THE ROYAL SOCIETY

CLIMATE CHANGE : SCIENCE AND SOLUTIONS | BRIEFING 7

The carbon cycle:
Better understanding carbon-climate feedbacks and reducing future risks

In brief

Carbon is everywhere on Earth. It is within all living organisms, in soils, in the ocean and in the atmosphere. It is also stored in rocks and fossils. It constantly flows between these reservoirs, which are interlinked through a variety of processes. This is the carbon cycle. More than half of the carbon dioxide (CO_2) emitted to the atmosphere by human activity has been absorbed by natural carbon reservoirs (or 'sinks'), which have therefore considerably dampened climate change. However, as we continue into an era of unprecedented CO_2 emissions, we are disrupting the carbon cycle, with potentially severe consequences for our climate.

Study of the carbon cycle is critical to narrow gaps in our understanding of the Earth system and more accurately project the effect of CO_2 emissions on global temperatures. While the fundamental processes driving flows of carbon are largely known, uncertainties remain, particularly in the magnitude of change. Understanding carbon-climate feedback processes – the effect that a changing climate has on the carbon cycle which in turn further changes the climate – is particularly important, as these are among the largest sources of uncertainty in climate change projections. Risks associated with large carbon-climate feedbacks are minimised by reducing CO_2 emissions as much and as quickly as possible.

INSIGHTS

- Nature's carbon cycle has alleviated climate change and its impacts by absorbing more than half of the carbon that human activities have emitted, but such a large uptake is not guaranteed to continue.
- The future of carbon sinks will depend on the level of CO_2 in the atmosphere and how fast it rises or decreases, on the impacts of climate change, and potentially on direct human intervention. Safeguarding the sinks, in particular forests, is essential to maintain their functions.
- Carbon-climate feedbacks are expected to amplify climate change and its impacts, with the greatest and most uncertain effects in a high carbon emissions future.
- Enhancement of natural carbon sinks by human intervention will be essential to achieve net zero emissions. This includes sustainable afforestation, reforestation, agricultural soil management, and peatland restoration.
- Research to improve understanding of the carbon cycle should include: continuous observational monitoring in the atmosphere, on land, and in the ocean, by both in situ and satellite data; better understanding of potential instabilities in carbon sinks, as well as the development of models that more fully represent the carbon cycle's complexity.
- The risks associated with carbon cycle uncertainties will be minimised by increasing momentum towards halving global emissions by 2030 and continuing with deep emissions cuts afterwards.

1. Climate change and the carbon cycle

For 800,000 years until the Industrial Revolution (starting around 1750), ice core data show CO_2 concentration in the atmosphere remained approximately around 300 parts per million, with CO_2 concentration fluctuating over glacial-interglacial cycles. CO_2 concentration reached 415 ppm in 2020 and continues to rise.

1.1 Why the carbon cycle matters

The processes of the carbon cycle are fundamentally tied to the climate of our planet. Carbon is constantly cycling between atmospheric, oceanic, and terrestrial reservoirs. Before humans perturbed the environment, the carbon emitted by natural processes (like decay of organic matter) was approximately equal to the carbon absorbed (for instance, by vegetation growth), leading to a relatively stable atmospheric CO_2 concentration since the end of the last glaciation ten thousand years ago. This helped ensure that surface air temperature was also relatively stable.

However, the carbon cycle can move out of its fragile equilibrium with the global climate. Cold and warm periods in Earth's history have shown that natural perturbations, such as glaciations triggered by changes to Earth's axial tilt and orbit around the sun, can disrupt the carbon cycle, altering the level of CO_2 in the atmosphere and other reservoirs, with implications for the Earth's climate. Such natural fluctuations reveal the intricate functioning of the carbon cycle and its influence on the climate system.

Anthropogenic, or human-generated, emissions have rapidly increased the concentration of CO_2 in the atmosphere to levels unprecedented in the last three million years. Some of these emissions are absorbed by the natural carbon cycle, but it has been disrupted beyond natural fluctuations. It is therefore essential to better understand the cycle in order to project future climate change.

1.2 The natural carbon cycle

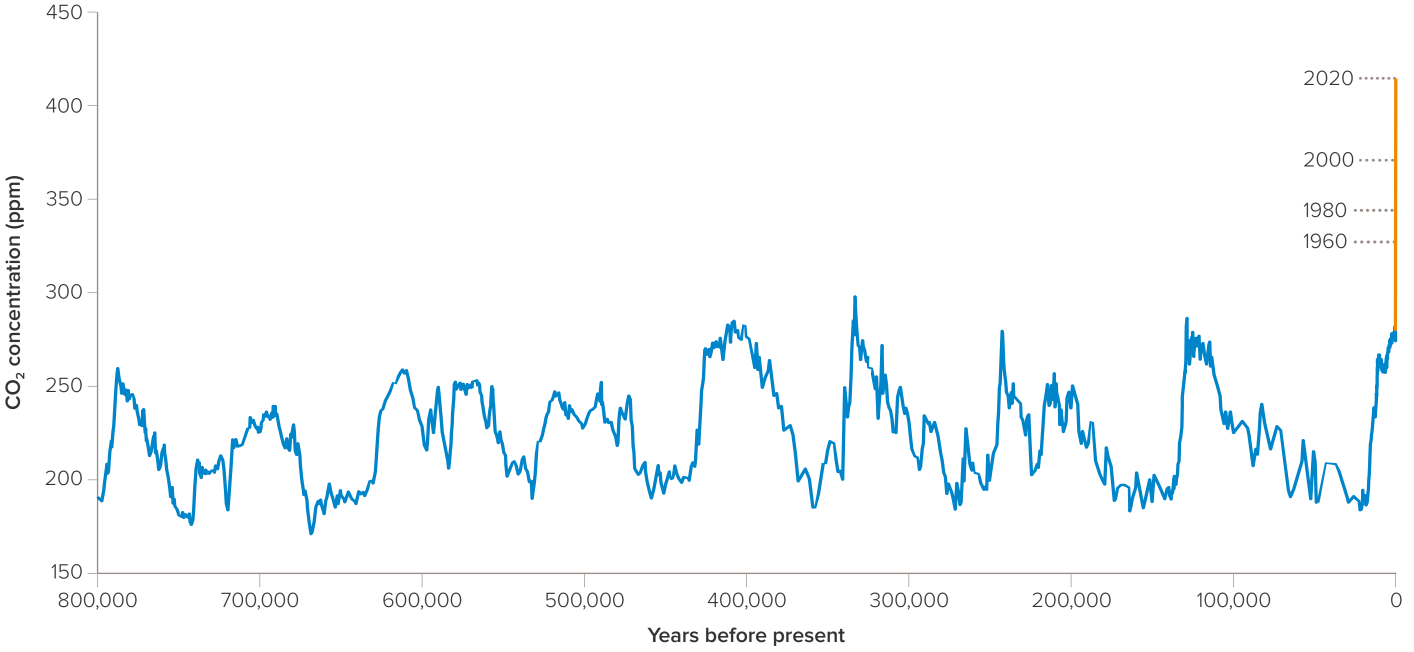
The Earth has an active natural carbon cycle, inhaling and exhaling carbon like a living organism. Before humans released CO_2 at large scale from burning fossil fuels, deforestation, and other use of land (termed 'the anthropogenic perturbation'), the atmospheric reservoir stored around 2200 billion tonnes of CO_2 (2200 $GtCO_2$). Each year, around 400 $GtCO_2$ is removed from the atmosphere by trees and other vegetation on land through photosynthesis, and a similar amount is returned to it by plant and soil respiration. In the ocean, around 330 $GtCO_2$ each year is exchanged between the atmosphere and surface waters, with more CO_2 absorbed in the cold waters of high-latitudes, and some CO_2 out-gassed in the tropical oceans where carbon-rich deep waters come to the surface via upwelling of ocean waters[1].

For 800,000 years until the Industrial Revolution (starting around 1750), ice core data shows CO_2 concentration in the atmosphere remained below approximately 300 parts per million (ppm), with CO_2 concentration fluctuating over glacial-interglacial cycles. In the centuries leading up to the Industrial Revolution, CO_2 concentration was around 270 – 280ppm[2]. While preindustrial humans emitted some CO_2 from fires and land clearance, such emissions were very small; it was not until the Industrial Revolution that anthropogenic emissions began to significantly perturb the carbon cycle.

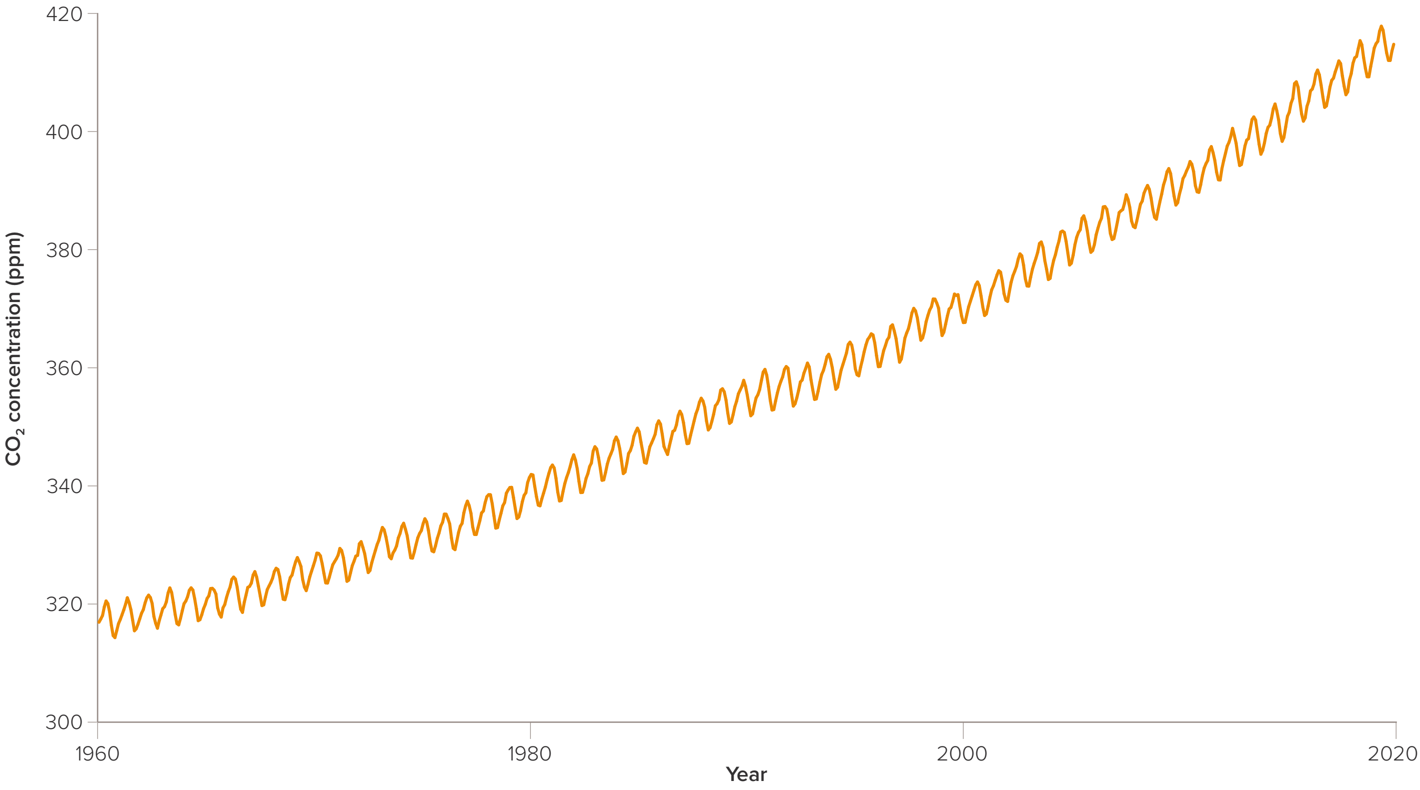
FIGURE 1

CO_2 concentrations in the atmosphere have fluctuated over the last 800,000 years as the Earth moves between glacial and interglacial periods, but human activity since 1750 is increasing CO_2 concentrations at unprecedented rates[1] (A). As of 2020, Earth's atmospheric CO_2 concentration is around 415 ppm and rising by around 2.5 ppm each year. This growth rate has accelerated in recent decades[11] (B).

(A)



(B)



Without the sequestration of carbon by the land and ocean, the level of CO_2 in the atmosphere would now be around 600 ppm, with an associated warming about double that currently observed.

1.3 The carbon cycle since 1750: the 'anthropogenic perturbation'

Since 1750, anthropogenic emissions of CO_2 have started to disturb the global carbon cycle, rising from negligible levels of anthropogenic CO_2 before the Industrial Revolution, to around 42 $GtCO_2$ in 2019 from burning of fossil fuels and land-use change[2]. This increase in CO_2 emissions is the main driving cause of climate change. With methane, nitrous oxide and other greenhouse gases (GHGs) included, annual emissions have risen to around 59 billion tonnes of CO_2 equivalent ($GtCO_2e$)[4] (see panel on methane and nitrogen cycles).

In the past decade, CO_2 emissions originated primarily from fossil fuel combustion, averaging 34 $GtCO_2$ per year during 2010 – 2019 (see figure 2). During the same period, land-use change emitted 16 $GtCO_2$, mainly from deforestation, and reabsorbed 10 $GtCO_2$, mainly from the regrowth of abandoned agricultural land, leading to net emissions of 6 $GtCO_2$.

BOX 1

The methane and nitrogen cycles

Stabilising the global climate does not depend only on CO_2 emissions but other greenhouse gases (GHG) which make up more than 25% of total anthropogenic GHG emissions, particularly methane and nitrous oxide[4]. Total GHG emissions, including CO_2, methane, nitrous oxide and other gases reached an estimated 59 $GtCO_2e$ in 2019[4], of which around 10 $GtCO_2e$ comprised methane and 3 $GtCO_2e$ nitrous oxide. Estimated methane levels have increased around 160% or 1,150 parts per billion (ppb) from 720 ppb in 1750 to around 1870 ppb in 2019[5, 6]. Estimated nitrous oxide levels have increased around 15% or 60 ppb from 270 ppb in 1750[7] to around 330 ppb in 2019[6]. Both are at their highest levels for 800,000 years[8]. These emissions present their own challenges as they have distinctive sources, with methane generated from livestock, rice farming, natural wetlands, landfill sites and gas production among other sources, while nitrous oxide emissions arise largely from production and application of fertiliser.

Total fossil plus land-use change emissions were partitioned among the atmosphere (19 $GtCO_2$), land (13 $GtCO_2$), and ocean (9 $GtCO_2$)[2].

Carbon sinks have prevented much higher levels of climate change and more severe impacts. Without the sequestration of carbon by the land and ocean, the level of CO_2 in the atmosphere would now be around 600 ppm, with an associated warming about double that currently observed[2].

The land and ocean respond to rising CO_2 in the atmosphere. Land has helped to alleviate climate change because elevated atmospheric CO_2 increases photosynthesis, which in turn tends to encourage more plant growth (especially of trees). More plant growth leads to more biomass, resulting in more carbon storage in living plants. When plants die, some of this additional biomass becomes soil organic matter, increasing soil carbon storage. This is a primary reason why the land sink has helped dampen anthropogenic climate change. However, this process has limits. The land sink will saturate when it becomes limited by other factors, such as the availability of water or nutrients, meaning it may sequester proportionally less of the future CO_2 humans emit. Impacts of climate change, such as forest droughts, fires and permafrost thaw, may even reverse the sink.

In the ocean, rising atmospheric CO_2 pushes additional CO_2 into the ocean, which leads to a proportional increase in the amount of CO_2 dissolved in the ocean surface. Most of this CO_2 reacts with carbonate ions in seawater to form bicarbonate, a process which enhances the capacity of the ocean to absorb carbon.

However, the chemical reaction becomes less efficient when the ocean has already absorbed a lot of CO_2, reducing the CO_2 uptake by the oceans, as well as leading to a more acidic ocean. Following this process, inorganic carbon in its various forms is then transported to the deep ocean through circulation. 75% of all carbon absorbed by the ocean remains in the top 1000m due to slow ocean circulation[9].

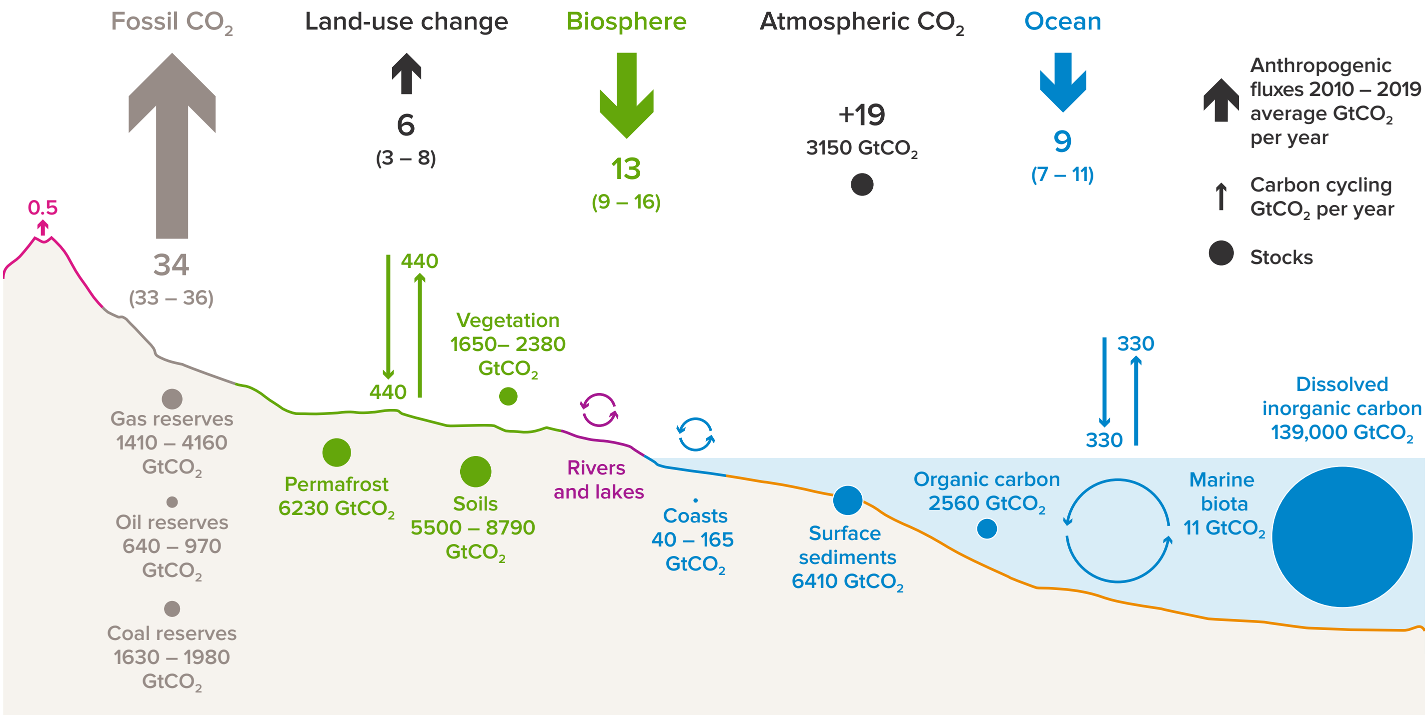
Unlike land ecosystems, marine plankton are primarily limited by the availability of nutrients rather than CO_2, and therefore plankton growth does not increase in response to increasing CO_2 in the ocean. However, the increased acidity of the ocean is already negatively impacting many marine species and ecosystems, and the indirect effect of ecosystem changes on the absorption of CO_2 by the ocean is unknown.

The cumulative amount of emissions is more important than annual emissions in determining the level of climate change because CO_2 molecules stay in the atmosphere for a long time (16 – 34% of CO_2 will stay in the atmosphere for more than 1000 years)[10]. If public policy and resulting changes to industry and consumer choices lead to annual emissions falling, atmospheric concentrations would still rise (albeit more slowly), as long as more CO_2 is emitted to the atmosphere than is absorbed by all carbon sinks. For example, in 2020, emissions from fossil fuel combustion are estimated to have fallen by around 7% (from about 36 $GtCO_2$ to 34 $GtCO_2$), as a result of restrictions put in place to fight the COVID-19 pandemic. Yet, during this period, atmospheric concentrations rose by 2.6 ppm to 415 ppm[11] because emissions were still much larger than annual carbon uptake by the land and ocean sinks.

Monitoring the carbon sinks through observation, in addition to modelling the carbon cycle to test understanding of the processes, will be particularly important. Such work is especially salient for governments that have stewardship of major carbon sinks such as forests and peatlands, and for the international community who have a shared stake in the global oceans.

FIGURE 2

'The anthropogenic perturbation' or how the natural carbon cycle has been disturbed by human activity (with figures averaged globally for the decade 2010 – 2019)[2]. The land and ocean released and absorbed around 440 $GtCO_2$ and 330 $GtCO_2$ respectively each year. Human activity emited around 34 $GtCO_2$ from fossil use and around 6 $GtCO_2$ from land-use change each year (made of emissions of 16 $GtCO_2$, mainly from deforestation, and uptake of 10 $GtCO_2$, mainly from the regrowth of abandoned agricultural land), 19 $GtCO_2$ of which has remained in the atmosphere while 13 $GtCO_2$ was sequestered by the land and 9 $GtCO_2$ absorbed by the ocean on average each year. A $GtCO_2$ is a billion tonnes of CO_2.



2. Opportunities for research progress

A critical concern is the impact of climate change on sink processes. As the sinks get disrupted by climate change, the proportion of future anthropogenic emissions they sequester may fall, leaving a greater proportion of our yearly emissions in the atmosphere.

2.1 Understanding the future of the carbon sinks – knowns and unknowns

With both CO_2 emissions and concentrations at unprecedented levels, the world is in uncharted territory. Some aspects of the processes controlling carbon sinks are relatively well understood, such as the response of seawater chemistry to rising CO_2, and to a lesser extent the transport of carbon from the surface to depth by ocean currents. However, other processes, such as the mechanisms responsible for the land sink, are less certain, which makes it difficult to predict future sink behaviour with confidence.

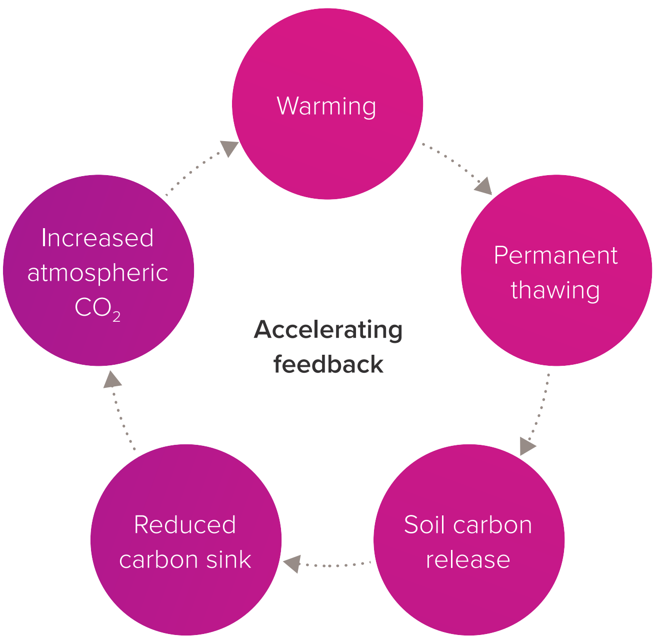
A critical concern is the impact of climate change on sink processes. As the sinks get disrupted by climate change, the proportion of future anthropogenic emissions they sequester may fall, leaving a greater proportion of our yearly emissions in the atmosphere.

This means the dampening effect the sinks have played on climate change to-date may reduce, and greater mitigation action will be needed to meet the objectives of the Paris Agreement. The potential pace and scale of such a reduction is poorly known and increases the urgency for both emissions reduction and a deeper understanding of the carbon cycle.

Scientists are now questioning to what degree the land and ocean sinks will continue to sequester carbon now that they are being affected, not only directly by rising atmospheric CO_2 concentration, but also by the impacts of climate change itself[2]. A carbon-climate 'feedback' refers to the effect that a changing climate has on carbon sinks, altering the amount of carbon they absorb or release, which in turn either dampens or further exacerbates climate change.

FIGURE 3

Accelerating feedback loops between the climate and carbon cycle may amplify warming. In this example of such feedbacks, thawing permafrost releases soil carbon into the atmosphere, which serves to amplify warming and causes further thawing. Anthropogenic disruptions to the carbon cycle may unlock feedbacks that continue to warm the Earth for centuries[12].



Carbon-climate feedbacks are thought to be largest on land. Some feedbacks, like vegetation growth in previously arid or cold areas, would slow climate change by absorbing more carbon. Other feedbacks, such as die-back of carbon-absorbing forests pushing them into savannah-type landscapes, or release of carbon from thawing permafrost, would accelerate climate change by releasing carbon (see figure 3). There is significant concern based on a range of observations and current understanding that the feedbacks will act globally to amplify warming, but the timing and magnitude of this effect, and the exact contribution of different processes, is highly uncertain[13]. For example, changes in wildfires as a result of a warmer climate release CO_2 to the atmosphere, but the effect in the long-term depends on how the vegetation will regrow after fire events[13, 14, 15].

Carbon-climate feedbacks are also significant in the ocean. Warming of the ocean surface leads to less absorption of carbon, as warm waters hold less CO_2 than cold waters. Warming and changes in the water cycle can impact ocean circulation, mostly reducing the rate at which surface waters are renewed through exchange with deep water. This can reduce ecosystem productivity and the carbon sink in the tropics. Conversely, stronger wind conditions may increase this renewal rate in the Southern Ocean, which can lead to outgassing of carbon from natural carbon-rich deep waters.

Such changes in the rate of carbon transfer between the shallow and deep ocean affect how much carbon is “locked” in the deep ocean, and how much is available for cycling back to the atmosphere where it will contribute to the severity of climate change.

Models suggest that the combined feedback processes in the ocean will act globally to amplify warming, but the specific contribution of different processes is highly uncertain[12].

Most of the known feedbacks are, to some extent, included in current climate change projections[16]. A notable exception is permafrost thawing, which the IPCC's 2013 report assessed could further enhance warming by 2.5 to 12.5% compared to existing climate projections under a high-emissions scenario[17, 18].

A critical outstanding question is how much a given level of cumulative emissions alters global surface air temperature. The IPCC estimated in 2013 that the global mean surface temperature rise per 1000 billion tonnes of carbon emissions (equivalent to 3,664 $GtCO_2$), was likely to be 0.8°C to 2.5°C. The three-fold range of temperature rise reflects both the scale of uncertainty in climate change research and the risks posed by climate feedbacks[12], as well as uncertainties in non-CO_2 emissions[9] (see panel: the methane and nitrogen cycles). Reducing uncertainty on the carbon cycle will help narrow this range (see briefing 1: *Next generation climate models*).

While much is known about the carbon cycle, these questions illustrate some important areas where more research is needed. Reducing unknowns via targeted research would support policymakers with critical evidence to make robust decisions.

There is significant concern based on a range of observations and current understanding that carbon-climate feedbacks will act globally to amplify warming.

To create a low carbon future and reach net zero emissions, enhancement of the natural sink capacity of the land by human intervention will become essential.

2.2 Understanding low and high-carbon futures

In developing policy, it is useful to consider what science can tell us about the expected behaviour of the carbon sinks in low and high carbon futures.

Reducing emissions is essential but will alter carbon sink behaviour. If emissions are reduced in line with the temperature goals of the 2015 Paris Agreement – a low carbon future – the carbon sinks will absorb atmospheric CO_2 more slowly. This is because the magnitude of carbon sinks, especially in the ocean, is mainly related to the rise and/or level of CO_2 concentration in the atmosphere. This low-carbon future would set in motion a new set of dynamics of the carbon cycle, which will re-equilibrate with future elevated atmospheric CO_2 levels, a process never experienced before. Feedbacks may disrupt stabilisation to some extent but will be more limited due to the lower warming. Regardless of the evolution of the natural carbon cycle, reducing human carbon emissions is essential to climate stabilisation.

To create a low carbon future and reach net zero emissions, enhancement of the natural sink capacity of the land by human intervention will become essential. The net zero objective of the Paris Agreement is "to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century…". This statement refers to the proactive management and enrichment of land and ocean sinks to enhance removal of CO_2 from the atmosphere.

Examples include restoring forests, mangroves and peatlands, sustainable afforestation, the sustainable management of agricultural soils, and protection of marine carbon sinks like sea grass ecosystems and salt marshes. Artificial sinks, if they can be produced sustainably and economically, could also enhance the potential for carbon uptake[19].

A high carbon future, such as that which will unfold if countries' current 'Nationally Determined Contributions' are not strengthened, will bring greater risks. As of December 2020, the UN calculated that pledges to date still leave the world heading for a temperature rise in excess of 3°C this century[4]. If climate change on this scale unfolds, the sinks will likely persist but become less efficient at absorbing carbon under higher atmospheric CO_2 levels, leaving proportionally more of our CO_2 emissions in the atmosphere. There is also an additional risk that carbon cycle feedbacks described in this briefing will become much stronger, further reducing the sink efficiency and leading to additional warming and climate impacts.

The risks that climate change poses to the carbon cycle highlight the need for rapid and deep emissions reduction. Such risks can be reduced by moving as quickly as possible towards lowering our emissions in line with the UN target of halving anthropogenic emissions by 2030 compared to a 2019 baseline[4] and continuing with deep emissions cuts afterwards.

3. Priorities for research and development

Understanding the processes of the carbon cycle will enable better projections of future atmospheric CO_2 concentrations and associated temperature changes. Whereas the fundamentals of the carbon cycle are well known, critical questions remain over the future dynamics of the carbon cycle as well as the magnitude of changes. These relate both to the global cycle and to specific environments such as the Southern Ocean, the upper ocean, the Arctic, tropical forests, peatlands and permafrost regions. More knowledge of these areas will help us make informed adaptation and mitigation policies, as well as better understanding how systems will respond to climate change and the impacts which may subsequently arise.

Improving our knowledge can be done through continuous monitoring of the multiple features of the global carbon cycle, with expanded long-term field and satellite observations, including measurements of atmospheric carbon, partial pressure of CO_2 at the ocean surface, organic and inorganic carbon within the ocean, vegetation and soil, in addition to proxies of carbon cycle activity such as leaf area index and ocean colour.

More detailed models of the carbon cycle would also help improve understanding of the risk of saturation or reversal of sinks, for example by quantifying the risks of carbon release from permafrost, peatlands, and tropical forests as well as the implications of ocean acidification on marine ecosystems and the ocean carbon sink. However, in Earth system models – models that integrate the interactions of atmosphere, ocean, land, ice, and biosphere – there are challenges to address. Data driven approaches such as machine learning or data assimilation techniques, which make use of satellite measurements and in situ data to provide spatial and temporal information on the dynamics of the carbon cycle, can help improve models.

Finally, the global nature of the carbon cycle means that collaboration is vital, between countries and between disciplines. Specialists in ecosystem ecology, biogeochemistry, the carbon cycle and Earth system modelling, process level observation, machine learning and other salient fields all have a role to play in continuing to deepen our understanding of this fundamental cycle.

Improving our knowledge can be done through continuous monitoring of the multiple features of the global carbon cycle.

4. Conclusion

Over two centuries on from the Industrial Revolution, the climate impacts of fossil fuel burning and land-use change are having tangible and widespread impacts on the carbon cycle, from ocean acidification to widespread wildfires. Such severe environmental changes are unprecedented in human history. The combined effect on the carbon cycle from climate change and continued anthropogenic emissions will impact ecosystems, society, and our ability to mitigate climate change. While science has advanced to demonstrate the principles and operation of the carbon cycle, questions remain over the magnitude and timing of impacts of higher atmospheric CO_2 levels, rising temperatures and climate feedbacks on the carbon cycle. Greater understanding of the terrestrial and oceanic carbon sinks and potential sources is therefore a major priority for the decade ahead.

This briefing is one of a series looking at how science and technology can support the global effort to achieve net zero emissions and adapt to climate change. The series aims to inform policymakers around the world on 12 issues where science can inform understanding and action as each country creates its own road map to net zero by 2050.

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