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Trends in the land and ocean carbon uptake

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Only about 45% of the total CO_2 emitted from fossil fuel burning and land use change stayed in the atmosphere on average during the past few decades. The remaining CO_2 was taken up by the carbon reservoirs (the 'CO_2 sinks') in the ocean and on land. The sinks are sensitive to climate and elevated CO_2 levels. Their efficiency in removing CO_2 emissions from the atmosphere is expected to decrease in the future under increasing atmospheric CO_2 because of their response to elevated CO_2 levels, warming and other climate changes. Recent evidence from observations and models suggests that the efficiency of the sinks could have already decreased in the past few decades, but the uncertainties are very large. There is an urgent need for reducing these uncertainties by better monitoring the CO_2 emissions and sinks, and by improving our understanding of the sinks dynamics.

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Introduction

Despite important advances in the quantification of CO_2 sinks during the past two decades, including their location [1•], magnitude [2], driving processes and underlying time-scales [3•], important components in the global CO_2 budget remain poorly constrained. CO_2 emissions from fossil fuel combustion are known to an uncertainty of ~±6% [4], CO_2 emissions from deforestation and other Land Use Change (LUC) to an uncertainty of ~±50% [5••], atmospheric CO_2 growth rate to an uncertainty of ~±4% [6], the ocean CO_2 sink to an uncertainty of ~±20% [2,3•,7] and the land CO_2 sink to an uncertainty of ~±35% [5••] (Figure 1). The uncertainties reported here are estimates of $\pm 1\,\sigma$ assessed directly from observations for atmospheric CO_2 growth rate, and indirectly by expert assessment for the other components based on the spatial coverage in the data and errors in methods, as in [3•].

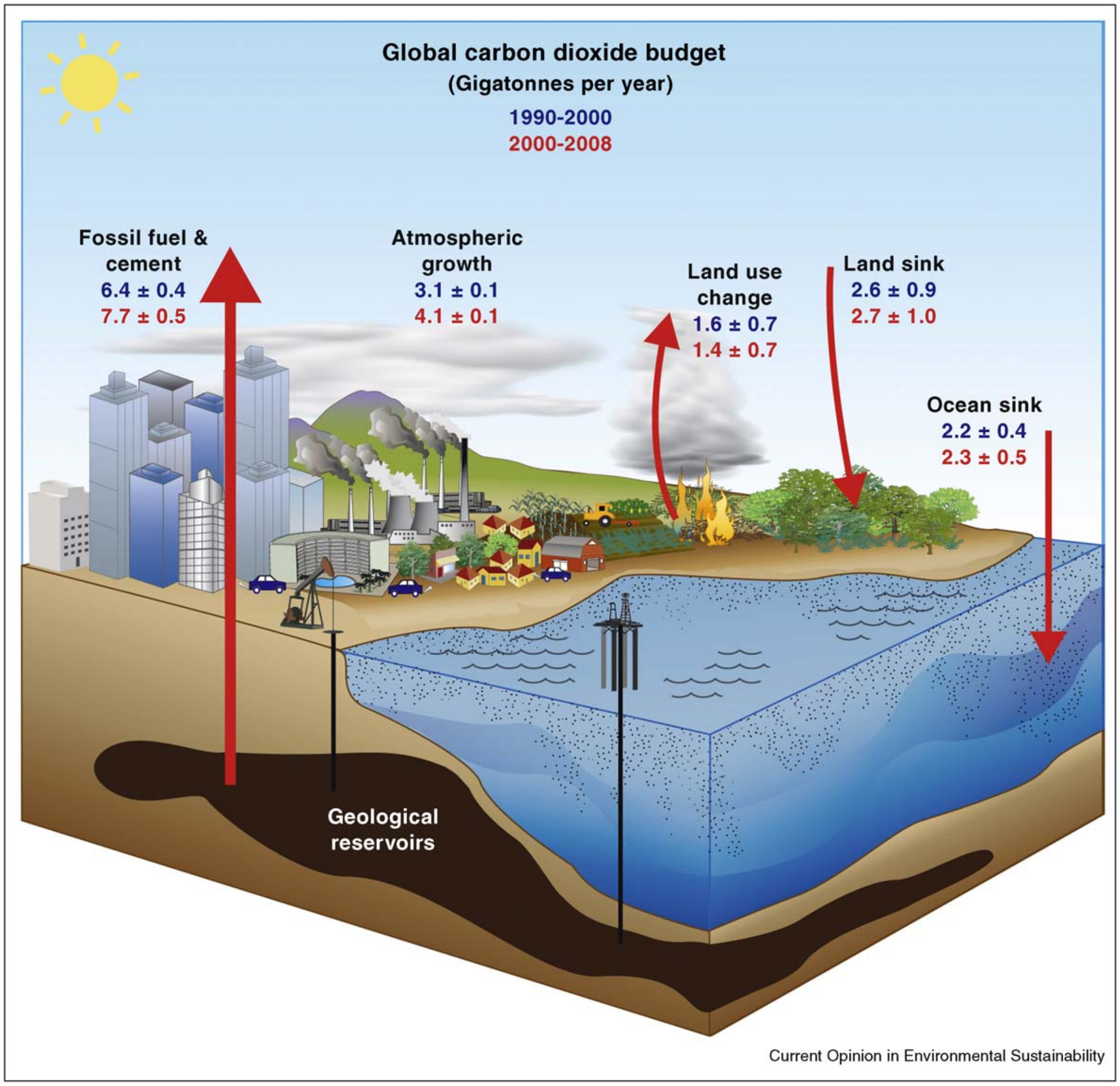
Relatively little attention had been given to the quantification of the trends in CO_2 emissions and sinks until after the publication of the fourth assessment of the Intergovernmental Panel on Climate Change (IPCC-2007). At the close of IPCC-2007, many questions remained open, particularly regarding the response of the CO_2 sinks to elevated CO_2 and climate change [8]. This paper reviews the recent publications that analyse evidence of recent trends in the CO_2 sinks published since IPCC-2007. It discusses the available evidence and the various interpretations of the underlying drivers, and recommends ways to improve our knowledge and understanding.

Trends in the airborne fraction

The fraction of total CO_2 emissions that remain in the atmosphere – the 'airborne fraction (AF)' – has implications for radiative forcing and global warming. It is thus an important quantity to understand and monitor. By definition, AF is a measure of the capacity of the CO_2 sinks to keep up with the CO_2 emissions, which I call the 'sink efficiency' in this paper. Although AF is only an indirect measure of the sink efficiency, it is the only available long time series based on observations. There are many factors that influence AF: First the rate of increase in CO_2 emissions plays a predominant role because the sinks are limited by processes that have specific time-scales, such as the growth of vegetation on land and the vertical transport of carbon in the ocean. Second, the level of CO_2 in the atmosphere influences the uptake by the sinks because CO_2 fertilisation on land (a main cause of the land sink) should saturate at high CO_2 and the dissolution of CO_2 in the ocean reduces the chemical capacity of the ocean to take up additional CO_2. Finally, the land and/or ocean CO_2 sinks or carbon reservoirs could respond to changes in climate [9,10•] and other environmental changes such as ocean acidification.

AF is highly variable because the growth of CO_2 in the atmosphere is strongly influenced by the impact of climate variability on the CO_2 sinks (Figure 2). By contrast, the emissions of CO_2 have generally low year-to-year variability. To detect trends in AF, the known interannual variability induced by El Niño events and volcanic eruptions needs to be removed from the atmospheric CO_2 growth rate. This was done by Canadell *et al.* and Raupach *et al.* [11•,12] who detected a positive trend in airborne

Figure 1



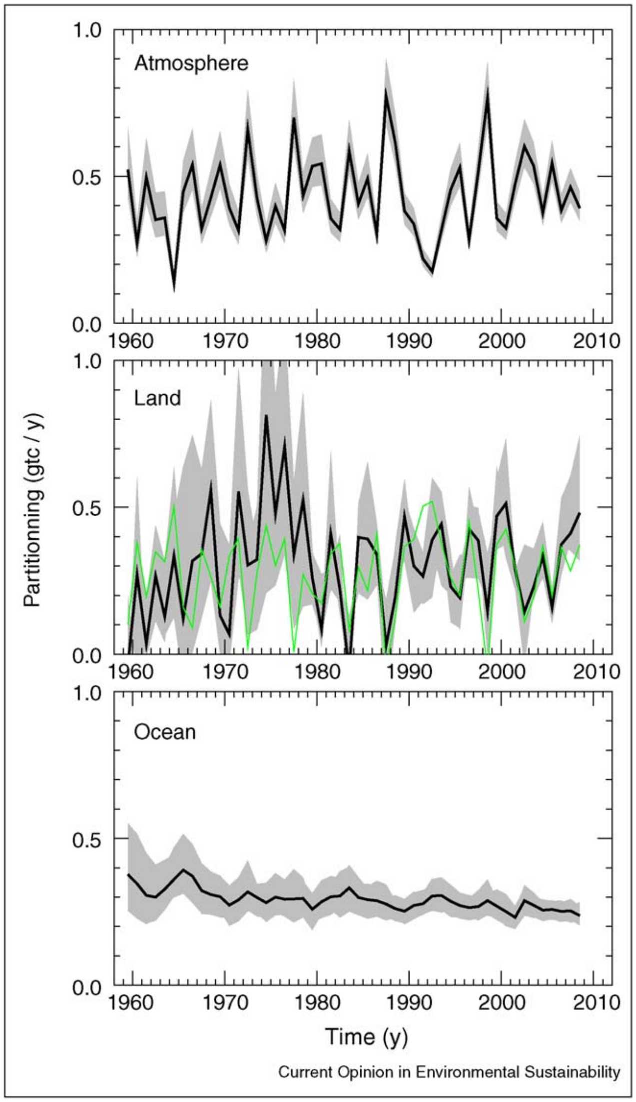
The global budget of CO_2 for the 1990–2000 (blue) and 2000–2008 (red) based on data in [5••]. Emissions from fossil fuel and land use change are based on economic and deforestation statistics [4,49]. Atmospheric CO_2 growth is measured directly [6]. The land and ocean CO_2 sinks are estimated using observations for the 1990–2000 [3•]. For 2000–2008, the ocean CO_2 sink is estimated using an average of several models, while the land CO_2 sink is estimated from the balance of the other terms.Figure reproduced from [50].

fraction of 0.25 ± 0.21% per year since 1959, with 90% probability ($p = 0.9$) that the signal exceeds the noise in the data. These studies suggested that while about 40% of the emissions of CO_2 remained in the atmosphere in the 1960s, this fraction increased to about 45% in the past decade (Figure 2).

However, the significance of a trend in AF is also influenced by the uncertainty in CO_2 emissions, particularly the large LUC uncertainty [13–15], which was not directly considered in [11•,12]. In a follow up study, Le Quéré *et al.* [5••] used a set of nine published LUC estimates to quantify the impact of LUC uncertainty on the trend in AF. The positive trend in AF was found to be robust to the LUC estimates considered. Using a wider range of LUC uncertainty with no prior constraints on LUC, Knorr [16] found that the trend in airborne fraction was positive during 1961–2007 but not significant. Further differences in methodology (e.g. the use of monthly data in [16] versus annual data in [5••]) can explain some of the difference in significance between the two studies, but it is nevertheless clear that the trend in AF is at the detection limit and thus that choices of methodology and prior uncertainties have an important impact on the level of significance of the trend detected.

Independent insight on the trend in AF can be obtained from an examination of its potential origin, by looking at trends in the oceanic and land CO_2 sinks separately.

Figure 2



Fraction of the total emissions of CO_2 that remains in the atmosphere (the airborne fraction – top), fraction taken up by the land (middle) and by the ocean (bottom) Units of GtC/y (billion tons of C per year). The total emissions include fossil fuel burning, cement production (about 3% of emissions), deforestation and other land use change [4,49]. The airborne fraction is calculated from the measured growth in atmospheric CO_2 [6]. The land and ocean fraction are an average (full line) of five and four models, respectively (as in [5••]). The grey shading encompasses the range of model estimates and the uncertainty in emissions. The green line in the middle panel is the fraction of the emissions taken up by the land when the land sink is calculated from the difference of the other terms (land CO_2 sink = total CO_2 emissions – atmospheric growth – ocean sink). The difference between the black and green lines on the middle panel provide a measure of the remaining uncertainty in the global CO_2 budget, which can be primarily attributed to uncertainties in the estimates of land CO_2 fluxes [5••].Figure updated from [5••].

Trends in the ocean carbon uptake

The oceanic sink of CO_2 is mainly a physico-chemical response of the ocean to increasing atmospheric CO_2. CO_2 dissolves in surface waters and is transported from the surface to the deep ocean by ocean currents. The rate at which carbon is transported to the deep ocean is the main factor limiting the uptake of CO_2 by the ocean. The chemical capacity of the ocean and the response of the ocean to surface warming and other climate changes can further alter the rate of uptake of CO_2 by the oceans.

Repeated surveys of the surface ocean CO_2 have been done in many regions for decades. The completion (and continuation) of repeated surveys has led to the publication of several key papers identifying recent trends in surface ocean CO_2. In large regions of the North Atlantic, oceanic CO_2 has increased at the same rate or faster than atmospheric CO_2 since about 1990 [17–20], indicating a local weakening of the CO_2 sink. A similar signal was detected in parts of the Southern Ocean [21,22] first identified from the spatio-temporal variability of atmospheric CO_2 around Antarctica and elsewhere [23], and in the western equatorial Pacific ([24] as updated in [5••]). By contrast, oceanic CO_2 increased at a slower rate than atmospheric CO_2 in the North Pacific [25], as is expected from a response to increasing atmospheric CO_2 alone [26].

The observed trends in oceanic CO_2 have been attributed to various processes. In the Atlantic, different interpretations have been proposed, including changes in marine productivity [18], surface warming [19], changes in physical circulation [20] and natural variability [27]. In the Southern Ocean, models suggest that the ocean is responding to an increase in surface winds [23,28–30], which has been attributed to stratospheric ozone depletion [31]. However this process is not fully coherent with observations of physical changes in the ocean [32] and the mechanisms by which the oceans respond to enhanced winds remain an active area of research [33]. Models have been used to quantify the impact of changes in climate on the global ocean CO_2 sink. All models used so far show a weakening of the global CO_2 sink when the observed changes in climate are imposed on the models [26,28,5••] (Figure 2). The response further analysed in one model was mainly caused by wind changes in the tropical and Southern ocean and surface ocean warming, with important non-linear effects [26].

Despite the short observational record, recent data and modelling studies suggest that the ocean is responding to recent climate change and variability. However, future projections will be difficult to make without a better knowledge of the underlying processes and of the projected changes in surface wind and atmospheric conditions [34•,35,36].

Trends in the land carbon uptake

The land sink of CO_2 is mainly caused by the fertilisation effect of atmospheric CO_2 on terrestrial vegetation and by the regrowth of forests [3•]. Changes in the land CO_2 sink at the regional or global scale are difficult to detect directly from observations because vegetation and soil biomass are very heterogeneous. Traditionally, the trend in the global land CO_2 sink was estimated by subtracting all other terms in the global CO_2 budget (e.g. land CO_2 sink = total CO_2 emissions − atmospheric growth − ocean sink). However this equation transfers all uncertainties to the land CO_2 sink, and does not test our understanding of the underlying processes.

Understanding and modelling of CO_2 fluxes from terrestrial vegetation have made important progress in recent years. New field measurements, flux towers and forest inventories now provide a better picture of the carbon balance of terrestrial vegetation and the distribution of carbon among compartments [37]. Satellite products such as the leaf area index and fire counts provide constraints on the extent and timing of relevant processes. As a result, improved knowledge exists, for instance, in quantifying the contributions of fires [38,39•] and nitrogen limitation [40–42] on terrestrial fluxes. Improved information is also beginning to emerge in our understanding of the role of diffuse light following volcanic activities [43] and the effect of surface ozone levels on leaf openings [44].

It remains challenging to scale up the existing knowledge on processes to global land CO_2 sinks estimates. Thus the global net CO_2 fluxes estimated by models are still poorly constrained and there remain large differences between models (e.g. [39•,45]). Nevertheless several important points emerge from recent model analysis: models can account for ~30% of the year-to-year variance in atmospheric CO_2 [5••], they simulate a larger sink in the 1990s compared to the 1980s in agreement with the CO_2 budget approach [39•], and they allocate the sink half in the tropics (compensating deforestation) and half in the Northern Hemisphere in agreement with atmospheric inverse studies [1•].

Attribution of recent trends

Ocean and terrestrial carbon cycle measurements have limited temporal and spatial coverage, and cannot be used directly to infer trends in the CO_2 sinks at the global scale. Four terrestrial and three ocean models were used by Le Quéré *et al.* [5••] to assess the effect of recent climate change and variability on the trends in CO_2 sinks and the AF since the early 1960s. When the models were forced by increasing atmospheric CO_2 alone (no changes in climate), AF of the combined results decreased with time by 0.8% per year. In these models, the time scale regulating the absorption of CO_2 by the sinks was faster than the growth in CO_2 emissions from fossil fuel burning and land use change. However when the models were forced by both increasing atmospheric CO_2 and changes in climate, AF increased by 0.1% per year, close to the trend estimated from observations. The land and ocean models both contributed to the reversal of the trend in about equal proportions. Climate variability could play an important role in setting the trends of the past few decades. For instance, the 1970s was a particularly warm and wet decade, which led to an enhanced land CO_2 sink early in the time series [39•].

The attribution of a trend in AF to the response of CO_2 sinks to climate change and variability in these models is critically dependent on the ability of the models to correctly characterise the time response of the sinks to increasing atmospheric CO_2 alone. In a discussion paper, Gloor *et al.* [46] argues that it is not possible to attribute trends in AF to the climatic impact on CO_2 sinks because of the dominance of the growth rates of atmospheric CO_2. An in-depth evaluation of global models in the context of AF trend attribution remains to be done.

Although the detection of the AF trend [16] and its attribution [46] have been individually challenged, I argue here as in [5••] that the combined evidence from global ocean and land models, ocean observations and from the AF trend based on observations is coherent enough to maintain that a positive trend in AF in the past decades was 'likely'. Likely here is used following the IPCC definition that the probability of occurrence of a positive trend is greater than 66%. Global models suggest that the positive trend in AF can be explained by the response of the CO_2 sinks to climate change and variability. I think that the level of confidence ascribed is a fair representation of recent evidence. I suggest below ways to reduce uncertainty and improve confidence.

Conclusion

It is only recently that sufficient observations exist to constrain the trends in various components of the global carbon cycle. The detection of trends is thus necessarily controversial, because we are at the detection limit of the information. Another decade of observations will certainly help clarify the significance and causes of the observed trends, but time can be gained by improving synergies between models and observations. Improved constraints on the CO_2 sinks would put us in a far better position to project the expected changes this century, to assess the potential for large and/or abrupt changes in biogeochemical cycles with consequences for future climate, and possibly to even provide independent information to constrain the reported emissions of CO_2 at the level of large regions [47]. Such information is important to sustain climate policies and monitor their implementation.

To produce information relevant to climate policies however, there is an urgent need to reduce uncertainties in recent trends and to improve confidence in their attribution and in future projections. Progress can be made immediately on three fronts: First the large interannual variability in AF estimated from observations (Figure 2) could be reduced by developing more sophisticated methods to remove known variability, as was done by Thompson *et al.* [48] to remove noise in global temperature estimates. Second, the uncertainty in LUC could be better constrained by focusing separately on the mean LUC and its evolution in time since the early 1960s. A more extensive comparison of LUC from methods using different input data and assumptions would help to quantify a time-dependent uncertainty in LUC, and provide more relevant prior information than was used by either Le Quéré *et al.* [5••] or Knorr [16]. Finally, the attribution of recent trends in AF to underlying processes could be improved by an extensive validation of the trends in CO_2 sinks in models, particularly at the regional scale where *in situ* observations exist. It is thus paramount that repeated observations that can constrain CO_2 trends in models be maintained and expanded in order to improve the reliability of model projections.

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