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Climate change weakens carbon sinks and further amplifies climate change

ScienceBrief Review **OCTOBER 2021**

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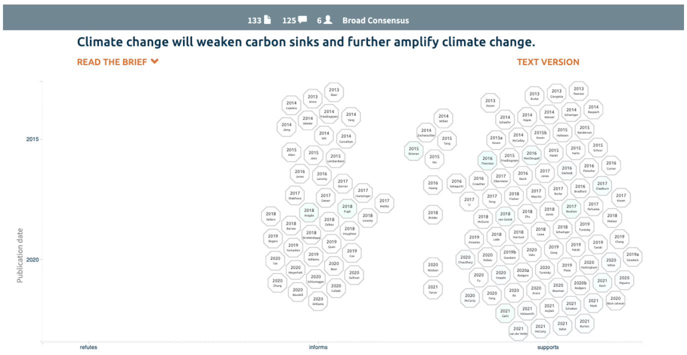
Approach. This ScienceBrief Review examines the links between climate change (warming) and the carbon cycle where amplifying feedbacks can strengthen climate change. It synthesises findings from more than 130 peer-reviewed scientific articles gathered using ScienceBrief. The Brief and evidence can be explored at: https://sciencebrief.org/topics/carbon/future.feedbacks.

Summary. Climate change affects carbon cycle processes in a way that amplifies the increase of carbon dioxide (CO_2) in the atmosphere and causes additional warming. Models suggest that climate change would act to reduce carbon sinks, leading to an additional increase in atmospheric CO_2 of about 10 to 70 parts per million (ppm) per degree Celsius of global warming on decadal to century time scales. Additional carbon feedbacks from permafrost thawing and methane hydrates are uncertain but probably add no more than 30% above this range on century timescales. No runaway carbon-climate feedbacks are anticipated this century.

Key points

The evidence suggests that aspects of the carbon cycle will be impacted by climate change to weaken future carbon sinks, through multiple feedback loops that can amplify climate change.

- The size of the carbon–climate feedback is estimated to be a carbon loss to the atmosphere between 20 and 180 GtC per °C of warming (Friedlingstein, 2015), i.e. land and ocean carbon storage is reduced by warming, resulting in greater atmospheric CO_2 concentration and an additional warming of up to 30 %.
- The ocean carbon-climate feedback is irreversible on timescales of decades to centuries (Schwinger & Tjiputra, 2018).
- The increasing frequency and intensity of wildfires, particularly in Arctic peatlands, have already increased CO_2 emissions and may reduce future forest carbon-storage potential (Bowman et al., 2020; McCarty et al., 2021).



Snap shot of the Brief at the time of publication showing the consensus among the evidence analysed. Click here to visit the Brief.

- Both land and ocean carbon sinks will experience amplifying feedbacks this century, reducing the carbon uptake compared to a constant climate, but both remain a carbon sink under all elevated atmospheric CO_2 and warming scenarios (Canadell et al., 2021).
- The higher the emissions scenario the smaller the proportion of emissions the sinks remove, leaving a larger proportion in the atmosphere, amplifying climate change.
- Modelling suggests that feedbacks that are self-reinforcing and accelerating in size over decades to centuries - runaway feedbacks - are not projected to occur this century, under projected warming levels (Canadell et al., 2021).

Background. Climate change modifies the rate at which different sources and sinks of carbon operate, which varies the rate of growth or decline of CO_2 concentration, amplifying or damenping climate change respectively, known as 'feedback'. In addition to the carbon–climate feedback discussed in this review, there is a carbon–CO_2 concentration feedback as the land and ocean carbon sinks are primarily due to the increase in atmospheric CO_2 concentration. This feedback dampens climate change and is the dominant feedback in the Earth's carbon cycle. This review focuses on the smaller carbon–climate feedback that acts in the opposite direction and enhances climate change.

The carbon–climate feedback is estimated from the change in global carbon per degree of average global warming (Friedlingstein et al., 2006, Arora et al., 2020). Its size remains moderately uncertain but evidence from models and indirect observations suggest the feedback is positive and amplifies warming. The size of the carbon–climate feedback is constrained using indirect ('proxy') observations, such as ice core and tree ring data (Friedlingstein, 2015) and quantified using output from a collection of Earth system model simulations (Arora et al., 2013, 2020; Williams et al., 2019).

Processes & insights from observations and models

Land feedbacks

The response of terrestrial ecosystems dominates the carbon–climate feedback, with the land contribution around three times larger than the ocean, while uncertainty estimates are an order of magnitude larger as well (Arora et al., 2020). Using idealised CO_2 concentration experiments, the average value for the land carbon-climate feedback from the sixth coupled model intercomparison project (CMIP6) is -45.1 ±50.6 billion tonnes of carbon per degree (GtC $^{o}C^{-1}$)* (Arora et al., 2020), compared to -58.4 ±28.5 GtC $^{o}C^{-1}$ for CMIP5 (Arora et al., 2013). While uncertainty around the CMIP6 model mean is large, it is not symmetrical, meaning the land climate–carbon feedback is much more likely to be negative than positive. However, the overall (land plus ocean) carbon-climate feedback is likely to be positive. Modelling historic data, the land climate–carbon feedback is -28 GtC per degree warming for the 20th century, representing a loss of 25 ±10 GtC due to observed warming (Friedlingstein, 2015). Land models that include nitrogen cycle representation reduce the size of land climate–carbon feedback due to soil warming-induced enhanced nitrogen availability for photosynthesis, but also reduce model spread uncertainty (Arora et al., 2020).

*1 gigaton (GtC) = 1 billion tons carbon = 10^{15} grams of carbon; 1 GtC = 3.664 $GtCO_2$

The role of tropical and boreal forests is a major source of uncertainty in estimating the size of the land carbon sink. For example, Earth system models do not represent the recent saturation of the tropical forest carbon sink (Koch et al. 2021) including the reduction of the Amazon carbon sink (Hubau et al., 2020). Furthermore, the negative impacts of temperature increases on carbon uptake by photosynthesis and losses from tree respiration appear to be non-linear (Sullivan et al. 2020). More broadly, the Amazon basin as a system may be transitioning to a carbon source because of a combination of emissions from deforestation and degradation (logging and fires), plus rising temperatures and increasing drought elevating tree mortality in the southeast portion of the basin, as predicted by some Earth system models suggesting an Amazon dieback later this century (Huntingford et al., 2013; Aragão et al., 2018; Gatti et al., 2021). In the boreal zone, lengthening growing seasons and the poleward advance of the tree-line may increase carbon storage (Pugh et al., 2018), though this could be offset by increases in boreal wildfire carbon emissions. The balance of these factors ultimately depends on future forest succession (McCarty et al., 2020, 2021; Mack et al., 2021).

Land carbon–climate feedback processes that amplify warming include enhanced respiration from soil microbes due to warmer temperatures, which raises atmospheric CO_2 concentration (Bradford et al., 2016; Crowther et al., 2016; Feng et al., 2017; van Gestel et al., 2018; Williams et al., 2019). Short-term experiments reveal that +4°C warming of tropical soils for 2 years increased CO_2 emissions by a sustained +55%, suggesting a potentially large amplifying feedback (Nottingham et al., 2020). The richness of soil organic carbon in peatlands means climate warming in these environments may generate large quantities of CO_2 and methane (CH_4), as demonstrated by decade-long, in situ experiments (Hopple et al., 2020). While alternative modelling suggests peatlands will remain a carbon sink under future climate change scenarios, the total peatland sink strength reduces under a high emissions scenario (Chaudhary et al., 2020).

High latitude permafrost holds around 1460-1600 GtC or about 30% of the world's soil organic carbon, much of it stored in carbon-rich peat soils (Koven et al., 2015a; Schuur et al., 2015; Meredith et al. 2019; Rafat et al., 2021), so microbial decomposition has the potential to generate significant greenhouse gas emissions to the atmosphere, further enhancing climate change (McCalley et al., 2014; Hollesen et al., 2015; Schuur et al., 2015; Mauritz er al., 2017; Chang et al., 2019, Feng et al., 2020; Rafat et al., 2021). In Alaska, at a site undergoing rapid thaw, soil carbon degradation rates of 5.4% per year were measured over a 5 year period (Plaza et al., 2019). Model simulations for 1970-2006 estimated 11.6 GtC within thawed soil organic matter were exposed to microbial decay, releasing approximately 3.7 GtC to the atmosphere as CO_2 (Hayes et al., 2014).

Overall rates of permafrost degradation are occurring much faster than traditional models of permafrost thaw suggest, increasing the rate of greenhouse gas emission from Arctic and boreal landscapes, due to the sensitivity of ice-rich permafrost to warming and disturbance. Abrupt thaw, where melting of the ice within permafrost soils leads to rapid subsidence and erosion, exposes deep organic-rich soils to microbial decay much more quickly than gradual active layer thickening. Abrupt thaw also contributes to the emission of greenhouse gases in two ways not currently captured by Earth system models (Schuur et al., 2015; Turetsky et al., 2019; Nitzbon et al., 2020). First, areas most likely to experience abrupt thaw store a disproportionate amount of soil carbon relative to areas that are likely to thaw more gradually (Olefeldt et al., 2016; Turetsky et al., 2019). Second, abrupt thaw leads to greater emissions of methane due to collapse and inundation of thawing permafrost soils (Turetsky et al., 2020). These abrupt thaw processes also occur in coastal permafrost regions, exacerbated by human-caused sea level rise and sea ice decline (Jones et al., 2018; Tanski et al., 2019). Observations indicating potentially significant concentrations of CH_4 present in some permafrost landscapes in Siberia (Streletskaya et al., 2018), could suggest an additional source of greenhouse gas emission during coastal erosion, also a process that is not captured by Earth system models. Together, these observed processes could produce emissions across 2.5 million km^2 of abrupt thaw that provide an equivalent climate feedback as gradual thaw emissions from the entire 18 million km^2 permafrost region, under the warming projection of Representative Concentration Pathway (RCP) 8.5 (Turetsky 2020).

Observed increases to the frequency and intensity of wildfires, driven by climate change among other factors, have the potential to contribute to the carbon–climate feedback through additional CO_2 emissions. Extreme and often record-breaking fires have recently been encountered in southeastern Australia (Bowman et al., 2020), western North America (Higuera et al., 2020) and Siberia (McCarty et al., 2020; Witze, 2020). The scale of these fires has resulted in substantial CO_2 emissions, for example the 2019-20 Australian fires are estimated to have emitted 0.14-0.24 GtC (Bowman et al., 2020; van der Velde et al., 2021). The combination of repeat fires and drought have limited capacity for eucalyptus forests to recover and reabsorb emissions, possibly reducing future forest carbon stores (Bowman et al., 2020). In the Arctic, a new wildfire regime appears to be emerging, with climate change causing longer and more intense fire weather (McCarty et al., 2020; Scholten et al., 2021) and more frequent lightning ignitions (McCarty et al., 2021). The occurrence of overwintering or 'zombie fires' (McCarty et al., 2020; Scholten et al., 2021) mean wildfires are not dependent on ignition sources and are burning deeper into peat soils, which are extremely rich in organic carbon, further increasing CO_2 emissions (McCarty et al., 2020, 2021; Scholten et al., 2021). Landscape and vegetation changes mean previously fire-resistant landscapes are burning (McCarty et al., 2020, 2021). However, following wildfires, former boreal black spruce forests are regenerating with a mixture of fast-growing, deciduous broadleaf trees and conifers, which can increase subsequent forest carbon-storage by a factor of 5, offsetting some fire emissions (Mack et al., 2021) and limiting the feedback effect. On the other hand, more severe burning in peatlands, particularly those impacted by drought or drainage, is likely to result in much greater emissions than have been documented to date (Turetsky et al. 2011).

Ocean feedbacks

Warming of the ocean creates an amplifying feedback that reduces the rate of CO_2 uptake from the atmosphere, contributing to higher atmospheric CO_2 concentration and further warming. Changes in wind, heat, and freshwater fluxes driven by anthropogenic climate change may inhibit ocean CO_2 uptake by reducing the solubility of carbon in a warmer ocean; affecting change in the biological drawdown of carbon; and reducing ventilation of the ocean interior by stratifying the surface ocean (Williams et al., 2019). In addition to reduced CO_2 solubility, the re-emergence of anthropogenic carbon in shallow overturning circulation cells in the subtropical oceans, further amplifies, though only slightly, the solubility feedback and further reduces net CO_2 uptake by the ocean (Rodgers et al., 2020b). Utilising idealised CO_2 concentration experiments, the average value for the ocean carbon–climate feedback from CMIP6 is -17.2 ±5.0 GtC $^{o}C^{-1}$ (Arora et al., 2020), compared to -7.8 ±2.9 GtC $^{o}C^{-1}$ for CMIP5 (Arora et al., 2013). Modelling historic data between 1750-2011, the ocean feedback is estimated to be -8 ±3 GtC $^{o}C^{-1}$, representing a loss of around 7 ±4 GtC, given a historical warming of 0.85 ±0.2 ^{o}C (Friedlingstein, 2015).

Subsea permafrost carbon stores are small potential sources of greenhouse gas emission to the atmosphere, if they slowly destabilise with future warming (Schuur et al., 2015; Shakhova et al., 2017). The Arctic seabed accumulates methane gas bubbles leaking from natural biogenic and thermogenic sources; including methane clathrates, a frozen matrix of ice and methane kept stable at subsea depths by low temperatures and high pressures; and eroded permafrost sediment transported from coastlines and Arctic rivers (Schuur et al., 2015). Estimated CH_4 emission to the atmosphere, from both subsurface escape and permafrost thaw, ranges from at around 3-17 Tg* per year for the whole East Siberian Arctic Shelf (Thornton et al., 2016; Shakhova et al., 2017), but these emissions could rise with ongoing warming of Arctic ocean bottom waters.

*1 teragram (Tg) = 1 million tons = 1 trillion grams = 10^{12} grams

Future projections

Land feedbacks

Throughout this century, the land carbon sink is projected to continue absorbing CO_2 under all emissions scenarios and, despite considerable uncertainty, is projected to decrease by 2100 (Randerson et al., 2015). Future scenario modelling suggests Amazon dieback may reduce forest area by at least 25%, due to the effects of increased temperature and dry-season length overwhelming any gain due to the CO_2 fertilisation effect (Boulton et al., 2017). Experimental results (Terrer et al., 2021) indicate that as CO_2 concentration rises and plant biomass increases, soil organic carbon is reduced as plants take up more nutrients. In permafrost landscapes, short-term experiments (Li et al., 2017) suggest that warming initially enhances CO_2 uptake by plants during the early part of the growing season but this weakens or disappears later in the growing season. In boreal and temperate forests, long-term experiments (Reich et al., 2016) indicate additional warming will increase the CO_2 flux due to enhanced plant respiration, however plants acclimatise to warming, which limits the size of this increase.

Permafrost thaw is modelled to emit between 12 GtC and 174 GtC by 2100 depending on emissions and modelling scenario (Koven et al., 2015a; Schuur et al., 2015; MacDougall & Knutti, 2016). In extended modelling to 2300, under a high emissions scenario, around half of permafrost thaw is projected to occur before 2100 (Kovan et al., 2015a), with peak carbon emission and loss of carbon storage occurring after 2100 (MacDougall & Knutti, 2016; McGuire et al., 2018). Expert judgement presented by Schuur et al. (2015) predicted between 5%-15% (66-237 GtC) of stored permafrost carbon could be degraded and emitted to the atmosphere as greenhouse gases by 2100. Although, if models were to account for abrupt thaw (thermokarst) processes more accurately (Turetsky et al., 2019), the area of permafrost thaw within model projections could increase by 2100, between four-fold and twelve-fold for medium (RCP4.5) and high (RCP8.5) emissions scenarios, respectively (Nitzbon et al., 2020). This may also alter whether peak carbon emissions occur prior to, or after, 2100. In terms of projected future global mean warming, thawing permafrost may result in an additional +0.05^{o}C to +0.5^{o}C, by 2100 (Schaefer et al., 2014; Schuur et al., 2015).

Future emissions from wildfires are expected to increasingly contribute to the carbon–climate feedback by increasing emissions and, in some regions, limiting forest carbon-storage. Biomass burning is projected to increase under climate change in some regions and could contribute to a centennial-scale feedback of -6.5 ±3.4 ppm CO_2 per degree of land surface warming (Harrison et al., 2018). In South America, future warming of +4°C is projected to result in a -30% reduction in forest-stored carbon, compared to just a -7% reduction if warming is limited to +1.5°C (Burton et al., 2021).

Ocean feedbacks

The future ocean carbon sink is projected to weaken (stronger ocean feedback) under a high emissions scenario, by over 20%, amplifying further warming. Future projections suggest that with rising ocean heat content and associated ventilation and circulation changes, the ocean carbon–climate feedback will be amplified by 2100, weakening the ocean carbon sink (Randerson et al., 2015). In an extended single-model simulation to 2300, under a high future emissions scenario (RCP8.5 and its extension), the ocean carbon sink is projected to weaken by more than 20% or 330 GtC (Randerson et al., 2015).

The ocean carbon–climate feedback is irreversible on timescales of decades to centuries (Schwinger & Tjiputra, 2018). A modelling study that simulates a future hypothetical scenario where CO_2 is removed from the atmosphere (so-called "negative emissions") indicates that the ocean carbon–climate feedback continues to restrict oceanic carbon uptake and produces anomalously high (+52 ppm) atmospheric CO_2 concentrations, compared to a simulation without climate change (Schwinger & Tjiputra, 2018).

This ScienceBrief Review is consistent with the IPCC Sixth Assessment Report (AR6 WG1) Chapter 5, which concluded that both the land (*medium confidence*[§]) and ocean (*high confidence*[§]) carbon sinks will experience amplifying feedbacks, reducing the carbon uptake compared to a simulated constant climate. Under all scenarios, the land and ocean continue to act as a carbon sink throughout this century, but under higher emissions, the land and ocean sinks take up a smaller proportion of emissions, leaving a larger proportion in the atmosphere, amplifying climate change.

[§]*See an explanation of IPCC calibrated language.*

References

The full Brief and references can be explored on ScienceBrief with the following link: https://sciencebrief.org/topics/carbon/future.feedbacks, where the search filter can be used for e.g. Author name or keyword.

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