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PERSPECTIVE

IPCC and the effectiveness of carbon sinks

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1. Introduction

In the context of climate change, a major concern is the possibility that carbon sinks will become less effective in taking up carbon when the CO_2 concentration increases and the climate changes. According to the Working Group 1 contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6 WGI), '[w]hile natural land and ocean carbon sinks are projected to take up, in absolute terms, a progressively larger amount of CO_2 under higher compared to lower CO_2 emissions scenarios, they become less effective, that is, the proportion of emissions taken up by land and ocean decrease with increasing cumulative emissions' (IPCC 2021).

The Summary for Policymakers illustrates this point with a figure displaying results for the cumulative uptake of carbon by the land and ocean sinks as a proportion of the cumulative emissions over the period 1850–2100 for five different Shared Socioeconomic Pathways (SSPs) (see figure SPM.7 in IPCC 2021). IPCC notes that the proportion of cumulative emissions taken up by the sinks by 2100 decreases with increasing cumulative emissions. This is then used to lend support to the statement that carbon sinks become less effective with higher cumulative emissions.

In this perspective, we show that the declining proportion in figure SPM.7 cannot solely be attributed to that carbon sinks become less effective with higher cumulative emissions. The reason for this is that the proportion of cumulative emissions absorbed by sinks until the year 2100 would drop with higher cumulative emissions even if the sinks remain as effective as today.

We demonstrate this by calculating the proportion of carbon taken up by the sinks over the period 1850–2100 (i.e. the measure used by the IPCC to illustrate that sinks become less effective). We do this for the CO_2 emissions trajectories in the five SSPs presented in IPCC (2021), under the assumption that the sinks in 2020 and beyond remain as effective as they were in the year 2019 during the rest of the century.

We agree with IPCC's conclusion that higher cumulative emissions cause the sinks to be less effective. However, we also show that the proportion of carbon absorbed by sinks by 2100 declines with increasing cumulative emissions for these five emission pathways, even if the effectiveness of the carbon sinks remains intact.

In addition, we calculate how the proportion of carbon taken up by sinks by the year 2100 is affected by state dependent feedbacks on the carbon sinks that depend on cumulative sink uptake and the change in global mean surface temperature using the same modelling framework. This lets us analyse the relative importance of the different factors that cause the declining proportion of cumulative carbon emissions being absorbed by sinks by the year 2100. We also show that the model used here provides results in line with the results presented in figure SPM.7 in IPCC (2021).

2. Method

We use the carbon cycle model in the reduced complexity climate model FaIR 2.0.0 (Leach *et al* 2021). The atmospheric CO_2 removal process is represented by a non-linear impulse response function approach that takes into account how increased cumulative uptake by sinks as well as the global mean surface temperature affect the effectiveness of atmospheric CO_2 removal. The model approach is simple, but has in several papers been shown to effectively emulate (the carbon cycle of) more complex Earth system, models (Millar *et al* 2017, Jenkins *et al* 2018, Smith *et al* 2018, 2021, Leach *et al* 2021), including those assessed in Coupled Model Intercomparison Project Phase 6 (CMIP6) (Leach *et al* 2021).

The global aggregated carbon cycle is represented in the following equations:

$$\frac{\mathrm{d}R_i}{\mathrm{d}t} = a_i E(t) - \frac{R_i(t)}{\alpha(t)\tau_i} \quad (1)$$

$$C(t) = C_o + \sum_{i=1}^{n} R_i(t) \quad (2)$$

$$\alpha(t) = g_o \mathrm{e}^{\frac{(r_0 + r_u G_u(t) + r_T T(t))}{g_1}} \quad (3)$$

$$G_u(t) = \sum_{s=t_0}^{t} E(s) - \sum_{i=1}^{n} R_i(t). \quad (4)$$

Here, $E(t)$ is the anthropogenic emissions, $C(t)$ the atmospheric carbon stock, C_o the pre-industrial atmospheric carbon stock, $R_i(t)$ can be interpreted as an atmospheric carbon stock reservoir, to which a fraction of the anthropogenic emissions is allocated, and a_i is the share of the emissions that go to that particular carbon stock reservoir $R_i(t)$. Furthermore, carbon is removed from each reservoir with a removal rate given by $1/(\alpha(t)\tau_i)$ multiplied by the carbon stock in that reservoir. If $\alpha(t)$ had been constant, this model would correspond to a carbon cycle model where the atmospheric CO_2 content is estimated through a convolution of the emission with a linear impulse response function (see e.g. Maier-Reimer and Hasselmann 1987, Harvey 1989). However, since $\alpha(t)$ depends on $G_u(t)$, i.e. the cumulative carbon uptake in the sinks, and the increase in global mean surface temperature $T(t)$, the model becomes nonlinear (Joos *et al* 1996, Hooss *et al* 2001). The parameters in equations (1)–(4), i.e. r_0, r_u, r_T, g_o, g_1, and τ_i, are set equal to the default values given in Leach *et al* (2021).

In figure SM1 (available online at stacks.iop.org/ERL/17/041004/mmedia), we display the impulse response to CO_2 emissions under different background conditions. It is shown that the removal process becomes slower the larger the cumulative uptake and the larger increase in global mean surface temperature. This illustrates what we mean by the carbon sinks becoming less effective.

The model is in this study driven with exogenous CO_2 emissions and exogenous temperatures. The emissions over the period 1750–1849 are from the Reduced Complexity Model Intercomparison Project (Nicholls and Lewis 2021) and for the period 1850–2020 from the Global Carbon Budget project (Friedlingstein *et al* 2020), while for the period 2021–2100 they are from the five SSPs as in figure SPM.4(a) (IPCC 2021). The cumulative emissions over the period 1850–2100 are about 2670, 3410, 5180, 7710, and 10170 $GtCO_2$ for SSP1-1.9, SSP1-2.6, SSP2-4.6, SSP3-7.0, and SSP5-8.5, respectively. The historic temperature record (1850–2019) is based on HadCRUT4.6 as reported in figure SPM.1(b) (IPCC 2021), while the temperature pathways for the five SSP scenarios are based on figure SPM.8(a) (IPCC 2021). The temperature data are used to drive the temperature-induced changes in the atmospheric CO_2 removal rate as in Jenkins *et al* (2018).

For each of the five scenarios, two cases are analysed: (a) a standard model run with a climate carbon cycle that yields less effective CO_2 sinks over time (as is the case in the default setting of FaIR 2.0.0), and (b) an alternative model run where the sink effectiveness in 2020 and beyond is kept constant at the level obtained in 2019 (the last year with temperature observations included in the SPM) by using a fixed $\alpha(t)$ set to the value obtained in 2019. With a constant sink effectiveness we mean a carbon cycle where the proportion of an emission taken up by sinks remain the same regardless of when that emission occurs and regardless of changes in global temperature and atmospheric concentration.

3. Results

We first show (see figure 1) that the carbon cycle in FaIR 2.0.0 (in its standard set up) largely reproduces the estimates by IPCC shown in figure SPM.7 regarding absolute amounts and the proportion of the cumulative CO_2 emissions over the period 1850–2100 taken up by the sinks by 2100 (compare the left and middle panels).

In the same figure, we also demonstrate that the proportion taken up by the sinks falls with higher cumulative emissions, even when the carbon sink effectiveness is kept constant (see right panel). Hence, a reduction in the proportion of carbon taken up by ocean and terrestrial sinks by the year 2100 is not sufficient to conclude that the carbon sinks have become less effective.

The reason the proportion of cumulative emissions taken up by sinks by 2100 drops even when the sink effectiveness is constant (i.e. fixed removal time constants) has to do with the time profile of the emissions and that it takes time for the sinks to remove CO_2 from the atmosphere. The key here is that the higher the cumulative emissions are in the assessed scenarios, the more of those emissions *are emitted toward the end of the period*, see figure SM2. Hence, in the scenarios with the highest cumulative emissions, sinks have less time to take up CO_2 from the atmosphere when compared to scenarios with lower emissions in which a larger share of the emissions are emitted earlier (see SM3).

The reduced proportion of carbon absorbed by sinks in the high emission scenarios presented in IPCC figure SPM. 7 thus results from a combination of the reduced effectiveness of the carbon sinks, in the sense of increased sink removal time scales as given by equations (1)–(4) above and illustrated in figure SM1, and the time profile of the emissions in the scenarios

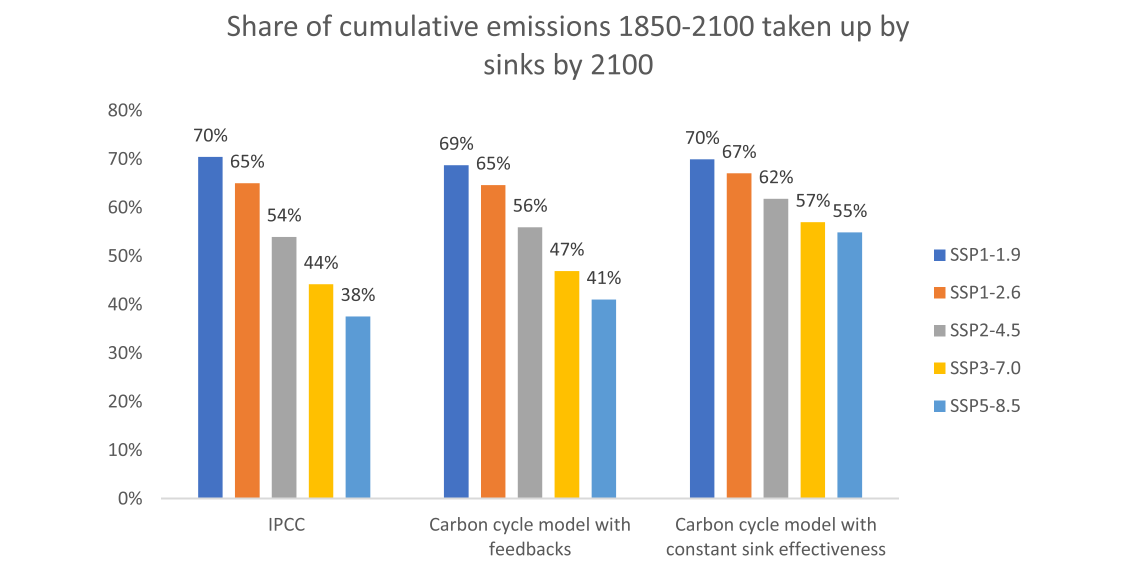

Figure 1. The proportion of cumulative emissions 1850–2100 taken up by sinks by 2100 in five scenarios and for three different modelling approaches. Five illustrative scenarios (SSPs) that cover a wide range of possible future developments of anthropogenic drivers of climate change are used. The left panel shows results from IPCC AR6 WG1 SPM (IPCC 2021). The middle panel shows results based on the carbon cycle in the reduced complexity model FaIR 2.0.0. The right panel shows results from a version of the carbon cycle model in FaIR in which the carbon sink effectiveness is constant after 2019 (implemented in FAIR by assuming CO_2 removal time constants that are fixed and independent of the cumulative CO2 uptake and the global average temperature).

as illustrated in figures SM2 and SM3. In figure SM3 we show that the (emission weighted) time the sinks have to absorb emissions prior to 2100 is shorter the larger the cumulative emissions are in the five considered emission pathways, e.g. in the SSP1–1.9 the average time is 130 years but in the high emission scenario SSP5–8.5 it is a mere 56 years.

According to the estimates presented in figure 1, the two effects are roughly equally important in explaining the reduction in the proportion of the cumulative emissions taken up by the sinks.

4. Conclusion

In this perspective we have shown that the illustration used by IPCC to demonstrate an expected weakening of the carbon cycle effectiveness is incomplete. They find that a lower share of cumulative emissions is absorbed by carbon sinks the higher the cumulative emissions are over the period 1850–2100. However, this is not a sufficient argument to conclude that sinks are expected to be less effective. The reason for this is that a drop in the share absorbed by sinks will also follow even if the effectiveness of the carbon sinks remains intact. The proportion of cumulative CO_2 emissions (over the period 1850–2100) taken up by sinks by the year 2100 depends both on the impacts of higher CO_2 concentrations and climate change on the effectiveness of the CO_2 sinks as well as the time profile of the emissions.

For a given amount of carbon emitted over a given period, say 1800–2100, the share taken up by sinks by the end of that period will be lower the larger share of those emissions that have taken place towards the end of this period. The key point here is that in pathways with high emissions towards the end of the period, there will be less time for the sinks to remove carbon from the atmosphere and hence less carbon will have been removed by the year 2100.

For valid and robust estimates of how the effectiveness carbon sinks change under a changing climate, the impact of the time profile of the emissions thus needs to be considered separately. A broader recognition of the fact that both these aspects matter when assessing carbon sinks is warranted.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare no competing interest.

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