Targeting All Anthropogenic Carbon Dioxide Emissions

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Abstract

As targets more ambitious than IPCC RCP 1.9, such as zero cumulative emissions are seldom studied, we show how to determine the amount of carbon to remove to affect cumulative emitted anthropogenic carbon dioxide to simplify creating Carbon Dioxide Removal (CDR) targets, provide historical context and present pathways for complete climate restoration. We explore the historical context of cumulative anthropogenic carbon dioxide emissions and how it's induced increases to each of the natural sinks. To obtain more comprehensive CDR targets, we present a method how to determine the total amount of carbon to remove from cumulative CO_2 emissions that are present in natural sinks. Determining total emissions to reach a desired target is often obscured when only examining yearly emissions flux. A possible baseline CO_2 concentration of 280.9 ± 0.9 ppm for pre-human change stretching from 600 BCE to 1750 CE, was found and could be explored separately. We model multiple pathways to zero cumulative CO_2 emissions for complete climate restoration. For groups seeking climate restoration which completes in less than half a human lifespan, a pair of pathways is presented which complete in twenty years. The pathways bound complete climate restoration in the shortest time and the more typical end of the century, 2100 target. This work does not prescribe how carbon dioxide can or should be removed from the atmosphere. Determining the appropriateness of a given CDR technology over another, or constructing a blend of technologies is beyond the scope of this work. This work exclusively focuses on the greenhouse gas carbon dioxide calculations for climate restoration and subsequently CDR, and does not cover other greenhouse gases. There is a tradeoff between how fast the climate can be restored compared to how long humans can continue to emit carbon dioxide from the use of fossil fuels and land use change. We hope the historical context and significant challenge of complete climate restoration additionally underscore the need for peak emissions and total anthropogenic carbon removal. As the scale of complete anthropogenic carbon dioxide removal is massive, we hope more, swift effort is made to phase-out fossil fuel use, consume and, or create non-fossil fuel based energy sources and storage, and additionally use and create carbon products derived from the atmosphere.

1. Introduction

As the Earth is a closed system, anthropogenic CO_2 emissions move to reside in natural sinks. Human activity from fossil fuel emissions and land-use change has radically increased the carbon composition of the Earth's natural sinks by exponential emissions increases since pre-industrial times.

The carbon dioxide between the atmosphere and oceans sinks are balanced by atmospheric chemistry: atmospheric CO_2 exerts pressure on CO_2 dissolved in the ocean surface waters (Takahashi et al., 2002). When CO_2 is removed from the atmosphere, the reduced CO_2 pressure allows the dissolved CO_2 remaining in the surface waters to outgas back to the atmosphere. Even though only about 50% of anthropogenic carbon stored in the ocean sink is in the top

400 meters (Sabine et al., 2004), the top 100 meters of surface waters contains the highly bioactive euphotic zone and is strongly negatively impacted by induced warming and acidification from anthropogenic carbon, additionally causing further damage to the rest of marine ecology. Carbon dioxide dissolved in surface waters should be moved to more permanent storage, to stop affecting the surface waters or atmosphere.

The exponential forcing of cumulative emissions is often not considered as it's not readily apparent in the reporting of yearly changes in emissions. Even considering the uncertainty of ±5% at medium confidence level of the current estimated cumulative anthropogenic emissions of 432 gigatonnes carbon (GtC) per the Global Carbon Budget (Le Quéré et al., 2018), there is a large difference between achieving the Representative Concentration Pathway (RCP) 1.9 which could lower cumulative emissions under 200 GtC, and zero GtC. Additionally complicating removal efforts is how to determine the entire amount of carbon dioxide to remove. Without considering the carbon dioxide from all sinks, and the rebalancing that occurs when carbon dioxide is removed from a sink, only converting atmospheric carbon dioxide concentration in ppm for a removal target leads to drawing down only the atmospheric sink.

In order to more accurately estimate the amount of carbon dioxide to remove for Carbon Dioxide Removal (CDR) and ultimately climate restoration, we examine the total accumulation of carbon to the natural sinks from anthropogenic carbon dioxide emissions. We cover the differences between cumulative and yearly changes in emissions and highlight possible misinterpretation in solely examining yearly changes in emissions. We then provide estimates on possible carbon removal pathways.

2. Anthropogenic Emitted Carbon, What and Where?

The fossil fuel emissions from humans burning carbon-based fuels have over the years shifted between three major natural carbon sinks: land, ocean, and the atmosphere. Including the latest 2017 estimates, the total emitted carbon from anthropogenic CO_2 since 1750 is 627 GtC where 432 GtC is from fossil fuel emissions and 195 GtC from land-use change (Le Quéré et al., 2018). The atmosphere currently sinks about 271 GtC (Dlugokencky et al., 2018) in anthropogenic emissions. Emissions from human-induced land use change which roughly equals the land sink. The natural sinks contain more carbon than the introduced anthropogenic carbon. This work focuses on the increases to the total carbon in the natural sinks from anthropogenic emissions sources only. Carbon quantities are listed in gigatonnes carbon (GtC) or the equivalent petagrams carbon (PgC). To obtain gigatonnes CO_2, multiply by a conversion factor of 3.664 (Le Quéré et al., 2018).

Total Cumulative Anthropogenic Emissions	Fossil Fuel Emissions	Land-use Change Emissions	Land Sink	Ocean Sink	Atmospheric Sink*	Budget Imbalance
627.1	431.6	195.5	-189.8	-157.5	-271.3	-8.5

Table 1 | All values are from the Global Carbon Budget (Le Quéré et al., 2018) except the Atmospheric Sink. The atmospheric sink was generated from the current Global CO_2 Concentration from Mauna Loa (Dlugokencky et al., 2018) and converted to GtC via subtracting 277 ppm and multiplied by the conversion factor 2.12 (Ballantyne et al., 2012).

The year to year change in cumulative anthropogenic fossil fuel emissions results in a strongly growing exponential curve that is highly correlated to carbon growth in atmospheric, ocean and land sinks. Figure 1 plots the cumulative anthropogenic carbon from fossil fuels and land-use change CO_2 emissions per year, and how that carbon dioxide, more generally known as a greenhouse gas, is distributed to the natural sinks. To complete the atmospheric dataset the Keeling Curve is shown in light blue overlaying the cumulative atmospheric yearly growth

from the Global Carbon Budget (Le Quéré et al., 2018). The Keeling Curve is the globally averaged CO_2 concentration measured at Mauna Loa from 1980 to 2017 (Dlugokencky et al., 2018) was converted to GtC by the conversion factor of 2.12 (Ballantyne et al., 2012). Natural sink curves also show slower growing exponential curves. The steepest part of the cumulative fossil fuel emissions curve happened within the last two decades.

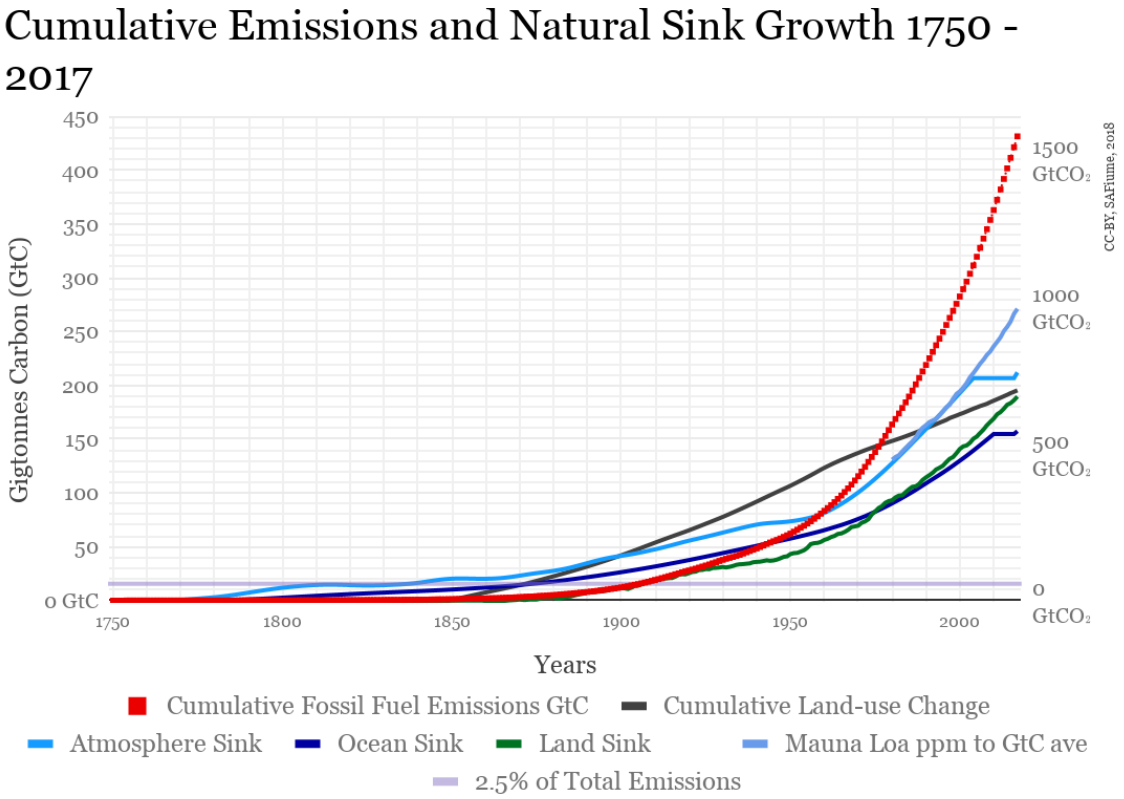

Figure 1 | After 1750 anthropogenic emissions have experienced exponential growth and starting around the 1850s, human-induced land-use change experienced close to linear growth. The natural sinks have experienced related exponential growth. Not all data points have values prior to 1860s. The ocean and atmospheric sinks have additional gaps starting in 2005 onward. The break for the atmospheric curve is completed by the overlay of the globally averaged Mauna Loa Keeling curve displaying anthropogenic emissions (value parts per million volume - 277 ppm) for the time period 1980-2017 and converted to GtC with the stock conversion factor of 2.12.

The Global Carbon Budget Equation:

$$E_{ff} + E_{luc} = G_{atm} + S_{ocean} + S_{land} + B_{im}\,, \qquad [1]$$

(Le Quéré et al., 2018) states the yearly growth of the fossil fuel and land-use change emissions are equal to the total yearly growth in CO_2 concentration for all natural sinks: atmosphere, ocean, and land sinks. This yearly growth rate equalling the natural sink yearly growth rate can be expanded to total cumulative emissions equalling the current anthropogenic carbon that is distributed to a natural sink. Where the GCB equation concerns yearly flux, equation [2] shows the cumulative emission sources are equal to the total anthropogenic carbon among the three sinks for a given year n:

$$E_{\Sigma ff_n} = \sum_{i\,=\,1750}^{n} E_{ff_i}, \qquad [2]$$

$$E_{\Sigma ff_n} + E_{\Sigma luc_n} = A_{atm\ sink_n} + A_{ocean\ sink_n} + A_{land\ sink_n}. \qquad [3]$$

From the equation, we can see the current total anthropogenic atmospheric CO_2 concentration is the total atmospheric CO_2 concentration minus the year 1750's CO_2 concentration of 277 ppm. Multiplying the current anthropogenic CO_2 ppm by 2.12 (Ballantyne et al., 2012) yields the anthropogenic carbon content in GtC.

The relationship between total carbon emitted and how it's distributed to each natural sink is shown in Figure 2, by stacked columns of cumulative anthropogenic fossil fuel and land-use change emission sources and Earth's three natural sinks. The negative quantity of the natural sinks shows the amount of carbon that ought to be removed to balance out the total amount of carbon emitted. The oceanic anthropogenic carbon is about roughly 58% of the atmospheric anthropogenic carbon or roughly 36% of the total emitted from fossil fuel emissions. The atmospheric anthropogenic carbon accounts for the remaining 63% of fossil fuel emissions.

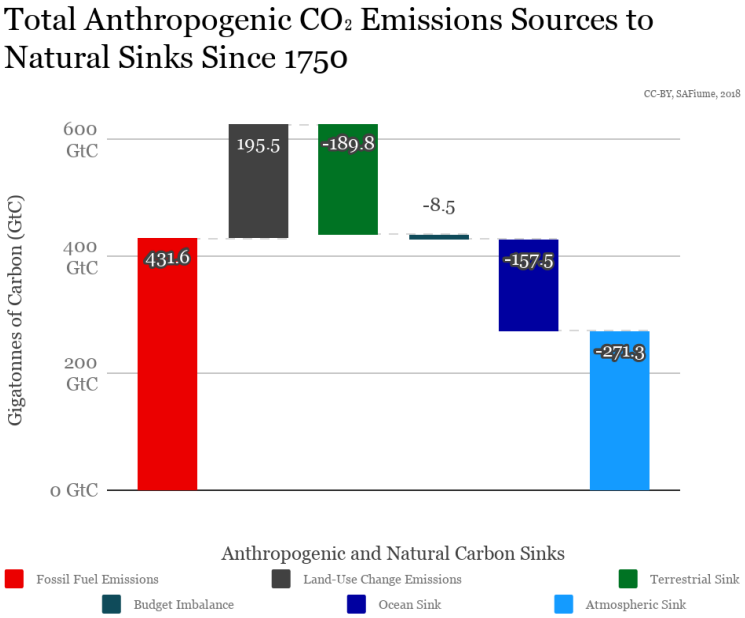

Figure 2 | Emissions sources are distributed nearly 36% to the ocean and 63% to the atmosphere, assuming Land-use change roughly equals the land sink. The budget imbalance is due to carbon missing from a natural sink, possibly from seasonal change and differing accounting methods.

Total anthropogenic carbon emissions experienced strongly accelerating growth compared to the stable historic CO_2 concentration. Figure 3 is a composite graph of CO_2 concentration data from multiple Antarctic ice cores studies performed on the Dome Concordia (Dome C) (Luethi et al., 2008; Flückiger et al., 2002; Monnin et al., 2001), Vostok Dome (Siegenthaler et al., 2005; Pépin et al., 2001; Petit et al., 1999;), Taylor Dome (Indermühle et al., 2000), WAIS Divide (Bauska et al., 2015), Maud Dome and the South Pole (Siegenthaler et al., 2017), and Law Dome (Etheridge et al., 1996; MacFarling Meure et al., 2006 and MacFarling Meure 2004), stretching for about two thousand years, from 600 BCE to 2004 CE and completed with the globally averaged CO_2 concentration from Mauna Loa from 1980 CE - 2017 CE, resulting in the top adjoined blue curves. This atmospheric curve has been shifted upwards to start above the top of the ocean sink curve. The mean CO_2 concentration of 280.9 ± 0.9 ppm for 600 BCE to 1750 CE, is shown in light green. The left axis has been calibrated to set 281 ppm equal to 348 GtC such that the green line meets 190 GtC - the top of the land curve added to 158 GtC - the top of the ocean curve. The curve in red is total anthropogenic emissions from both fossil fuel and land-use change. The dark blue and green lines are the ocean and land sinks respectively, which are cumulatively stacked below the atmospheric curve to illustrate the relationship to total carbon emissions. The top blue line doesn't meet the red emissions curve due to the budget imbalance.

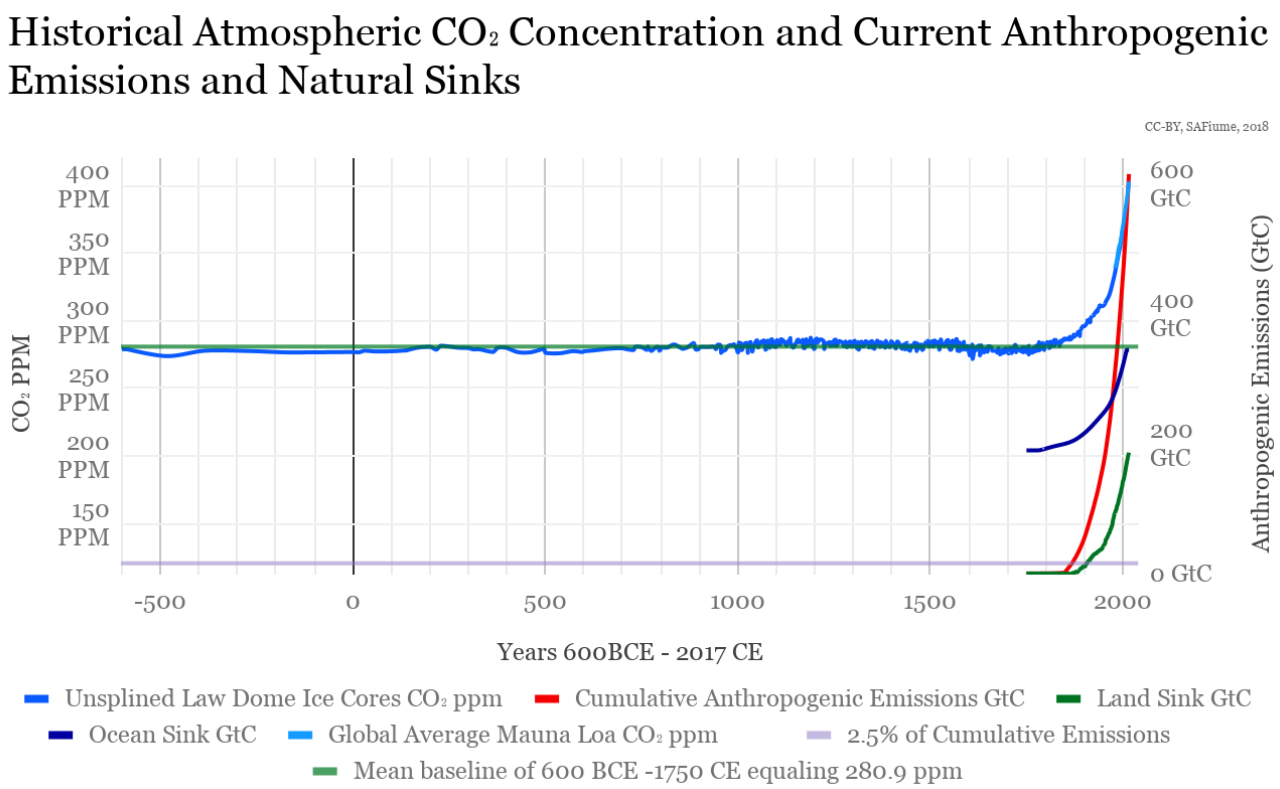

Figure 3 | Historical atmospheric CO_2 concentration is shown stacked above the ocean and land sink totals. The ice core CO_2 concentration data is from the Dome C (Monnin et al., 2001; Luthi et al., 2008), raw Law Dome data points (Etheridge et al., 1996; MacFarling Meure 2004; MacFarling Meure et al., 2006), WAIS Divide (Bauska et al., 2015), Maud Dome and the South Pole (Siegenthaler et al., 2017). Law Dome data from the present reads slightly lower ppm than Mauna Loa's global average. The data to generate the graphs are open and listed in Data Availability section. Cumulative anthropogenic emissions from fossil fuels and land-use change total 627 GtC and start picking up in the mid-1800s. The line in light purple is 2.5% of total emissions about 15.7 GtC. The light green line is the mean CO_2 concentration equaling 281 ppm from 600 BCE to 1750 CE.

The line in light purple corresponds to 2.5% of 627 GtC, or total anthropogenic emissions for both land-use and fossil fuel emission, equalling about 15.7 GtC, or 284 ppm.

The baseline of 277 ppm is the mean ppm for the time 1739 to 1772 CE. To check that this ppm wasn't a local minimum for only that time span the historical CO_2 concentration was examined and shown in Figure 4. Antarctic ice cores from Law Dome, Dome C, Maud Dome, Taylor Dome, WAIS Divide, Vostok and the South Pole yielded that CO_2 concentration has varied only slightly, ranging from 182.2 ppm to 287.5 ppm, for 137,000 BCE to 1750 CE. For modern times CO_2 concentration has been stable since 1750 back to about 600 BCE. Before 600 BCE, the concentration slowly trends lower than 275 ppm and eventually dropping to 184 ppm. A mean from the ice core samples gives a baseline of 280.9 ± 0.9 ppm for the recent stable past of 600 BCE to 1750 CE.

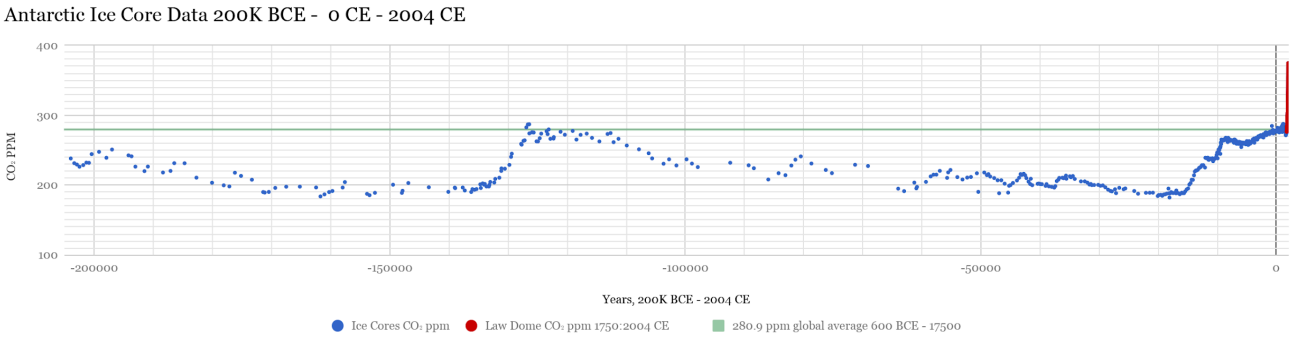

Figure 4 | Scatter plot of Antarctic Ice Core CO_2 concentration data from multiple ice cores: Law Dome, Dome C, Maud, Taylor Dome, WAIS Divide, Vostok and the South Pole from the time of 125000 BCE to 2004 CE. The pale green line is the mean of 280.9 from 600 BCE to 1750 CE.

Given the exponential forcing from the total cumulative emissions, the line in purple from Figure 3 is a possible upper bound of a safe region to reduce major CO_2 concentration increase from outgassing. However, it's also possible the only safe region to prevent major CO_2 concentration increase from outgassing, is the total removal of all cumulative anthropogenic emissions since 1750.

3. Determining Carbon Dioxide to be Removed

By removing carbon dioxide from the atmosphere, we can set the CO_2 concentration to a specific ppm level. If the total anthropogenic emissions were removed from the atmospheric sink equalling 271.3 GtC, given there are still hundreds of gigatonnes of carbon remaining in the other sinks outgassing and diffusion would transfer the CO_2 in the land and ocean sinks back to the atmosphere. Specifically, if we were to remove 271.3 GtC (627.1 - 271.3 = 355.8 or 431.6 - 271.3 = 160.3), we'd still have a remaining 356 GtC for the ocean plus land, or 160 GtC assuming the land-use change is roughly equal to the land sink. Still assuming the land-use change is roughly the same as the land sink, the natural rebalancing would move atmospheric CO_2 concentration from 277 ppm upwards depending on how much the land sink outgasses. 160 GtC was last seen during 1980 when cumulative fossil fuel emissions were 164 GtC. After we reach a desired atmospheric concentration level, we need to continue to remove additional carbon dioxide to lower the anthropogenic carbon diffused in the ocean surface waters.

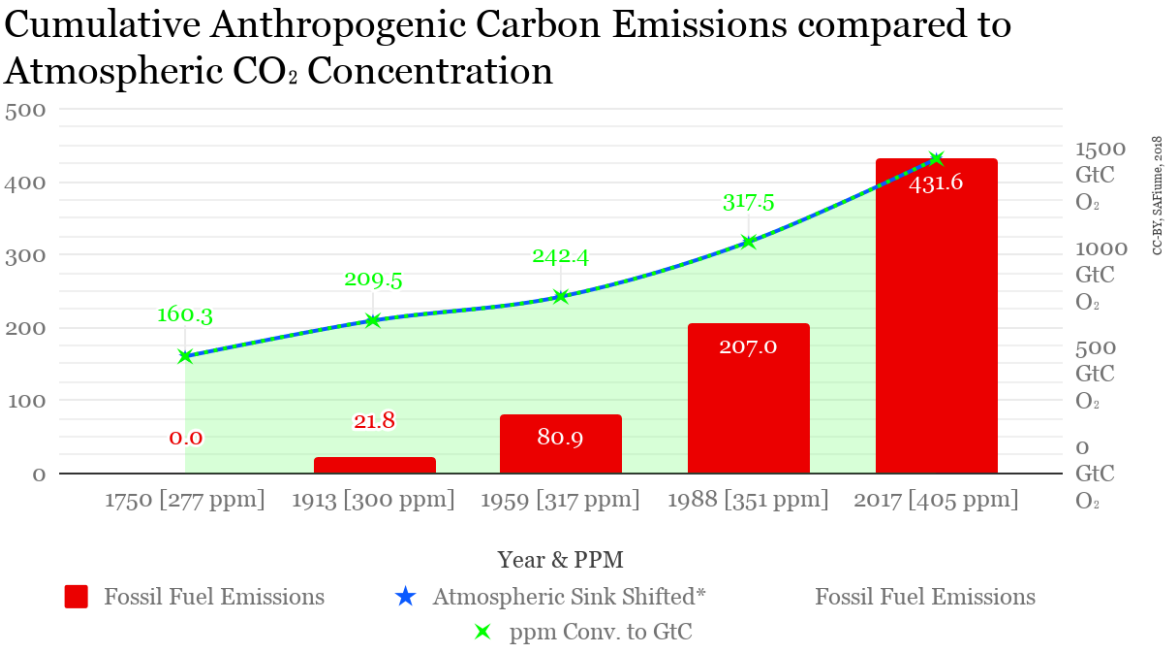

Figure 5 | Fossil Fuel Emissions and CO_2 ppm concentration converted to GtC for the years, 1750, 1913, 1959, 1988, 2017. The horizontal axis scaling isn't to scale and hides the true exponential extent of these curves. The ppm curve in green closely matches the global average CO_2 concentration when converted to GtC. Atmosphere shifted data points for 1998, and 2017 are from the Mauna Loa yearly global average CO_2 ppm minus 277 ppm converted to GtC.

Figure 5, shows the atmospheric curve in blue is very close to the CO_2 concentration in ppm converted to GtC, shown in green. The curves are practically equal as anthropogenic atmospheric CO_2 is atmospheric CO_2 ppm - 277 ppm.

For illustration purposes, we'll examine a common target of 350 ppm. 350 ppm ~~is a pathway below 2ºC, which~~ was roughly seen in 1988 when atmospheric emissions were about 317 GtC, or if starting from now equals a removal of 431.6 - 317.5 GtC = 114.1 GtC. The data point for 351 ppm is shown 114.1 GtC lower than 431.6 GtC in Figure 5. If we remove 114.1 GtC, the atmosphere would likely increase upwards above 350 ppm, from the ocean and possibly land outgassing.

To more accurately affect and remove carbon deposited to all sinks, we refer to the historical anthropogenic concentrations for each sink. To illustrate how to determine how much carbon to remove, find the year the desired ppm or emissions occurred, then take the current cumulative emissions and subtract the historical cumulative emissions for that year. For 350 ppm, the actual removal should be 431.6 - 207.0 GtC equalling 224.6 GtC. Note, that 350 ppm is significantly far from the baseline of 280.9 ppm and which represents about 207 gigatonnes of carbon that wasn't previously in the atmosphere or oceans since the mid-Pliocene warm period or about 3.2 MyBP (million years before present, or million years since 1950 CE) (Raymo et al., 1992).

Figure 6 shows the cumulative stacking of all natural sinks and emissions sources for five individual years. The ppm curve is the same as above, and like above practically overlays the atmospheric curve. The atmospheric sink in the dashed blue line has been upshifted by the final total of the ocean sink (157.5 GtC) to show total growth in sinks from emissions. The ocean and land sink show very similar growth rates. The exponential increase in emissions radically increases the amount of carbon that ought to be removed to stabilize Earth's climate.

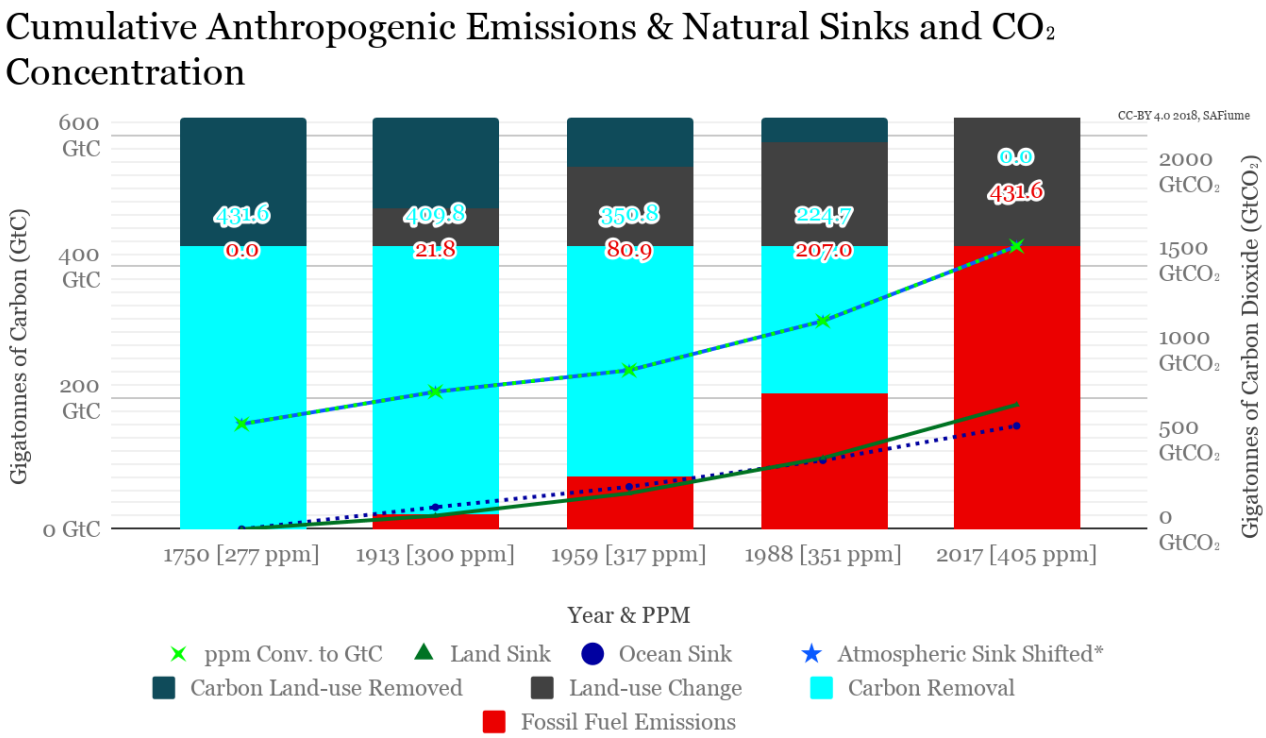

Figure 6 | This graph shows a conversion of ppm to GtC shifted to descend from 431.6 GtC, and the rate increase for the natural sinks over time. It has stacked columns of fossil fuel, land-use change emissions, and carbon removal targets for the years, 1750, 1913, 1959, 1988, and 2017, corresponding to 277, 300, 317, 351, 405 ppm, and natural sink growth. CO_2 ppm concentration is converted to GtC. The Carbon Removal is the total amount of carbon that would have to be removed to restore the carbon dioxide concentration in all sinks and emissions for that time. If we remove a total of 409.8 GtC and also 174 GtC from land-use change emissions, we would achieve 300 ppm last seen in 1913.

'We infer from Cenozoic data that CO_2 was the dominant Cenozoic forcing, that CO_2 was ~450 ± 100 ppm when Antarctica glaciated, and that glaciation is reversible.' (Hansen et al., 2008) The error margin of 100 ppm is wide enough to place reversing glaciation possible at 350 ppm. Given the radical nature of the exponential increase from 277 ppm and temperature increase from pre-industrial times, 350 ppm isn't likely to yield a long-term stable climate.

Given the magnitude of outgassing by the three sinks, effort should focus on removal of total cumulative anthropogenic carbon for a given time period to achieve a specific CO_2 concentration, not only by the conversion of ppm to GtC for the atmospheric sink. To achieve 277 ppm, focus on removing total cumulative anthropogenic emissions, all 431.6 GtC (approximately 1.5 trillion tonnes CO_2) and forcing the land sink to zero emissions, not by just removing 272 GtC (approximately 1 trillion tonnes of CO_2).

3.1 Comparison with Yearly Change

To better visualize the magnitude of growth in total emissions, total cumulative carbon emissions were graphed opposed to the year to year change in emissions. In comparison Figure 7 shows the yearly change of emissions more commonly seen in the SSPs and most emissions papers. The yearly change graph hides the true exponential nature of emissions curves and doesn't easily show how much carbon may need to be removed to restore climate to a desired emissions target. For illustration in Figure 7, the SSP2 RCP 2.6 by the GCAM4 team was modeled in orange with the existing sinks and emissions data as well as four possible hypothesis pathways to zero cumulative emissions. SSP2 RCP 2.6 GCAM4 is the lowest emitting scenario of all the existing SSPs: under this scenario, we

slow emissions the fastest and cumulatively drop and remove CO_2 the fastest (SSP Public Database version 1.1, 2018). The SSP2 RCP 2.6 GCAM4 emissions data spline was extrapolated from the emissions per decade starting from 2010 to 2100 and including emissions from 2005 as listed from the SSP database. The newer RCP 1.9 data wasn't available at the time of this paper. RCP 2.6 sets radiative forcing at 2.6, which is roughly 451 ppm of CO_2-eq. Actual CO_2 ppm would be lower at about 376 ppm, due to forcing circa 2005, or 2004 which was 277 * exp(1.63/5.35) = 376 ppm (NOAA, 2016). In Figure 7, it's not readily apparent what cumulative emissions will be at the end of each pathway. Our hypotheses pathways drop down to zero cumulative emissions in 2040, and 2100 (shown in detail in Figure 8), whereas GCAM4 drops cumulative fossil fuel emissions down to about 576 GtC, roughly equivalent to radiative forcing 2.6 and holding carbon dioxide concentrations to about 450 or 376 ppm by the end of 2100.

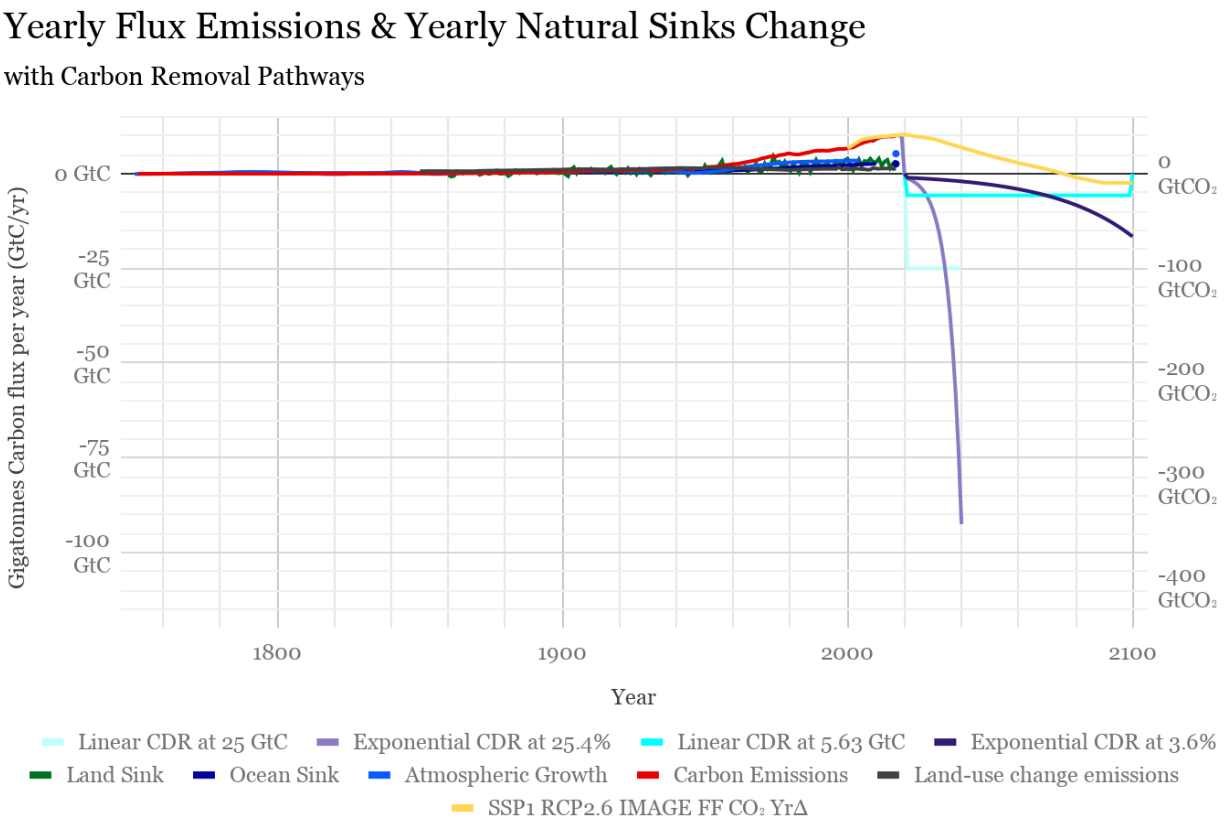

Figure 7 | This is the yearly graph of emissions and sinks change. Included are the pathways for carbon removal to achieve zero cumulative emissions. Most of the standard SSPs cross zero GtC after 2040 and end by 2100 or later. The SSPs only remove the equivalent carbon to equal the given radiative forcing and not all anthropogenic emissions.

As the SSPs don't list the cumulative staring emissions, Figure 8 lists SSP 2.6 GCAM4 yearly change emissions modeled on both cumulative fossil fuel and total cumulative emissions (fossil fuel added to land use-change) starting from levels in 2005. It also uses the extrapolated emissions data spline for SSP 2.6 GCAM4 like in Figure 7. Unlike the other pathways or sinks which list direct carbon dioxide emissions, the SSP modeling represents radiative forcing of total warming converted to carbon dioxide equivalent or CO_2-eq. The lines shown here are modeled directly with the data from the SSP (therefore CO_2-eq) and not an extraction of the actual CO_2 emissions from the radiative forcing. The actual CO_2 from emissions would be lower as radiative forcing includes data from other more potent GHGs such as methane and sulfur hexafluoride. The orange dotted line could end at a lower

point equivalent to 376 ppm or 319 GtC as opposed to its current endpoint of 576 GtC. Even using the lower value of 376 ppm, 319 GtC in cumulative fossil fuel emissions is quite a difference from 21.8 GtC for 300 ppm or zero cumulative emissions. Under the newer RCP 1.9, CO_2 emissions could be as low as 184.3 GtC corresponding to CO_2 forcing of 1.14 seen in 1984 (NOAA, 2016). Although 184.3 GtC is less than 207 GtC (cumulative fossil fuel emissions at 1988, and 351 ppm), it is still a magnitude larger than 21.8 GtC.

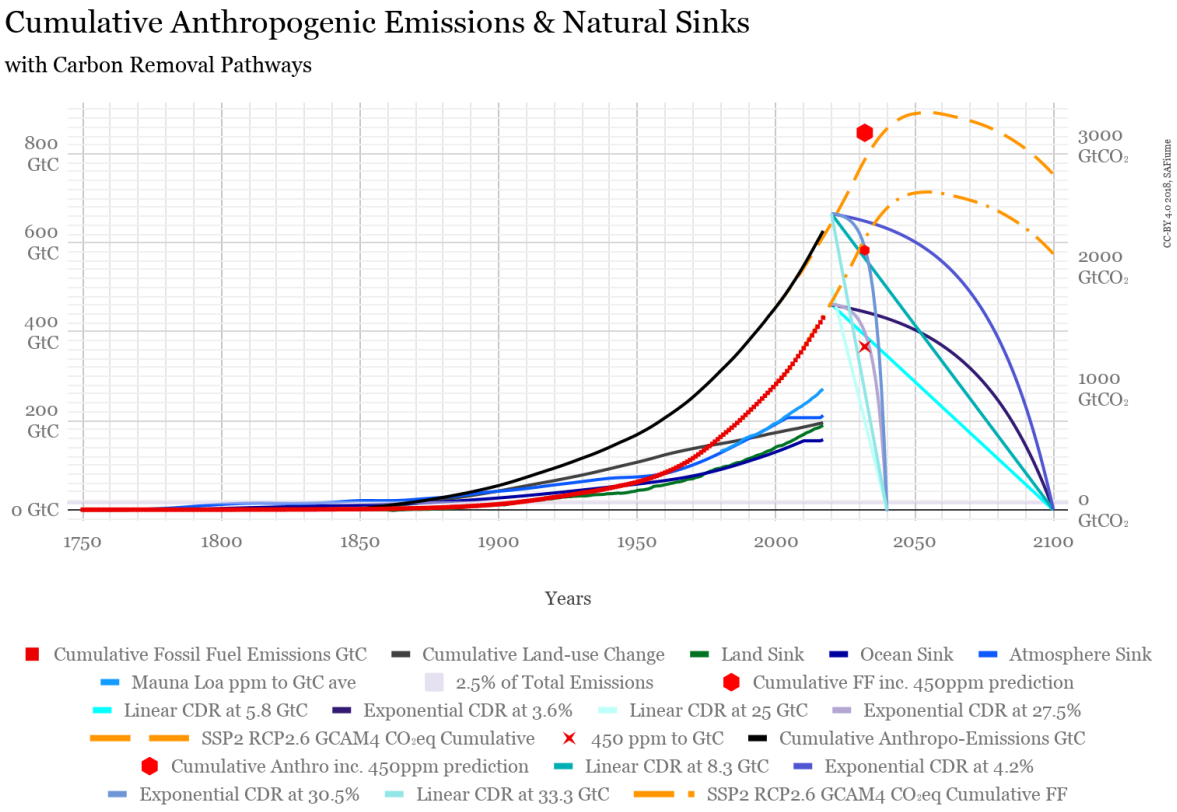

Figure 8 | Also included is the SSP with the fewest total emissions, SSP2 RCP 2.6 GCAM4, and shown in the dashed orange lines. As the SSPs don't list what the starting total cumulative carbon emissions quantity, or list if they use the total cumulative carbon from fossil fuel emissions or emissions added to land-use, the 2.6 GCAM4 pathway has been modeled on both total emissions shown in black and fossil fuel emissions shown in red squares. In both cases RCP 2.6 for radiative forcing 2.6 or about 450 ppm CO_2-eq. Note, actual CO_2 ppm could be as low as about 376 ppm, due to the radiative forcing for only CO_2 circa 2005, or 2004 => 277 * exp(1.63/5.35) = 376. The RCPs should be on their own graph that's calibrated to CO2-eq. Adjusting where 376 ppm would be, there's not enough information to tell if the polar regions would return to a solid state. The difference is that the lowest orange line should end about 319 GtC in the year 2100.

Given exponential forcing of emissions, some small region starting at 277 ppm possibly up to 300 ppm is likely to lead to a stable climate where little to no outgassing from the other sinks. 300 ppm (last seen in 1913 when fossil fuel emissions were 22 GtC, and land-use change was 57 GtC) and less should be investigated to find the determining factor or Earth system configuration for climate stability. The investigation model or hypothetical should be able to set carbon concentration simultaneously within all sinks: atmosphere, ocean and land, and also model large volume carbon removal over time spans of ultrashort, short, medium and long time frames.

Since the direct consequence of lowering CO_2 concentration results in outgassing and as the fossil fuel emission curve is a steep exponential of growing carbon, climate stability is likely with a very low to zero percentage of fossil fuel emissions. If verified, nearly all, or the cumulative total amount of carbon from fossil fuel emissions,

should be removed from ocean surface water and atmosphere sinks before we can see a stable climate. By removing the total amount of carbon it should additionally force the ocean sink to become more basic, and should hopefully, return natural albedo cooling and natural restoration of the cryosphere.

As the originating source emissions and subsequent natural sinks are exponentially increasing, at our current growth rate of 2% per year we have a little over 14 years before hitting 450 ppm as shown in Figure 8. We have little time to hit peak emissions, and then zero yearly emissions.

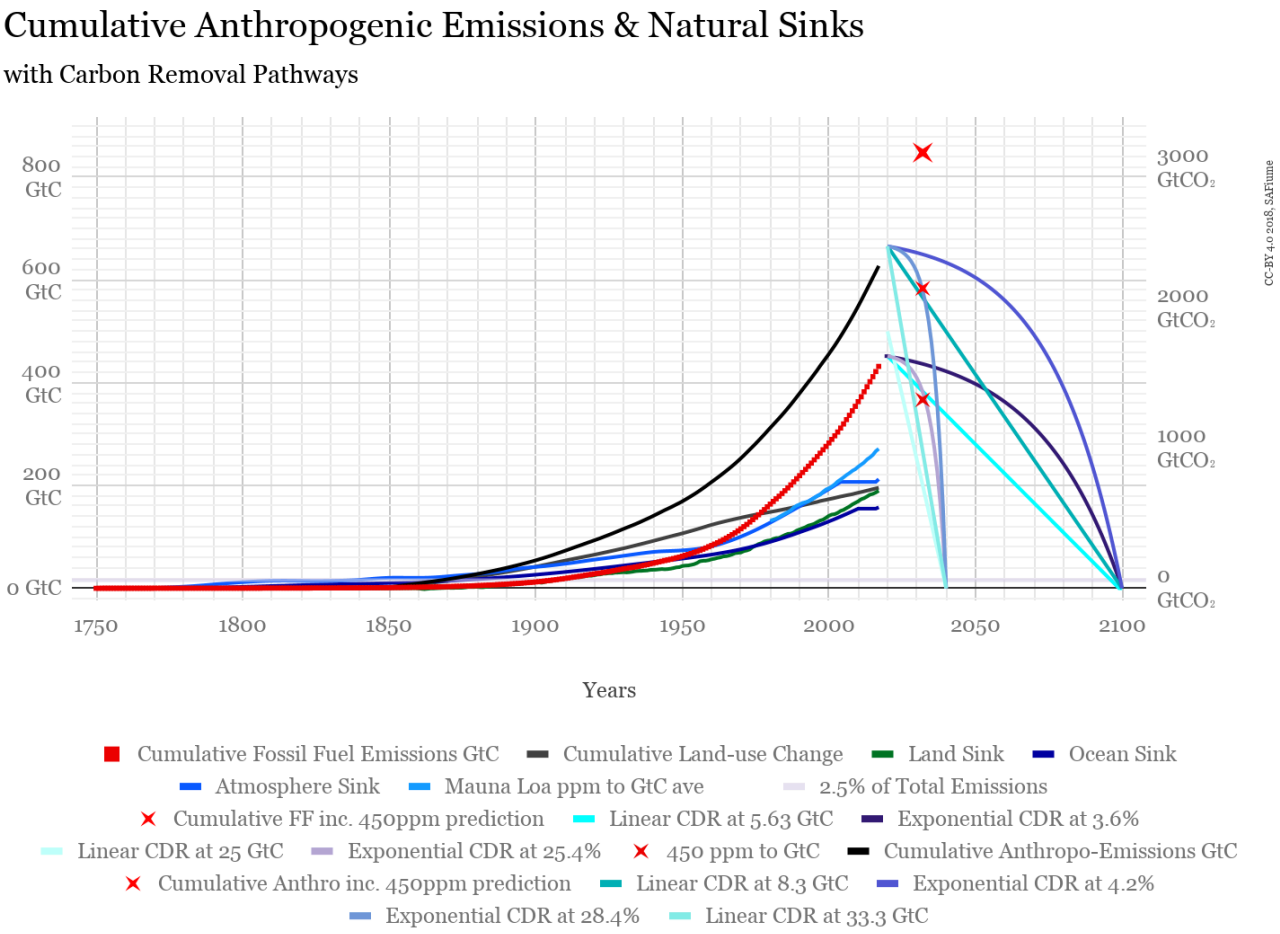

Figure 9 | Cumulative Anthropogenic Emissions & Natural Sinks and pathways to zero cumulative emissions.

4. Possible Pathways to Zero Degrees Warming

Four hypothetical pathways are presented to show linear and exponential declines to bound removal in a minimum and maximum timeframe. In Figure 9, zero degrees warming pathway can be achieved by the curves in shades of cyan or purple. A possible maximum cumulative emissions removal is shown spanning eighty years. The cyan line is a hypothetical linear carbon removal of 5.8 GtC year $^{-1}$ for eighty years, starting at 500 GtC. By 2080, there would only be about 115 GtC left to remove. Depending on how the CO_2 concentration was split between the sinks, the oceans should see significant recovery as well as slight global cooling by 2080. The dark purple curve shows an exponential decline of 3.5% starting from 461 GtC in 2020 finally trending to below zero in 2100.

For climate restoration in less than half a human lifespan, the pale lines show hyper-aggressive carbon removal in 20 years. The pale purple shows an exponential decline of 27.5% starting from 461 GtC in 2020 finally trending to below zero in 2040. The pale cyan shows a linear removal of 25 GtC year $^{-1}$ for twenty years, and 125 GtC would be remaining at year 15. How fast the oceans recover, or permafrost regenerates in response to an abrupt drop in CO_2 concentration should be explored. In an abrupt CO_2 concentration drop scenario, solid carbon could additionally be distributed to the land sink, to keep the land sink absorption high.

The exponential decline pathways are ones that mimic a slow exponential increase of reduction in carbon emissions. Exponential curves are more similar to a rapid technology adoption model, or crash in price from technological improvements and follow Moore's Law.

5. Data Availability

All data and graphs are available in the open google spreadsheet: Total Emitted Carbon Graphs and Comparisons. SSP2 RCP 2.6 GCAM4 data was obtained at the SSP Public Database version 1.1 and generated in 2018. This paper is open and licensed under the Creative Commons CC-BY 4.0 International License.

6. Conclusion

The exponential nature of cumulative growth in emissions is obscured when only considering a radiative forcing level or purely looking at the yearly change in emissions. The complex nature of emissions diffused in surface waters and interaction with the atmospheric sink justifies a more involved approach to generating CDR targets, rather than a plain conversion of ppm to bulk carbon. Given the exponential nature and magnitudes larger than zero cumulative emissions, CDR to 22 GtC fossil fuel + 57 GtC land-use change ranging to CDR to zero cumulative emissions would highly benefit from additional study. By creating CDR targets from total cumulative emissions, we aid in progress toward eventual complete climate restoration. Given the vast amounts of carbon that needs to be removed for complete climate restoration, carbon dioxide removal technologies: geo-engineering, bio-engineering, and others engineering and processes comprising negative emissions technologies, and natural processes, should aid the existing portfolio of technologies, processes, and policies, such as, renewables, non-fossil fuels, clean nuclear, energy storage, and phase-out of fossil fuels, etc., to seek peak and zero emissions, and ultimately climate restoration. The sooner we hit peak then zero yearly emissions; the less CO_2 we have to remove. All efforts should be made to hit peak followed by zero yearly emissions as soon as possible, to start the removal of potentially more than 1.5 trillion tonnes of carbon dioxide. As nature abhors a vacuum, we have a massive opportunity to create with carbon derived from pollution.

7. Error and Uncertainties

All measured data has an uncertainty up to one standard deviation. Uncertainty for the cumulative anthropogenic fossil fuel emissions is ± 5% from the Global Carbon Budget (Le Quéré et al., 2018) and CDIAC (Boden et al., 2017). '*Generally, […] mature economies […] have uncertainties of a few percent[s] while developing countries such as China have uncertainties around ± 10%.*' (Le Quéré et al., 2018). Overall a medium confidence was given to the fossil fuel emissions dataset, as it was generated indirectly from energy data (Durant et al., 2011) and includes per country data variation. Land-use change emissions uncertainty is estimated at ± 0.7 GtC yr $^{-1}$ and was assigned a low confidence due to *'the inconsistencies among estimates and the difficulties to quantify some of the processes in DGVMs'* (Le Quéré et al., 2018). For the natural sinks: the land sink uncertainty for the Dynamic

Global Vegetation Models (DGVMs) averages to ±0.8 GtC yr $^{-1}$ from 1959 to 2016 and has a medium confidence level. The ocean surface water sink uncertainty yearly change is ±0.5 GtC and given a medium confidence. The atmospheric annual growth uncertainty is has a mean of 0.61 GtC yr $^{-1}$ for 1959-1979, and 0.19 GtC yr $^{-1}$ for 1980-2016, and was given a high confidence given the direct measurements comprising the datasets. The historical atmospheric CO_2 concentration from 1750-1959 has an uncertainty of ±3 ppm converted to ±1σ, from the Law Dome ice core data (Joos et al., 2008).

The 1980 - 2017 CO_2 concentration from Mauna Loa provided by NOAA/ESRL is listed with an uncertainty of 0.10 ppm. Antarctic Law Dome ice core data spline has an uncertainty of 1.2 ppm for 1-2004 CE (Etheridge et al., 1996; 2010), and individual ice core samples at 1.1 ppm for 1-1996 CE (MacFarling Meure et al., 2006). The Antarctic ice core data points for EPICA Dome Concordia (Dome C) (Monnin et al., 2001; Luthi et al., 2008), Vostock (Petit et al., 1999; Pépin et al., 2001; Siegenthaler et al., 2005; Luthi et al., 2008), Taylor Dome (Indermühle et al., 2001), WAIS Divide (Bauska et al., 2015), Maud Land and the South Pole (Siegenthaler et al., 2017), have uncertainty ranging from .1 ppm up to 2.62 ppm, a mean uncertainty of 0.8 ppm. For convenience, the combined datasets and individual uncertainties are listed in the Antarctic Historicals and graph tabs in the spreadsheet Total Emitted Carbon Graphs and Comparisons (Fiume, 2018).

The CO_2 concentration baseline of 280.9 ppm from 600 BCE to 1750 CE has an average uncertainty of 0.9 ppm for the non-splined ice core data points from Dome C (Monnin et al., 2001; Luthi et al., 2008), Law Dome (Etheridge et al., 1996; MacFarling Meure et al., 2006), WAIS Divide (Bauska et al., 2015), Maud Dome and the South Pole (Siegenthaler et al., 2017). The Mauna Loa records show slightly elevated concentrations over the modern Law Dome readings and as a precaution, lowers the confidence level slightly to medium-high.

8. Competing Interests

Shannon Fiume runs Open NanoCarbon (received $100 USD, in total donations) a presently unfunded open science think tank doing open research and development to solidify carbon from atmospheric CO_2, with the charter to enable complete climate restoration by removal of total anthropogenic emitted carbon dioxide.

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