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Less than half of the increase in atmospheric CO_2 is due to the burning of fossil fuels

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Abstract:

The question is: What fraction of the observed increase in atmospheric CO_2 since 1750 is due to the burning of fossil fuels? Is it close to 1.0 as the IPCC and the climate policy makers would have us believe by saying that all, or nearly all, of the increase is due to the burning of fossil fuels i.e., the climate changes we are seeing are caused by humans. This paper is all about this fraction. I use networks of boxes and arrows that visualize the carbon accounting. I incorporate the photosynthesis and the temperature dependent non-fossil emission. The networks are balanced by solving simultaneous, linear equations, one for each box. Based on the law of the conservation of mass, in addition to elementary linear algebra, I present and apply a simple, universal, method for global carbon accounting. Assuming that the atmosphere behaves like a physical system with constant residence time 4.1 years, I apply the method and calculate the fraction to be 0.25. In addition, I find that the fraction is linked to the greening of the Earth, quantified as the increase in the photosynthesis on land and in the ocean. Finally, I render it probable that the increase in the non-fossil emission is caused by the temperature increase, the warming of the globe.

Keywords: Carbon balance, atmospheric CO_2, residence time, photosynthesis, greening
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1. Introduction

At the onset of the industrial revolution, about 1750, the atmosphere's CO_2 concentration was about 280 ppm and had been so for several hundreds of years, IPCC (2013). In the 2010s, it was about 405 ppm and rising. The increase, ΔC=125 ppm, is the sum of two parts. One is due to the burning of fossil fuels, ΔC_f, where subscript *f* stands for fossil. The other is ΔC_n, the non-fossil part, where subscript n stands for non-fossil. We have $\Delta C = \Delta C_f + \Delta C_n$. This paper is all about determining the fraction $\Delta C_f / \Delta C$ in order to answer the question: What fraction of the observed increase in atmospheric CO_2 is due to the burning of fossil fuels? This question is important, perhaps the most important question in the climate debate. If the fraction is smaller than 0.5, then the climate policy is way off the track. If it is close to 0, there is no climate crisis at all. The climate change is then not at all caused by humans. It is natural.

2. Assumptions and general notes

Some of the carbon fixed by photosynthesis is 'burned off' in the internal plant metabolism. The plant respiration, also called the autotrophic respiration, returns carbon to the atmosphere. According to Kirschbaum et al. (2001), it typically amounts to about half the carbon fixed by photosynthesis. This is adopted as the main assumption that underlies the present analysis: *Plant respiration is half of the photosynthesis.*

In Section 4.2, I apply yet another assumption: *The atmosphere behaves like a physical system with constant carbon residence time of 4.1 years.*

The concentration of atmospheric CO_2 is in units of ppmv (parts per million by volume in dry air). I omit the "v". To convert this CO_2 concentration into the total mass of atmospheric carbon in GtC (Gigatons of carbon), multiply the ppm by 2.12.

Data for this paper, up to and including Appendix A, come from The Global Carbon Project's (GCP) Global Carbon Budget for the 2010s found in Friedlingstein et al. (2020).

3. Method

3.1 General

It is a matter of conservation of carbon and linear algebra. The global carbon balance is depicted as a network of five boxes (control volumes) connected by arrows symbolizing flows. The conservation equation states that the stock change, in all boxes, over a specified period of time, equals input minus output during the same period of time. This translates into five simultaneous, linear equations with five unknowns making the double-entry bookkeeping method, and the input-output method, a matter of elementary linear algebra.

The method owes a lot to the classical input-out analysis, Leontief (1986). The differences are that I use networks of boxes instead of input-output tables, and my "currencies" are not goods, services and money, but any conserved quantity, carbon in this case.

An ambition of this paper is to keep things as simple as possible, especially the network. The simplest possible network for the global carbon balance, I can think of, is shown in Figure 1.

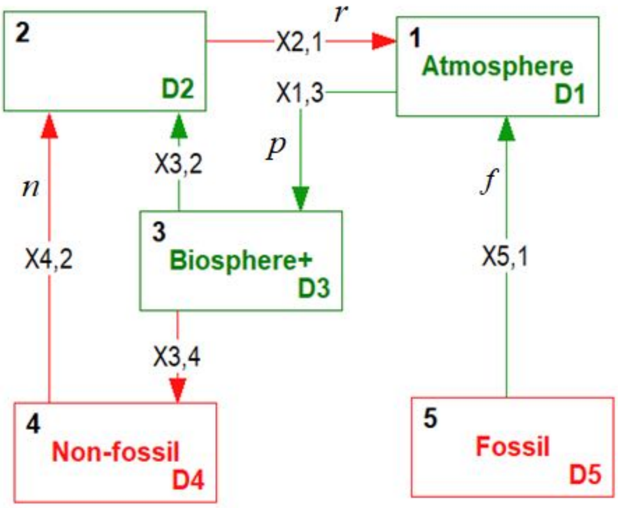

Figure 1. Flows and stock changes in the global carbon balance. Box numbers stand in upper left-hand corners. Xi,j is the flow of carbon from Box i into Box j. The stock change is placed in the lower right-hand corner. Green = knowns; Red = unknowns.

This is a simplified balance. It works on the assumption that there are two separate carbon cycles: A cycle linking land and the atmosphere, and another cycle linking the ocean and the atmosphere. In Figures 1, 3, 4 and 5, these cycles are added. In other words, I add the land-atmosphere cycle (annually fueled by 120 GtC fixed by land photosynthesis), and the ocean-atmosphere cycle (annually fueled by 90 GtC fixed by ocean photosynthesis), in order to keep the network as simple as possible. At the expense of simplicity, in Appendix C, I show the two cycles separately.

The flows are,

p is photosynthesis = X1,3

n is the non-fossil, temperature dependent, emission = X4,2

f is the emission from fossil fuels burning and cement production = X5,1

r is respiration = X2,1

The changes are,

*D*1 is the change of the stock of atmospheric carbon

*D*2 is nil by definition

*D*3 is land use change (mainly deforestation)

*D*4 is the change of the earth's stock of organic matter (recently) accumulated on land and in sediments of the ocean and the freshwaters

*D*5 is the change of the earth's stock of fossil fuels and limestone.

The sum of these stock changes must equal zero, because the system is closed.

Box 2 has no stock change since it is not a physical system; it merely serves to receive two flows, X4,2 and X3,2 and pass them on to the atmosphere. To mix physical and nonphysical systems is not normally done. Here I make an exception.

The balanced networks in Figures 1, 3, 4 and 5 incorporate the photosynthesis, *p*, and the non-fossil, temperature dependent flow, *n*, in the balance and links them to other variables, such as *f*, by linear algebra. Thereby, the carbon *balance* differs from IPCC's and GCP's carbon cycles or budgets.

Suppose we aggregate Box 2, 3 and 4 into a single box, in other words, that we add their balance equations. That would leave us with a diagram showing a one-way flow of carbon from the stock of fossil fuels into the atmosphere, and from there into land and ocean reservoirs. The photosynthesis, and the non-fossil emission cancel. This makes the burning of fossil fuels the only source of carbon to the atmosphere. This wrong perception becomes apparent, when the IPCC claims that carbon from the stock of fossil fuels is "distributed" to three reservoirs: The atmosphere, land, and the ocean.

It certainly looks so, since the negative change of the stock of fossil fuels carbon, added to the positive stock changes in the atmosphere, on land, and in the ocean is zero by virtue of the law of the conservation of mass. But we need to understand how this distribution to the three reservoirs comes about by applying linear algebra.

3.2 The equations

The conservation equation for atmospheric carbon is,

$$D1 = input - output \tag{1}$$

Referring to Figure 1, we have,

$$D1 = r + f - p \tag{2}$$

The main assumption translates into,

$$r = n + 0.5p \tag{3}$$

Insert this in Equation (2), and arrange terms to get,

$$D1 + 0.5p = n + f \tag{4}$$

By definition we have,

$$D1 = \frac{dA}{dt} \tag{5}$$

So, in recognizable mathematical notation, the equation for the conservation of atmospheric carbon is this first order differential equation,

$$\frac{dA}{dt} + 0.5p(A) = n(T(t)) + f(t) \tag{6}$$

On the left-hand side of the equation, A is the atmosphere's stock of carbon, and t is time. The photosynthesis $p(A)$ is a function of A, and therefore also of t.

On the right-hand side of the equation is the "forcing functions", called so because they are independent of the stock. The non-fossil emission $n(T(t))$ is a function of temperature T, which is a function of time; $f(t)$ is a function of time only.

The atmosphere can be thought of as a bathtub with two forcing functions represented by two faucet flows, n and f. We have an output of $0.5p$ 'down the drain', see Figure 2. Half of the total output, i.e., the photosynthesis, is returned to the atmosphere by plant respiration. This circular flow makes no difference to the balance since it is an input and an output.

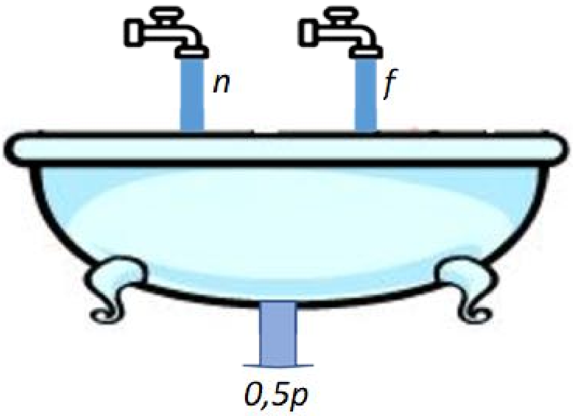

Figure 2. The atmosphere compared to a bathtub with two faucets.

The conservation equation is valid at any time. I consider two points in time: 1750 ($t = 0$), and the 2010s (t =265 years). Suppose the flows n and f increased in equal amounts, $\Delta n = \Delta f$, then they would each contribute half of the observed increase. In general, the fraction due to the burning of fossil fuels is,

$$\alpha_f = \frac{\Delta f}{\Delta f + \Delta n} = \frac{\Delta C_f}{\Delta C} \tag{7}$$

where Δf is the increase in the emission of CO_2-C due to the burning of *f*ossil fuels, and Δn is the increase in the non-fossil, temperature dependent, emission.

The fraction, α_f, is also the increase in atmospheric CO_2 concentration, due to the burning of fossil fuels, in proportion to the observed increase.

This is an approximation. Strictly speaking, it is valid only under steady-state conditions, i.e., when the stock changes are zero. It applies as an approximation to conditions in which the stock changes are so small, compared to other terms in the equation, that they can be omitted in a first order approximation. In the present case, the stock change term amounts to about five percent. Considering the other uncertainties involved, the approximation is considered acceptable.

4. Results

4.1 Determining Δn, the increase in the non-fossil, temperature dependent emission

First, consider the balance equation for atmospheric carbon,

$$D1(t) + 0.5p(t) = n(t) + f(t) \tag{8}$$

Second, set $t = 0$ to get the balance in 1750,

$$D1(0) + 0.5p(0) = n(0) + f(0) \tag{9}$$

At that time, the system, supposedly, was in a steady state. In other words, the change of the atmosphere's stock of carbon, $D1(0)$ was close to zero, and, of course, $f(0) = 0$. Hence,

$$0.5\,p(0) = n(0) \tag{10}$$

Subtract Equation (10) from Equation (8) to get,

$$D1(t) + 0.5\Delta p = \Delta n + \Delta f \tag{11}$$

in which Δp is the increase in the photosynthesis on land and in the ocean. Δn is the increase in the non-fossil emission, from land and from the ocean, and finally, Δf is the increase in the emission of carbon due to the burning of fossil fuels.

Rearrange to get,

$$\Delta n = 0.5\Delta p + D1(t) - f(t) \tag{12}$$

Note that $f(t) = \Delta f$ since $f(0) = 0$.

At $t = 265$ years, we have $D1(t) = 5.1$ GtC per year, and $f(t) = 9.4$ GtC per year, Friedlingstein et al. (2020), so that,

$$\Delta n = 0.5\Delta p - 4.3 \text{ (GtC per year)} \tag{13}$$

which lets us calculate Δn, and subsequently α_f, as a function of Δp, the increase in the global photosynthesis, the “greening of the Earth”.

Solve for Δp and get,

$$\Delta p = 2\Delta n + 8.6 \text{ (GtC per year)} \tag{14}$$

The IPCC and the climate policy makers seem to believe that there is only one source of carbon dioxide to the atmosphere: the burning of fossil fuels. This is true only if one assumes that the flow, n, has stayed constant since 1750 in spite of the warming. In other words, $\Delta n = 0$. Insert this in Equation to get $\Delta p = 8.6$ GtC per year, which is the corresponding increase in the photosynthesis.

Up to this point, I have only considered the increase in the photosynthesis without mentioning its actual magnitude. The Global Carbon Budget 2020, shown in Appendix A, indicates that the photosynthesis in the 2010s is 120 GtC per year on land, and 90 GtC per year in the ocean, a total of 210 GtC per year. For $\Delta n = 0$, the photosynthesis would therefore have increased by a factor of 210/(210–8.6) =1.04 or four percent, which is much lower than normally estimated in climate research.

IPCC (2013) estimates that $\Delta n = 34.1$ GtC per year, see Table B1. The factor then is 210/(210 –34.1) = 1.19 or 19 percent, which is likely, but it contradicts IPCC’s own claim that burning of fossil fuels is the only source of carbon to the atmosphere.

4.2 Calculation of α_f assuming the atmosphere behaves like a physical system with constant residence time 4.1 years

A commonly applied hypothesis in the modelling of physical systems, is that outflow is proportional to level, Berry (2021). In other words, output is proportional to stock. The photosynthesis, p, is the dominant output from the atmosphere. The residence time T_r, also called the turnover time, or the “e- time”, is defined as the stock, A(t), divided by the output, p(t),

$$T_r = \frac{A(t)}{p(t)} \tag{15}$$

The hypothesis output is proportional to stock, is equivalent to saying that T_r is constant, and that p is proportional to A, and hence to C. For t=256 years (the 2010s), $C(t) = 405$ ppm, so that,

$$T_r = \frac{2.12 \times 405}{210} = 4.1 \text{ years} \tag{16}$$

The hypothesis works well for physical systems, e.g., electrical circuits, but it has to be a first order approximation when applied to the global carbon balance. Nevertheless, tentatively assume that the residence time is constant, the same at all times, including $t = 0$. Then,

$$\frac{A(t)}{p(t)} = \frac{A(0)}{p(0)} \tag{17}$$

and therefore,

$$\frac{A(t)}{A(0)} = \frac{p(t)}{p(0)} = \frac{C(t)}{C(0)} \tag{18}$$

from which,

$$p(0) = \frac{C(0)}{C(t)} p(t) \tag{19}$$

and,

$$\Delta p = p(t)\left(1 - \frac{C(0)}{C(t)}\right) = 210\left(1 - \frac{280}{405}\right) = 65 \text{ GtC per year} \tag{20}$$

which inserted in Equation (13) gives $\Delta n = 0.5 \times 65 - 4.3 = 28.2$ GtC per year, which inserted in Equation (7), along with $\Delta f = 9.4$ GtC per year, gives $\alpha_f = 9.4 / (9.4 + 28.2) = 0.25$.

So, assuming a constant residence time of 4.1 years (in addition to the main assumption of this paper), 25 percent of the observed increase in the CO_2 concentration is due to the burning of fossil fuels.

4.3 Others' results

Berry (2021) applies a residence time, or "e-time" as he calls it, of 3.5 years. As opposed to the present analysis, he used IPCC data only and numerically solved four simultaneous differential equations using recursive, annual time steps from 1750 to 2020. He found $\Delta C_f = 33$ ppm and $\Delta C = 133$ ppm (in 2020) from which $\alpha_f = 33 / 133 = 0.25$.

Applying a constant residence time of 3.5 years, instead of 4.1 years, gives, $\alpha_f = 0.22$. Likewise, the number of years since 1750 plays a role. The present analysis deviates (slightly) from Berry's on both accounts. Yet, the result comes out to be the same to the second decimal place.

Skrable et al. (2022) established annual mean values in 1750 through 2018 of the atmosphere's specific activity of ^{14}C, which gets diluted when fossil CO_2-C (devoid of ^{14}C) enters the atmosphere. From this, they were able to calculate $\Delta C_f = 47$ ppm (in 2018) out of the observed increase of 129 ppm, which makes $\alpha_f = 47 / 129 = 0.36$.

Harde (2019) found $\Delta C_f = 17$ ppm. He sets the concentration increase since 1750 at 113 ppm, making $\alpha_f = 17 / 113 = 0.15$.

4.4. The fraction α_f is linked to the greening

There is a unique relationship between the greening, the increase in the photosynthesis, on the one hand, and the fraction α_f on the other. An estimate of Δp, translates into an estimate of α_f.

Table 1. Results in the framework of the present analysis.

	α_f	**Photosynthesis increase percent**	Δn **GtC/yr**	Δf **GtC/yr**	Δp **GtC/yr**	$n(t) / n(0)$
IPCC	1.00	4	0	9.4	8.6	1.00
For reference	0.50	15	9.4	9.4	27.4	1.10
Skrable et al.	0.36	25	16.7	9.4	42.0	1.20
Present + Berry	0.25	45	28.2	9.4	65.0	1.39
Harde	0.15	121	53.3	9.4	115.0	2.12

The increase in the photosynthesis is four percent in the very unlikely event that the rate of decomposition of organic matter stayed constant ($\Delta n = 0$) since 1750 – in spite of the warming. At 15 percent increase, $\alpha_f = 0.50$, and so on down to the bottom row, where $\alpha_f = 0.15$, i.e., 15 percent of the increase in atmospheric CO_2 is due to the burning of fossil fuels.

This result, however, does not fit the present analysis, since it is not likely that the photosynthesis more than doubled. An increase in the range 25 to 45 percent is more likely, corresponding to α_f in the range 0.36 to 0.25, say about a third.

5. Balanced networks visualize the carbon accounting

One can also determine Δn, and therefore also α_f, by means of networks of boxes, with stock changes, and arrows as flows, balanced by solving the simultaneous conservation equations.

In money accounting, one has to record all flows and stock changes to make sure money neither disappears nor appears. In carbon accounting, we know for sure that carbon is a conserved quantity. Each box in the network therefore holds its balance equation. This allows us to calculate, in the present case, five variables (flows and stock changes). This approach makes things easy; it is nothing but linear algebra. In addition, the visualization of the accounting makes the balance easier to comprehend.

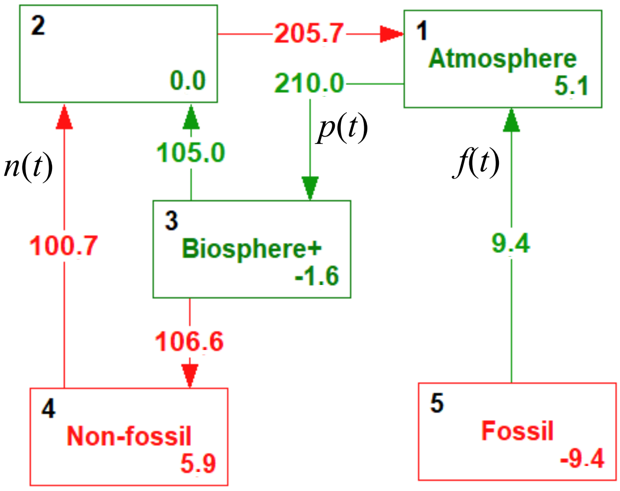

Figure 3. The global carbon balance averaged over the 2010s, GtC per year. Compare with the Global Carbon Budget 2020, Friedlingstein et al. (2020) shown in Appendix A.

The Global Carbon Budget 2020, and the present global carbon balance for the 2010s, are compared in Appendix A. Notice that

$$D3 + D4 = -1.6 + 5.9 = 4.3 = p - r = f - D1 \tag{21}$$

and that the sum of the stock changes equals zero.

There are five boxes, and therefore five linear conservation equations with five unknowns, dependent variables, data output shown in red.

In contrast, the green variables are independent variables, data input. So, if we enter the variables valid for the time around 1750, and solve the new set of simultaneous equations, we get the global carbon balance at that time.

In the pre-industrial era, $f(0) = 0$. The system supposedly was in quasi-steady state with stock changes close to zero – with one exception, namely the land use change, $D3$, which was minus 0.7 GtC per year at that time.

The photosynthesis in 1750 ($t = 0$) remains to be estimated in order to proceed. Take for example

$$p(0) = 145 \text{ GtC/year} \tag{22}$$

to make the fraction 0.25. Now, the five simultaneous equations can be solved to yield the balanced network for 1750 shown in Figure 4.

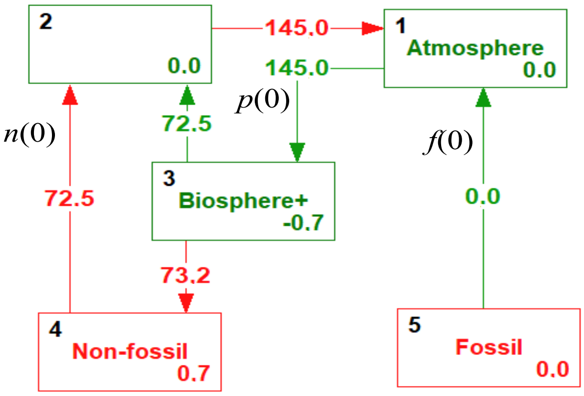

Figure 4. The global carbon balance 1750, GtC per year.

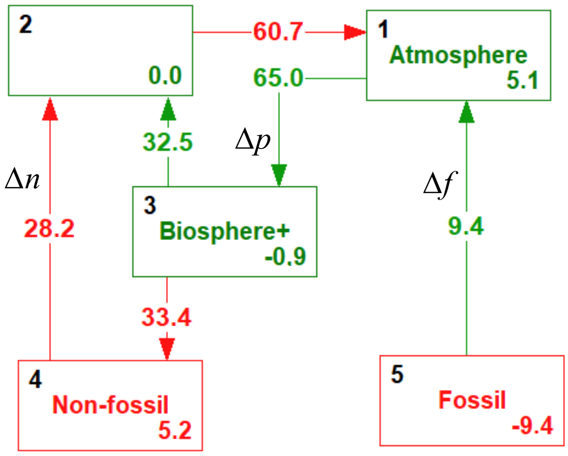

Figure 5. The balance in Figure 3 (2010s) minus the balance in Figure 4 (1750) in GtC per year.

In Figure 5,

$$\Delta n = 28.2 \text{ GtC per year} \tag{23}$$

and

$$\Delta f = 9.4 \text{ GtC per year} \tag{24}$$

Applying Equation (7), we get

$$\alpha_f = \frac{9.4}{9.4 + 28.2} = 0.25 \tag{25}$$

The input-output approach is easy to comprehend because of the visualization. It is a matter of using an easily programmed piece of software, which, based on the network, automatically sets up the simultaneous equations and solves them on command.

6. The role of the ocean

It is often asserted that the ocean plays a decisive role. During the glacial-interglacial cycles, the ocean has no doubt played an important role, but apparently not during the last 265 years.

My explanation is this: In the 2010s, the land sink was 3.4 GtC per year, and the ocean sink 2.5 GtC per year, see Appendix A. The total sink (stock change) is 5.9 GtC per year, which stands in the lower right-hand corner of Box 4 in Figure 3.

The land sink is caused by the photosynthesis, it is biological only, while the ocean sink has a physical component (governed by Henry's Law) in addition to a biological component, the biological pump.

The physical component has to be smaller than 2.5 GtC per year in order to leave room for the biological pump. I estimate it to be in the order of 0.5 GtC per year, which, considering the uncertainties involved, is too small to justify a (much) more detailed network to account for it.

7. Discussion

7.1 The hypothesis residence time is constant

The outflow is proportional to level (stock) hypothesis is equivalent to saying that the photosynthesis is proportional to the CO_2 concentration. Think of it as a giant plant nutrition experiment. The fertilizer, CO_2, is added to the atmosphere in increasing amounts.

In response, the yield, the photosynthesis, increases, but why exactly in direct proportion to the concentration? This would make the yield curve a straight line passing through the origin of the coordinate system. The yield curve, however, is expected to bend downwards, and it doesn't pass through the origin of the coordinate system since the photosynthesis ceases to work when the CO_2 concentration gets below 150 ppm.

Still, the result that about 25 percent of the increase in atmospheric CO_2 is due to the burning of fossil fuels, stands out. First, because the result has been obtained independently by two researchers. Second, because the result can be calculated using elementary mathematics.

7.2 Sensitivity to the main assumption

The main assumption is that the plant respiration is half of the photosynthesis: 0.5p. Had the coefficient instead been 0.4, it would change the fraction α_f from 0.25 to 0.30. Had it been 0.6, it would change it to 0.21. So, the result depends on the estimate of the coefficient, but not to an extent where it invalidates the conclusion.

7.3 The temperature increase explains the non-fossil emission increase

The temperature increase has a direct effect on the emission, *n(t)*, since it speeds up the rate of decomposition of organic matter. The temperature coefficient, Q_{10}, is defined as the factor by which the rate increases when the temperature is increased 10°C. For most biological systems, Q_{10} is between 2 and 3, say 2.5. The non-fossil emission today divided by the emission in 1750 is

$$\frac{n(t)}{n(0)} = Q_{10}^{\left\{\frac{\Delta T}{10}\right\}} \tag{26}$$

in which $\Delta T = 1.1$ °C is the increase in the average global temperature since 1750, so that the factor becomes $2.5^{0.11} = 1.1$. In other words, the non-fossil emission, *n*, would increase by about 10 percent, if the direct effect of temperature on the rate of decomposition were the only governing variable.

It isn't. A warmer climate is generally also a wetter climate because of increased evaporation. So, on land, there is an indirect, additional effect of the warming since the extra soil moisture enhances the rate of decomposition. Hence, the actual effect of the temperature increase is to make the above-mentioned factor greater than 1.1, and therefore α_f smaller than 0.5, see Table 1.

Harde (2019) concludes: "Thus, not really anthropogenic emissions but mainly natural processes, in particular the temperature, have to be considered as the dominating impacts for the observed CO_2 increase over the last 270 years."

Temperature is the only 'process' by which carbon can move from land and ocean reservoirs into the atmosphere. In conclusion, the increase in the non-fossil emission is caused by the temperature increase, the warming of the globe.

Berry (2021), Harde (2019) and others speak of n, the non-fossil, temperature dependent emission, as the "natural" emission. I prefer to call it the "non-fossil" emission, because not all of the temperature increase is natural.

Conclusion

Less than half of the observed increase in atmospheric CO_2 since 1750, probably about a third, is due to the burning of fossil fuels. The rest of the increase is caused by the warming.

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Appendix A

The Global Carbon Project's (GCP) global carbon budget for the 2010s and its transformation into a balanced network

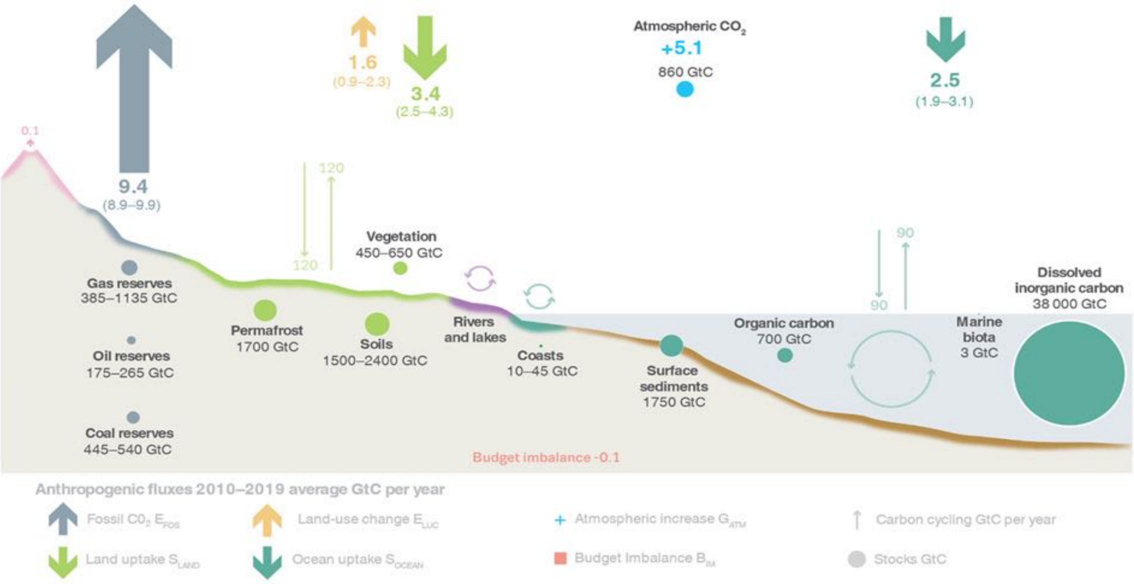

Figure A1. The Global Carbon Budget 2020, GtC per year for the 2010s, from Friedlingstein et al. (2020).

As mentioned in the main text, five data inputs are required in order to solve the balance equation and thus create a balanced network. Four of them are found in Figure A1:

$p(t)$ = Photosynthesis, land + ocean =120 + 90 = 210 GtC per year (X1,3)
$f(t)$ = Fossil fuels burning = 9.4 GtC per year (X5,1)
Stock change in the atmosphere = 5.1 GtC per year (D1)
Land use change = -1.6 GtC per year (D3)

The fifth follows from the main assumption,

$0.5p(t)$ = Plant respiration = 105.0 GtC per year (X3,2)

The balanced network is shown in Figure A2, which is identical to Figure 3 in the main text.

The balance equations are,

D1 = X2,1+X5,1–X1,3
0 = X4,2+X3,2–X2,1
D3 = X1,3–X3,2–X3,4
D4 = X3,4–X4,2
D5 = –X5,1

Green are independent variables, data input: X1,3; X5,1; X3,2; D1; D2(=0); D3. Red are dependent variables, data output: X4,2; X2,1; X3,4; D4; D5

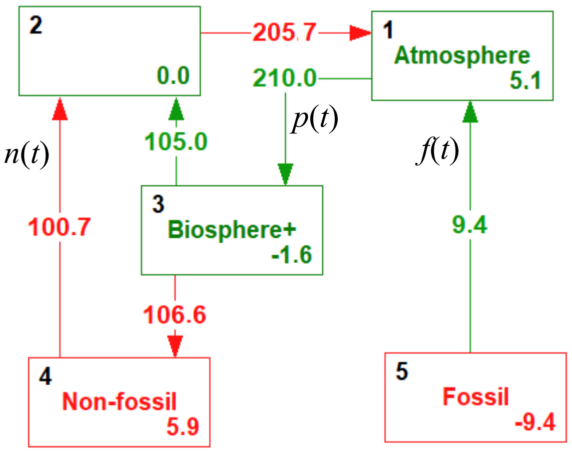

Figure A2. Figure 3 in main text. The Global Carbon Budget in Figure A1 transformed into a balanced network. The stock changes, and hence the grand balances, are the same. The difference is that the balanced network incorporates the photosynthesis, and the important non-fossil, temperature dependent flow of carbon, into a firm and simple mathematical structure, a set of (in the present case) five simultaneous linear equations.

Manually to set up the matrix of coefficients, and the right-hand side of the equations, is a tedious and time-consuming task. Fortunately, it is easily programmed. We draw a network of boxes connected by flows. The program automatically establishes the associated set of balance equations, and solves them as soon as one enters the green variables.

Appendix B

IPCC's carbon cycle and its transformation into a balanced network

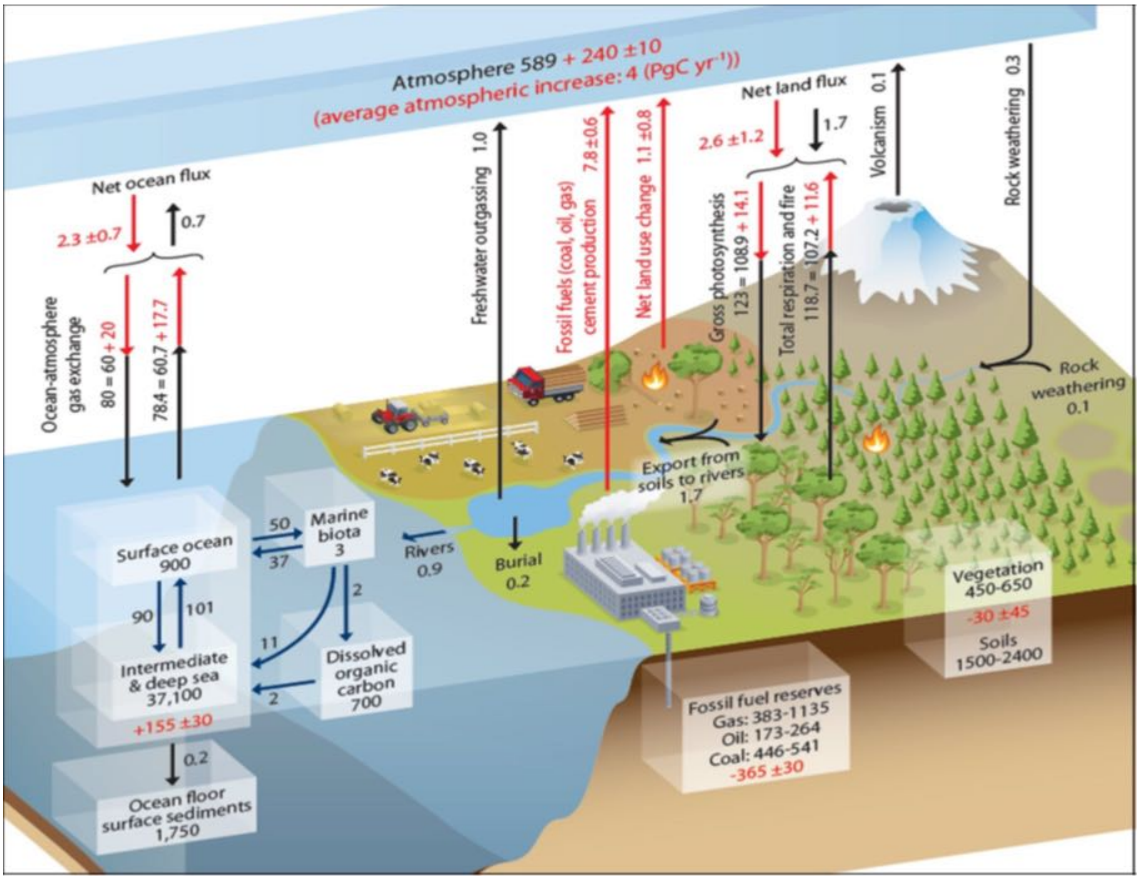

Figure B1 = Figure 6.1 in IPCC (2013) showing IPCC's data for natural (black) and human (red) carbon cycles.

IPCC's carbon cycle does not specifically mention the ocean photosynthesis, it only implies its presence by the arrows labelled "Ocean-atmosphere gas exchange". This gas exchange is generated by the ocean photosynthesis and respiration.

Likewise, IPCC does not distinguish between plant respiration (autotrophic) on the one hand, and respiration from bacterial decay (heterotrophic) on the other, but considers the total only, meaning autotrophic plus heterotrophic, not total in the sense global.

Table B1. IPCC data extracted from Figure B1.

GtC per year	Input to atmosphere			Output from atmosphere			Input - output = stock change		
	Natural	Human	Total	Natural	Human	Total	Natural	Human	Total
Land	107.2	11.6	118.8	108.9	14.1	123.0	-1.7	-2.5	-4.2
Surface ocean	60.7	17.7	78.4	60.0	20.0	80.0	0.7	-2.3	-1.6
Fossil fuels and cement prod.	0.0	7.8	7.8	0.0	0.0	0.0	0.0	7.8	7.8
Outgassing	1.0	0,0	1.0	0.0	0.0	0.0	1.0	0.0	1.0
Net land use change	0.0	1.1	1.1	0.0	0.0	0.0	0.0	1.1	1.1
Total	**168.9**	**38.2**	**207.1**	**168.9**	**34.1**	**203.0**	**0.0**	**4.1**	**4.1**

Note that the natural stock changes are not zero, as they should be. Another problem with IPCC's data is that the net land use change is not a flow, but a stock change. In addition, the fresh water outgassing seems to be greatly underestimated, Pollard (2022), see Appendix C.

Disregarding these shortcomings, Table B1 yields,

X1,3 = *p(t)* = Photosynthesis, land + ocean =123 + 80 = 203 GtC per year

X5,1 = *f(t)* = Fossil fuels burning = 7.8 GtC per year

D1 = Stock change in the atmosphere = 4.1 GtC per year

D3 = Land use change = –1.1 GtC per year

The last data input follows from the main assumption,

X3,2 = 0.5*p(t)* = Plant respiration = 0.5·203 = 101.5 GtC per year.

By entering these numbers, the five simultaneous linear equations can be solved. The result is the balanced network shown in Figure B2.

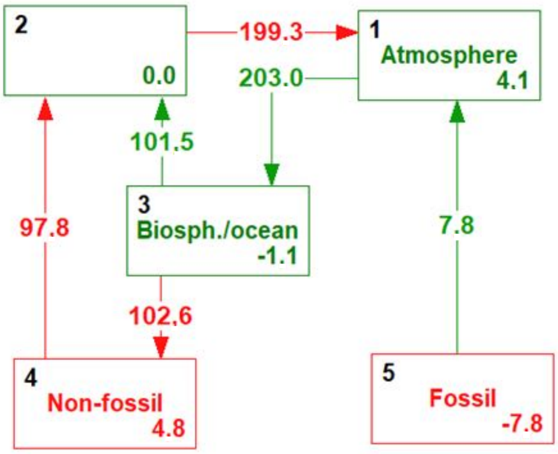

Figure B2. The global carbon balance for the 2000s derived from IPCCs carbon cycle data. GtC per year. The 4.8 GtC per year in the lower right-hand corner of Box 4 is the sum of the land sink of 2.5 GtC per year and the ocean sink of 2.3 GtC per year.

Compare with Figure A2. The difference between the balances in Figure A2 and B2 is explained by the fact that they are 10 years apart. The flow that drives the balance has increased 3.4 percent over 10 years, which looks reasonable. Oher variables, such as D1 and D5 are measured.

Note that the sum of the stock changes is zero. Also note that D3 + D4 = –1.1 + 4.8 = 3.7 = 203.0 –199.3 = 7.8 – 4.1. The ocean sink is 2.5 and the land sink is 2.3 making a total sink of 4.8, which stand in the lower right-hand corner of Box 4.

Table B2. Flows and stock changes in the balanced network a) according to the IPCC for the 2000s (2005) in Figure B2, and b) according to the GCP for the 2010s (2015) shown in Figure 3 (and Figure A2).

			IPCC	**GCP**
			2005	**2015**
			GtC per year	
Flows			Fig. B2	Fig. 3
$p(t)$	**X1,3**	**Photosynthesis**	**203.0**	**210.0**
$f(t)$	**X5,1**	**Fossil fuels and cement prod.**	**7.8**	**9.4**
$0.5p(t)$	**X3,2**	**Plant respiration**	**101.5**	**105.0**
$n(t)$	**X4,2**	**Non-fossil emission**	**97.8**	**100.7**
$r(t)$	**X2,1**	**Total respiration**	**199.3**	**205.7**
	X3,4	**Net primary production**	**102.6**	**106.6**
Stock changes				
	D1	**Atmosphere**	**4.1**	**5.1**
	D2	**Zero per definition**	**0.0**	**0.0**
	D3	**Land use change**	**-1.1**	**- 1.6**
	D4	**Non-fossil (organic matter)**	**4.8**	**5.9**
	D5	**Fossil fuels**	**-7.8**	**-9.4**

Appendix C

Detailing the network by separating the land and the ocean system and by including inland fresh waters

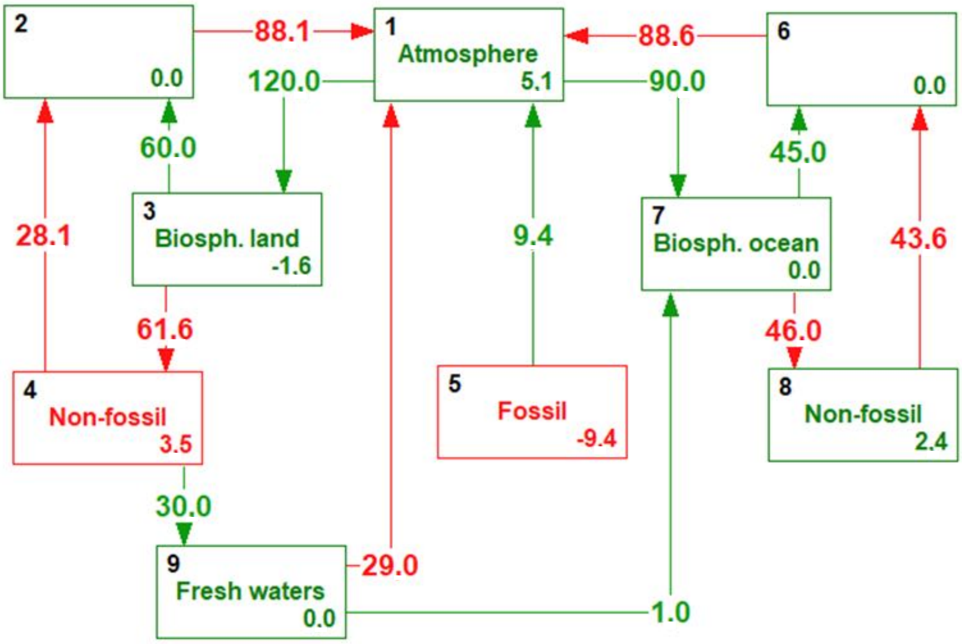

Figure C1. The network in Figure 3 detailed by separating the land and the ocean system, and by including inland fresh waters. GtC per year.

In the previous networks, I have added the land (120 GtC per year) and the ocean photosynthesis (90 GtC per year) to keep the network as simple as possible. At the expense of simplicity, I now separate the land balance from the ocean balance as shown in Figure C1. First, ignore Box 9 and notice the land sink = 3.4 GtC per year (Box 4), and the ocean sink = 2.5 GtC per year (Box 8), the total of which (5.9 GtC per year) stand in the lower right-hand corner of Box 4 in Figure 3. So, the land network on the left-hand side of Figure C1 added to the ocean network on the right-hand side yields the network in Figure 3.

To include the carbon emission from fresh waters, I add Box 9: Fresh waters. First consider Box 3, the Biosphere on land including inland (fresh) waters. The photosynthesis on land is about 120 GtC per year. According the main assumption of this paper, half of it is plant respiration, the other half is biomass. Hence, roughly half of the carbon fixed by photosynthesis, about 60 GtC per year, end up as biomass, dead or alive, on land and in fresh waters.

The magnitude of the fresh water outgassing

Then consider Box 4, labelled "Non-fossil" meaning it contains biomass accumulated on land and in fresh waters subject to bacterial decay. There is only one input to Box 4: X3,4. It is approximately half of the photosynthesis, hence about 60 GtC per year. There are two outputs from Box 4, one (X4,2) comes from solid land (excluding fresh waters), the other from fresh waters only (X9,1). In the numerical example, I have, for the sake of argument, taken X4,2 to be about equal to X9,1 so that about half of the carbon is emitted from land, and the rest from fresh waters.

Pollard (2022) finds that the emission of carbon from fresh waters on a global scale amounts to 58.5 GtC per year. For that to be true, there would be no emission from land. All of the decay of organic matter would take place in inland waters. It would take a violation of the law of the conservation of mass to fit the 58.5 GtC per year into the balance.

In the other extreme, the IPCC takes the fresh water outgassing to be in the order of 1 GtC per year. For this to be true, nearly all of the decay would take place from solid land, and comparatively nothing from fresh waters. In conclusion, the fresh water outgassing is somewhere in the interval between 1.0 and 58.5 GtC per year.

Guest editor: Stein Storlie Bergsmark. 2 anonymous referees.