Warming causes permafrost to thaw, releasing methane and CO_2, which leads to more warming, further thawing more permafrost, and so on.
- **Soil-carbon feedback**: Warming increases microbial activity, releasing more CO_2 from soils, which enhances warming, leading to more soil carbon release.

These feedbacks accelerate the amount of CO_2 staying in the atmosphere, increasing the airborne fraction.

4. Projected Changes in Airborne Fraction Due to Natural Emissions

Over the 21st century, **Earth System Models (ESMs)** predict that the airborne fraction will likely increase due to weakening carbon sinks and increasing natural emissions. The degree of change depends on the emission scenario:

- **In high-emission scenarios** (e.g., SSP5-8.5), large-scale warming is expected to significantly increase natural

CO_2 emissions (from sources like permafrost thaw and soil respiration), and carbon sinks will weaken more rapidly. In this scenario, the airborne fraction could exceed **50-60%** by 2100, as sinks become saturated or reverse their role as carbon absorbers.
- **In low-emission scenarios** (e.g., SSP1-1.9), the rise in the airborne fraction is more limited. However, even under these scenarios, some increase is expected because of warming-induced changes to natural processes. The airborne fraction may still rise to around **50%** by 2100, as sinks weaken in response to modest climate change.

5. Role of Natural Emissions in Shaping Future Carbon Budgets

The **increase in natural emissions** due to climate feedbacks and the subsequent increase in the airborne fraction have major implications for global climate targets:

- **Carbon budgets**: As the airborne fraction rises, more CO_2 remains in the atmosphere, meaning that future carbon budgets for limiting warming to 1.5°C or 2°C will shrink. This could necessitate more rapid and aggressive reductions in anthropogenic emissions or increased reliance on **Carbon Dioxide Removal (CDR)** technologies.
- **Climate mitigation**: Limiting future climate change will require not only reducing human emissions but also maintaining and enhancing natural carbon sinks. Reforestation, wetland restoration, and ocean protection could help stabilize or even reduce the airborne fraction over time.

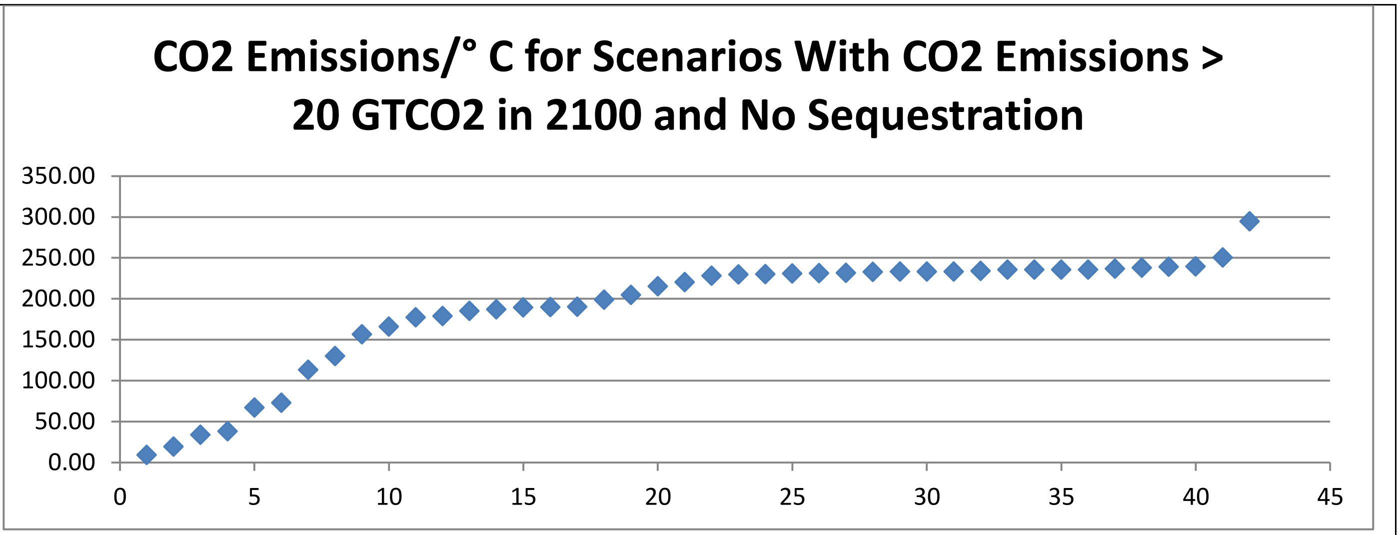
Conclusion

The **airborne fraction** is expected to increase over the century, primarily due to weakening natural carbon sinks and rising natural emissions driven by climate feedbacks. As warming accelerates natural emissions (e.g., from permafrost thaw and soil respiration), and as sinks such as oceans and forests become less effective at absorbing CO_2, a larger portion of total emissions will remain in the atmosphere. This underscores the importance of both reducing anthropogenic emissions and protecting natural carbon sinks to mitigate climate change effectively.

5

Calculation of CO2 Emissions/° C from AR6 Data

1. Data source: AR6 Scenario Explorer and Database hosted by IIASA
https://data.ene.iiasa.ac.at/ar6/#/login?redirect=%2Fworkspaces
2. Used 42 scenarios with CO2 Emissions > 20 GTCO2 in 2100 and no sequestration
3. Airborne Fraction in 2015 – 47.9
4. Airborne Fraction in 2100 – 55 (see #10 above)
5. Calculated natural emissions for each year based on anthropogenic emissions, atmospheric growth, and airborne fraction (Natural Emissions = Atmospheric Growth / Airborne Fraction - CO2 emissions/1000)
6. Summed emissions from 2025-2100
7. Calculated CO2 Emissions/° C (= sum/temperature increase) for each scenario
8. Plot of Calculated CO2 Emissions/° C



9. Averages

Average CO2 Emissions/° C	
Average (All)	198
Average between 150 and 250	217
Average between 200 and 250	234

10. Similar value to that obtained in #9 above (220)

11. Calculation in the spreadsheet at https://www.chesdata.com/documents/AR6 Natural Emission Analysis.xlsx

6 **Permafrost Emissions**

Today, at about 1.2°C, we are already committed to losing about 25% of surface permafrost, which would result in about 250 GTCO2.

Scenario	Temperature peak	Cumulative Gt CO2-eq (including CO2 and CH4) by 2100	Impacts
Low emissions	1.6- 1.8°C...and declining Peak reached between 2060-2080	150-200	Once permafrost thaw is initiated, including by extreme summer heat events, the resulting emissions continue for centuries. As a result, permafrost emissions will continue even if temperatures slowly decline. Future generations will need to deploy and continue CO2 removal strategies equal to these long-term emissions until they cease, simply to hold temperatures steady.
Optimistic fulfillment of all current pledges	1.9°C Peak reached between 2120-40	220-300	These emissions will continue for one-two centuries after peak temperature is reached. Future generations will need to deploy and continue carbon dioxide removal strategies equal to these long-term emissions until they cease, simply to hold temperatures steady. Permafrost soils will disappear in extensive regions above the Arctic Circle, as well as below, and nearly all existing infrastructure built on permafrost soils will require replacement.

https://unfccc.int/sites/default/files/resource/Permafrost.pdf

7 **Assessment of the impact of natural feedbacks on the IPCC carbon budget?**

ChatGPT

Natural feedbacks in the Earth’s climate system, such as those involving carbon sinks, albedo changes, and methane emissions, have a significant impact on the IPCC’s carbon budget for limiting global warming. These feedbacks can either amplify or dampen the effects of anthropogenic carbon emissions, and their inclusion is crucial for accurate carbon budget estimations.

Here are the key points on how natural feedbacks affect the IPCC's carbon budget:

1. Carbon Sink Saturation:

- **Forests and Oceans as Carbon Sinks**: Forests and oceans absorb roughly half of the carbon dioxide emitted by human activities. However, these natural sinks are expected to weaken over time as they become saturated. Forests may face declining growth rates due to nutrient limitations, heat stress, or increased frequency of wildfires, while the oceans could absorb less CO_2 as they warm, reducing their efficiency as a carbon sink.
- **Impact on Carbon Budget**: This saturation reduces the capacity of these systems to mitigate emissions, thus tightening the remaining carbon budget. Models that do not fully account for this risk may underestimate the reductions in CO_2 emissions required to meet climate targets.

2. Permafrost Thawing and Methane Release:

- **Permafrost Carbon Feedback**: Large quantities of carbon are stored in permafrost, which is currently thawing as temperatures rise. When this carbon is released, primarily in the form of methane (CH_4), it acts as a potent greenhouse gas, accelerating warming.
- **Methane Feedback**: Methane release from permafrost and wetlands, particularly in the Arctic, could create a positive feedback loop, exacerbating global temperature rise. Methane has a much higher global warming potential than CO_2, especially over short timescales.
- **Impact on Carbon Budget**: Methane feedbacks add an additional burden on the carbon budget by potentially lowering the amount of CO_2 that can be emitted while still meeting climate targets like limiting warming to 1.5°C or 2°C. The release of additional greenhouse gases from thawing permafrost can significantly reduce the available carbon budget.

3. Albedo Feedback:

- **Loss of Ice and Snow**: As polar ice caps and glaciers melt, less sunlight is reflected (albedo effect) and more is absorbed by the Earth's surface, particularly by darker ocean waters. This leads to further warming, which in turn causes more ice to melt—a classic positive feedback loop.
- **Impact on Carbon Budget**: This feedback accelerates the pace of warming, meaning that the remaining carbon budget must be adjusted to account for faster-than-expected temperature increases. It also puts more pressure on immediate emission reductions, as even slight delays can lead to rapidly accelerating warming.

4. Ocean Acidification and Marine Ecosystems:

- **Ocean Acidification**: As CO_2 is absorbed by oceans, it leads to ocean acidification, which affects marine life, particularly organisms that rely on calcium carbonate for their shells and skeletons. Coral reefs and shellfish populations are vulnerable to these changes.
- **Impact on Carbon Budget**: Disruptions to marine ecosystems can affect biological carbon sequestration

processes. For example, plankton and other marine organisms contribute to carbon drawdown through biological activity. Declines in these populations due to acidification and warming can reduce the ocean's ability to sequester carbon, altering the balance of the carbon cycle.

5. Forest Dieback and Land Use Changes:

- **Forest Ecosystems**: Changes in temperature, precipitation, and extreme weather events can lead to large-scale forest dieback, particularly in tropical rainforests like the Amazon. This not only reduces the capacity of forests to sequester carbon but also releases stored carbon back into the atmosphere through decay and combustion.
- **Impact on Carbon Budget**: Forest dieback effectively reverses the role of forests from carbon sinks to carbon sources, drastically tightening the remaining carbon budget. The IPCC carbon budgets are typically optimistic about future forest regrowth and continued sequestration, but if dieback occurs at large scales, this assumption may be flawed.

6. Tipping Points:

- **Threshold Effects**: Some feedbacks may operate in a non-linear way, with the potential to cross tipping points that lead to abrupt and irreversible changes. Examples include the collapse of the Greenland Ice Sheet, changes in the Atlantic Meridional Overturning Circulation (AMOC), or the dieback of the Amazon rainforest. Once these tipping points are crossed, the feedbacks become self-reinforcing and difficult to reverse.
- **Impact on Carbon Budget**: Crossing tipping points could lead to rapid and uncontrollable warming, rendering current carbon budget estimates inadequate. If tipping points are crossed, the remaining carbon budget for limiting warming to specific targets like 1.5°C or 2°C could effectively shrink to zero.

7. Uncertainty in Feedback Mechanisms:

- The magnitude and timing of natural feedbacks are subject to significant uncertainty, and the IPCC models often take a conservative approach in estimating their impact. However, as more data becomes available, it is increasingly clear that feedback mechanisms may accelerate climate change more than previously thought.

Overall Impact:

The IPCC's carbon budgets are based on models that account for some natural feedbacks, but uncertainties remain high, particularly with regards to nonlinear feedbacks and tipping points. The effect of feedbacks is generally to reduce the allowable CO_2 emissions while staying within safe climate limits. As a result, more aggressive mitigation measures may be needed to offset these feedbacks.

Conclusion:

Natural feedbacks significantly constrain the carbon budget available for human emissions. While the IPCC carbon budget provides a valuable framework for guiding policy, real-world feedbacks may require even more urgent reductions in greenhouse gas emissions than those currently proposed. A robust response that integrates rapid emission reductions and large-scale carbon removal technologies is essential to account for the impact of these feedback mechanisms.