CARBON AND CLIMATE

Carbon and Climate

Basic information on the major components of the global carbon cycle

Use the applet

Carbon Cycle Atmosphere Fossil Fuels Ocean Uptake Land Use

Land Uptake

Carbon and the Global Carbon Cycle

Carbon is a ubiquitous element on Earth. Most of the Earth's carbon is stored in rocks, but this carbon is essentially inert on the 100's to 1000's year timescales of interest to humans. The rest of the carbon is stored as CO_2 (carbon dioxide) in the atmosphere (2%), as biomass in land plants and soils (5%), as fossil fuels in a variety of geologic reservoirs (8%) and as a collection of ions in the ocean (85%). These are the "active" reservoirs of carbon of interest in this website.

How are the Global Carbon Cycle and Climate

Change / Global Warming connected?

The Earth is warmed by the Sun. This warmth is returned from Earth to the atmosphere in the form of heat radiation. Many gases in the atmosphere, including CO2, absorb the Earth's heat energy and radiate in all directions. The energy radiated downward warms the surface and lower atmosphere. Adding more CO2 to the atmosphere means more heat radiation is captured by the atmosphere and radiated back to Earth. Methane, CH4, is another very important greenhouse gas that is part of the carbon cycle. This website addresses only CO2.

Humans add CO2 to the Atmosphere, Nature removes about half of it.

From 2007-2016, humans added 10.7×10^15 grams of carbon as CO2 (1015 grams of carbon = 1 PgC) to the atmosphere each year, primarily by burning fossil fuels (~9.4 PgC/yr) and also from land use change (~1.3 PgC/yr). Best estimates indicate that the ocean took up 22% of this carbon (~2.4 PgC/yr), and the land biosphere absorbed 28% (~3.0 PgC/yr), while 6% of the estimated emissions remain unaccounted for in the sink reservoirs (LeQuere et al. 2017). Thus, over this recent decade, only ~50% of the emitted carbon remained in the atmosphere to cause climate warming. Though uncertainties remain in the global budget, it is clear that natural processes are significantly damping the rate of carbon accumulation in the atmosphere. Future climate warming depends on both CO2 sources from human emissions and CO2 sinks from natural sinks in the ocean and the terrestrial biosphere.

Carbon Cycle

The Basics

Carbon is transferred between CO_2 and living or dead organic material by the very basic photosynthesis / respiration reaction (shown here in simplified form).

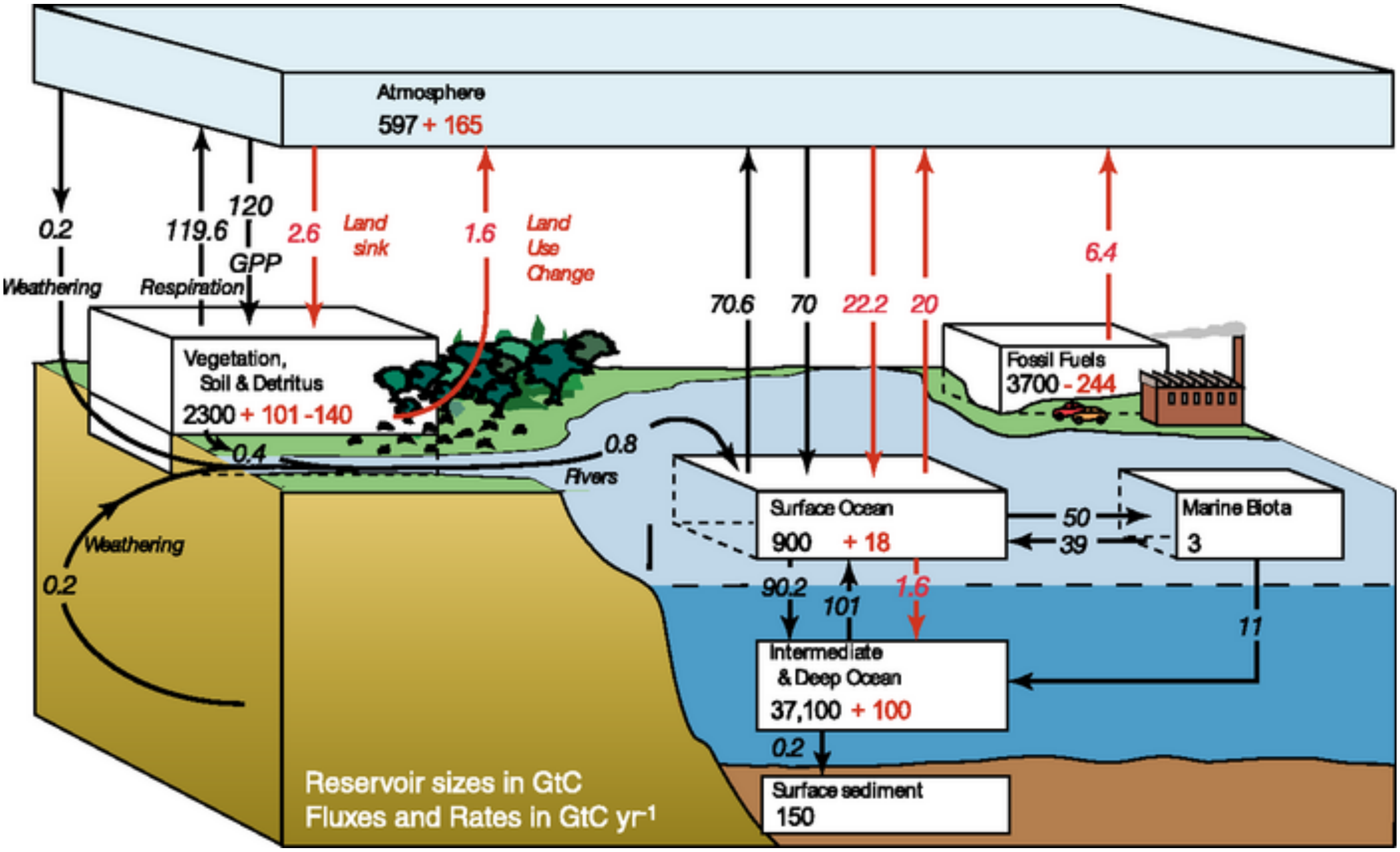
$$CO_2+H_2O+energy \Leftrightarrow CH_2O + O_2$$

When this reaction proceeds to the right, it is the fixation of carbon to organic matter by plants via photosynthesis; and when it proceeds to the left, it is respiration or combustion of that organic matter. Fossil fuels are the remnants of dead organic matter that lived millions of years ago.

The Global Carbon Cycle

The carbon cycle is a complex system of biological, chemical and physical processes. A schematic from the IPCC AR4 report is shown here. The schematic shows the major reservoirs of carbon in gigatons of carbon, GtC (1 GtC = 1 PgC: Petagram of Carbon) and the major fluxes in GtC/yr. The numbers shown are the best estimates for the 1990's.

These flux estimates are updated annually by the Global Carbon Project (LeQuere et al. 2017) and the state of carbon cycle science is reviewed in each IPCC report (Ciais et. al 2013).

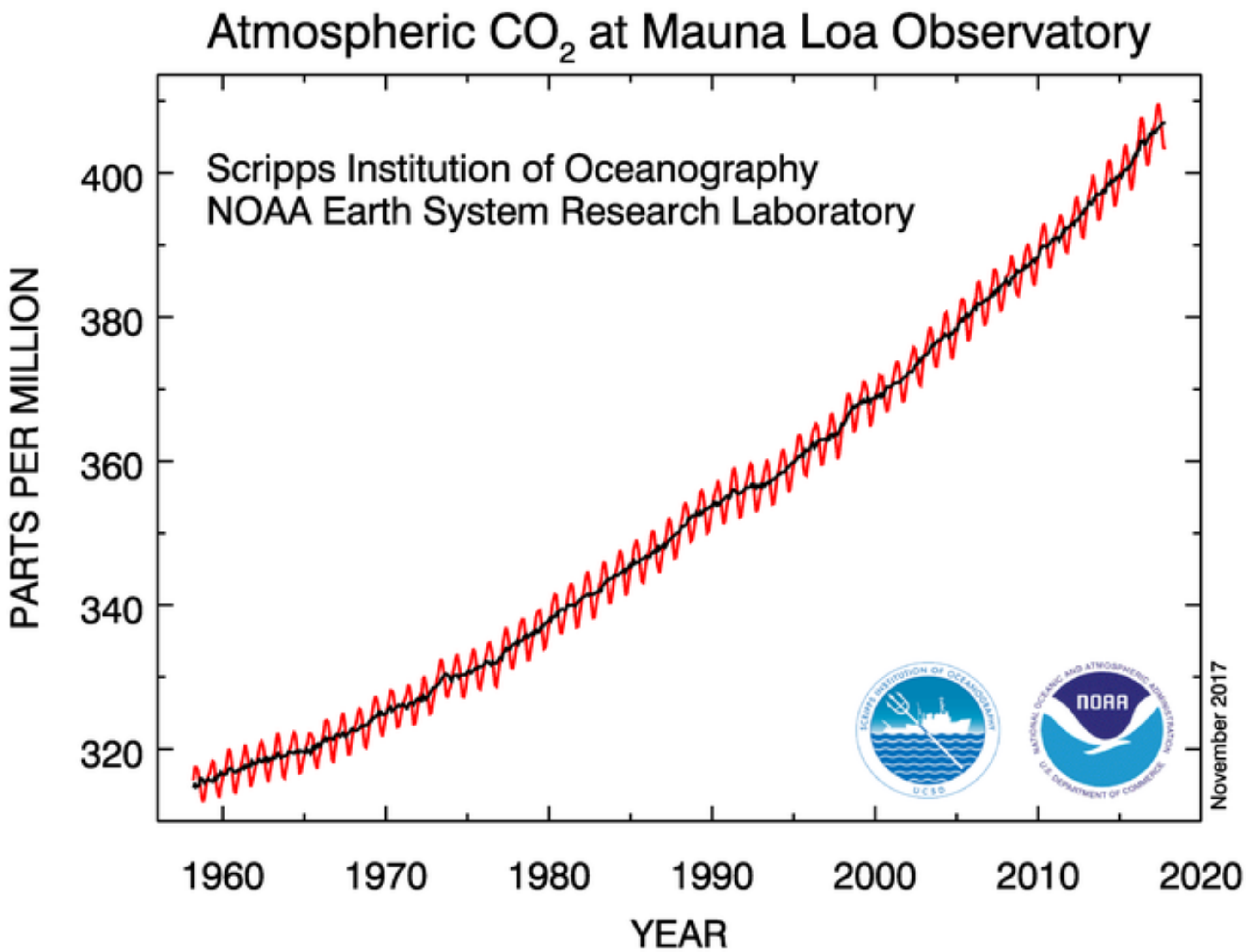


IPCC AR4 (2007) Fig 7.3. The global carbon cycle for the 1990s, showing the main annual fluxes in GtC yr –1 : pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red (modified from Sarmiento and Gruber, 2006, with changes in pool sizes from Sabine et al., 2004a). The net terrestrial loss of –39 GtC is inferred from cumulative fossil fuel emissions minus atmospheric increase minus ocean storage. The loss of –140 GtC from the 'vegetation, soil and detritus' compartment represents the cumulative emissions from land use change (Houghton, 2003), and requires a terrestrial biosphere sink of 101 GtC (in Sabine et al., given only as ranges of –140 to –80 GtC and 61 to 141 GtC, respectively; other uncertainties given in their Table 1). Net anthropogenic exchanges with the atmosphere are from Column 5 'AR4' in Table 7.1. Gross fluxes generally have uncertainties of more than ±20% but fractional amounts have been retained to achieve overall balance when including estimates in fractions of GtC yr–1 for riverine transport, weathering, deep ocean burial, etc. 'GPP' is annual gross (terrestrial) primary production. Atmospheric carbon content and all cumulative fluxes since 1750 are as of end 1994.

References

Atmosphere

In 1958, Charles D. Keeling began taking measurements of atmospheric CO2 at Mauna Loa, Hawaii. One can see both the seasonal cycle, dominated by the annual cycle of photosynthesis and respiration in the terrestrial biosphere of the Northern Hemisphere, as well as the clear upward trend. Learn more about Keeling's data from this short video



These data are now part of a global network that monitors atmospheric CO2. All observations show a steadily increasing trend. You can find the data and other information from NOAA . NOAA has also produced this great visualization of current observations across latitudes and puts them in context with historical CO2 records that stretch back to the ice ages.

As explained below, CO_2 is accumulating in the atmosphere because of human activities, primarily the burning of fossil fuels and the clearing of forests for cultivation. You will also learn about how natural processes on land and in the ocean are significantly modulating the rate of CO_2 growth in the atmosphere.

Fossil Fuels

The Basics

Burning fossil fuels puts carbon into the atmosphere. Other smaller sources include industrial processes such as cement manufacture and natural gas flaring. Fossil fuels provide most of the energy that supports human transportation, electricity production, heating and cooling of buildings, and industrial activity. Oil used to be the dominant fossil fuel, but as of 2016, coal is dominant (40% to oil's 34%) and the share from natural gas is steadily growing (19% in 2016).

In the 1990's, human fossil fuel use emitted 6.4 Petagrams of carbon (PgC) per year, and in from 2007-2016, 9.4 PgC/yr. Over 2000-2009, emissions increased by 3.3% per year, substantially faster than the growth rate of 1.0% per year in the 1990's. This dramatic increase was primarily due to growing emissions from developing countries. From 2012-2016, the rate of emissions growth substantially slowed. Nonetheless, emissions over 2007-2016 are largely are consistent with the most intensive fossil fuel emission projections used in the IPCC AR5 report (RCP8.5).

Evidence indicates that the rapid rise in emissions from developing countries, including China, are due to growth in international trade and a shift of developed countries toward service economies. The production of exports in developing countries is also an important driver of their increased emissions.

You can find information about the emissions from the developed world (so-called Annex 1 countries in IPCC terms) on the UNFCCC site.

The Future of Fossil Fuels

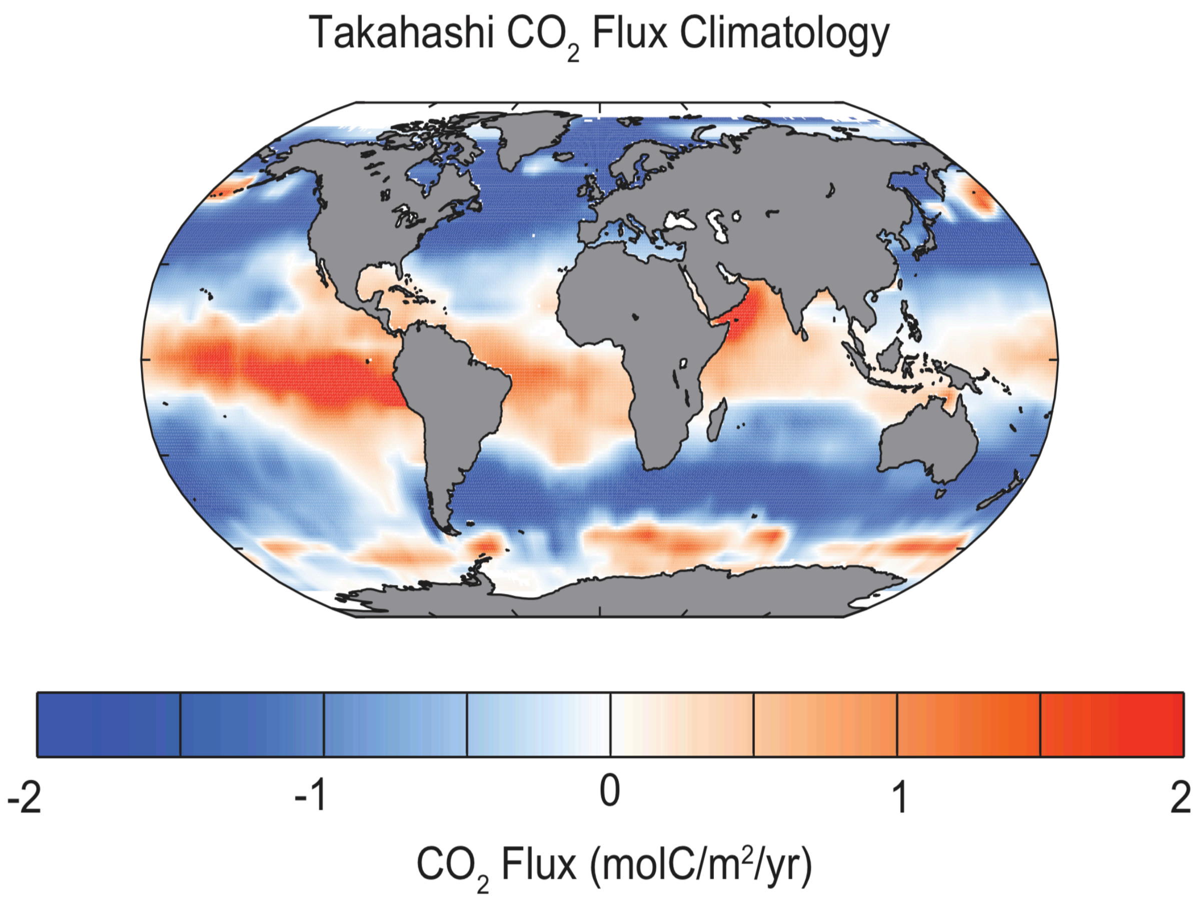
The future of anthropogenic fossil fuel use depends on human decisions about energy use at the international scale. If we collectively choose to depend more and more on fossil fuels, our emissions will increase. If we choose to focus on efficiency and renewable energy sources, our emissions will not increase so quickly or even stabilize or decline. These are difficult choices with potentially dramatic implications for economies, politics, environment, and society from the local to the global scale. These issues are the focus of the activities under the United Nations Framework Convention on Climate Change with the most significant recent development being the 2015 Paris Agreement. Current activities focus on the implementation of this plan.

References

Ocean Uptake

The Basics

CO_2 dissolves in seawater, and then reacts with the water so that it dissociates into several ions. This disassociation means that the oceans can hold a lot of carbon – 85% of the active reservoir on Earth. Cold seawater can hold more CO_2 than warm water, so waters that are cooling (i.e. poleward-moving western boundary currents) tend to take up carbon, and waters that are upwelling and warming (i.e. coastal zones and the tropics) tend to emit carbon. This is the basic reason for the pattern of the global sea-to-air CO_2 flux, as shown in this figure.



Annual mean air-sea CO2 flux, estimated by Takahashi et al. 2009. Positive is from ocean to atmosphere, negative from atmosphere to ocean.

The ocean is also teeming with plant life that photosynthesizes in the presence of nutrients and sunlight and makes organic matter out of the seawater CO_2. Though much of the CO_2 removed from seawater biologically is quickly recycled back to CO_2 by the surface ocean food web, a small portion (less than 1%) of the waste matter sinks down into the deep and enriches the abyss with carbon. This process moves carbon from the surface ocean to the deep ocean and stores carbon away from the atmospheric reservoir. Here's a video from NASA on ocean phytoplankton and their global importance.

As humans increase the atmospheric CO_2 concentration, more carbon is driven into the oceans. If not for the ocean, the atmospheric concentration of CO_2 would be about 80ppm higher than at present (155 PgC, Ciais et al. 2013, Khatiwala et al. 2009, 2013). Of all fossil fuel emissions to the atmosphere (375PgC), the ocean has cumulatively mitigated 41% (McKinley et al. 2017). This carbon is almost all in the surface 1km of ocean and has not penetrated any deeper because the ocean takes about 1000 years to mix completely. For more illustrations of the ocean carbon sink over time, check out these animations from the Ocean Carbon and Biogeochemistry Program.

The Future of Ocean Carbon Uptake

Scientists expect that the ocean will eventually take up about 85% of anthropogenic CO_2, but because the ocean takes ~1000 years to mix, this process will take many hundreds to thousands of years. Through the middle of the 21st century, the carbon sink is expected to grow. This will occur mostly because the increasing CO_2 in the atmosphere will drive more carbon into the ocean by the solubility mechanism. However, because of the chemistry of carbon in seawater, the ability of the ocean to absorb carbon decreases as the concentration increases. Anthropogenic forcings may slow down the large-scale overturning circulation of the ocean and reduce the efficiency of the ocean sink. Climate models suggest significant regional changes in biological removal of carbon to the deep ocean, but a small net effect on globally-integrated ocean carbon uptake.

It is clear that the ocean sink is quite variable in space and time. For example, multiple lines of evidence indicate that the global sink weakened in the decade of the 1990s, and then strengthened in the decade of the 2000s [Fay and McKinley, 2013; DeVries et al. 2017; Landschutzer et al. 2015; Ritter et al. 2017]. Though it is clear that ocean circulation is the primary driver of these changes, detailed understanding is limited in large part because of limited ocean observations [Peters et al, 2017].

In the US, the Ocean Carbon and Biogeochemistry (OCB https://www.us-ocb.org/) program coordinates research and education efforts on ocean carbon uptake. See a short film here that summarizes their carbon research portfolio. International efforts look to the International Ocean Carbon Coordinating Project (IOCCP)

The "Other CO2 Problem" = Ocean Acidification

There are additional consequences to the ocean's uptake of carbon. CO_2 dissolved in seawater and forms carbonic acid, and so adding more CO_2 to the water makes the ocean more acidic. From preindustrial times to present the pH of the ocean has declined 0.1 pH units, from 8.21 to 8.10, and it is likely to decline by another 0.3-0.4 pH units by the 2100, assuming atmospheric pCO_2 is about 800 ppmv by that time. Acidification will damage coral reefs and likely place significant stress on species important to ocean food chain, particularly in the Southern Ocean. Scientists are working hard to better-understand the impacts on organisms and the integrated effects on ocean ecosystems.

Here is a video from National Resources Defense Council on ocean acidification. For more detail, see these pages from NOAA and the Woods Hole Oceanographic Institution.

References

Land Use

The Basics

New agricultural land is typically created by cutting down forests. When trees are cut down and burned or left to decompose, carbon goes into the atmosphere. In the present day, deforestation and the resulting net carbon source to the atmosphere is primarily occurring in the tropics. However, in the last 200 years, forest clearing for agriculture in the middle latitudes of the Northern Hemisphere was also a substantial source of carbon to the atmosphere. Since the mid-1900's, much of the less-productive agricultural land in the US and Europe has been allowed to regrow as forests – making for uptake of carbon from the atmosphere through carbon accumulation in woody biomass and soils.

Uncertainty in estimates of the land use source are large in part because estimates of deforestation are, themselves, uncertain, and also in part because the amount of carbon stored in the forests is not well-quantified.

The Future of Land Use

A variety of models were used to project future land use for the emissions scenarios use for the IPCC AR4 report (IPCC Special Report on Emission Scenarios, Chapter 6, Figure 6-6b). These models suggest that deforestation will peak by about 2025 and then gradually decline with time. This trend is primarily driven by reduced rates of population growth and improving agricultural productivity. Eventually, several scenarios predict that land use, currently a substantial source of CO_2 to the atmosphere, will become a sink of CO_2 from the atmosphere as forests grow back.

What is the difference between Land Use and Land Uptake?

These terms are separated to clarify the direct impact of humans in forest clearing and subsequent regrowth (Land Use), and the natural system's response to anthropogenic addition of carbon to the atmosphere and climate warming (Land Uptake). In many studies, however, it is impractical to precisely distinguish between these two terms and so often some component of the Land Use term (such as afforestation in the mid-latitudes) is effectively subsumed into the Land Uptake term.

References

Land Uptake

The Basics

The land biosphere takes up and releases enormous amounts of carbon each year as it cycles through periods of growth and dormancy. Growth leads to the accumulation of carbon in leaves and stalks, woody parts, roots, and in soils. Decay of dead matter, primarily on the ground and in soils, returns carbon to the atmosphere. This cycling can be seen in the atmospheric CO2 observations on the Atmosphere tab, and in the animation at the bottom of this page.

Because land plants are sensitive to short-term changes in climate that make for variable quality of growing seasons, and is also vulnerable to extreme events such as fire, drought and flooding, there is substantial year-to-year variability in the magnitude of the carbon uptake by the terrestrial biosphere. This can be seen in the historical record shown in orange in the applet.

Why is the Land Biosphere Absorbing Atmospheric CO2?

The current net carbon uptake by the land biosphere is primarily due to the physiological or metabolic responses by plants to the increasing CO2 concentration in the atmosphere or to climate warming. (1) Warming may stimulate growth, and allow growth of trees at higher latitudes than previously possible. (2) The leaves of plants must open their stomata to take in CO2, but this opening also leads to loss of water. Thus, if there is more CO2 in the air, the stomata don't need to be open so much, and thus water loss can be lessened. (3) Humans are also substantially modifying the global nitrogen cycle, increasing the nitrogen available to plants. This is likely stimulating some additional growth. (4) There may be important synergies between the carbon, nitrogen, and warming effects on plants.

Yet, there is large uncertainty in the uptake of carbon by natural component of the terrestrial biosphere; and studies using independent data and methodologies do not tend to agree as to the size of the land uptake. Heterogeneity across and within forests, prairies, and agriculture lands makes extrapolation from small-scale studies difficult; there are poorly-quantified horizontal transfers in groundwater, inland waters and to the coastal ocean [Tranvik et al. 2009]; and global scale budget efforts are confounded by insufficient data and uncertainty in the atmospheric transport that connects and mixes terrestrial flux signals on their way to distant observation locations [Gurney et al. 2002].

The Future of Land Uptake

In the applet, you can see that the IPCC range for future Land Uptake is large. This is because we have a poor handle on the processes responsible for Land Uptake at present, and so cannot make precise predictions for the future.

The "CO2 fertilization effect" of enhanced growth by plants with more CO2 has been shown to be primarily a temporary effect that saturates after a few years. Much of the range of IPCC predictions, shown in the applet, is due to a range of assumptions about this process. There is less information about nitrogen fertilization and its possible future role, and even less about possible synergies of the mechanisms.

In addition, the land may become a natural source of carbon to the atmosphere. Persistent drought may cause dramatic forest fires and large "natural" losses in tropical forests. There is also lots of organic carbon stored in the permafrosts at high latitudes and in soils. Warming temperatures will lead to thawing and increased microbial activity, and so CO2 will be released as this organic matter decomposes. The magnitudes of these reservoirs and their sensitivities to warming are important research questions at present. In the applet, the Land Uptake range crosses into the realm of a CO2 source primarily because of these effects.

It is very important that we better understand the mechanisms of land uptake. As understanding improves, predictions will be of greater assistance to carbon management decision-making. Improving mechanistic understanding is a central focus of the US-led North American Carbon Program and Europe's CarboEurope.

References

Back To Top