

An Introduction to the *Global Carbon Cycle*

Carbon: the building block of life. You may have heard this phrase, but have you fully considered what it really means? All living things are made of elements, the most abundant of which are, oxygen, carbon, hydrogen, nitrogen, calcium, and phosphorous. Of these, carbon is the best at joining with other elements to form compounds necessary for life, such as sugars, starches, fats, and proteins. Together, all these forms of carbon account for approximately half of the total dry mass of living things.

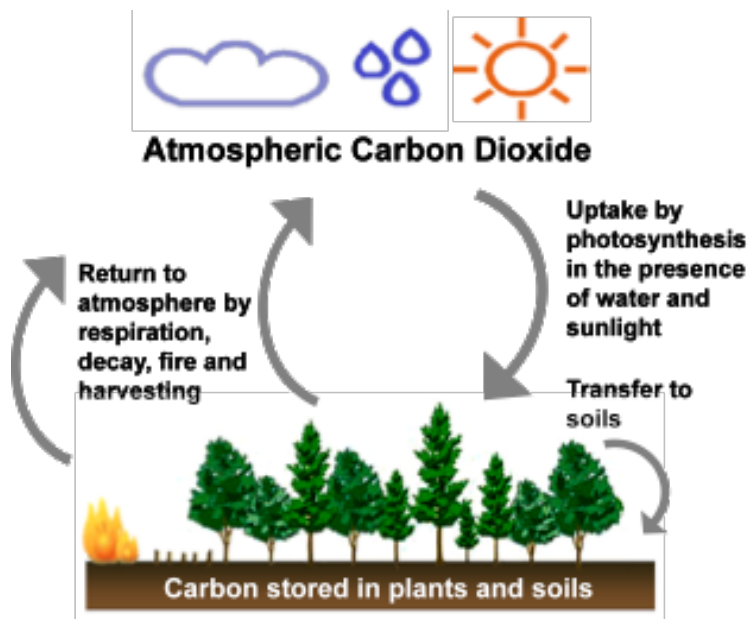


Figure 1. A sub-cycle within the global carbon cycle. Carbon continuously moves between the atmosphere, plants and soils through photosynthesis, plant respiration, harvesting, fire and decomposition.

Carbon is also present in the Earth's atmosphere, soils, oceans, and crust. When viewing the Earth as a system, these components can be referred to as carbon pools (sometimes also called stocks or reservoirs) because they act as storage houses for large amounts of carbon. Any movement of carbon between these reservoirs is called a flux. In any integrated system, fluxes connect reservoirs together to create cycles and feedbacks. An example of such a cycle is seen in Figure 1 where, carbon in the atmosphere is used in photosynthesis to create new plant material. On a global basis, this processes transfers large amounts of carbon from

one pool (the atmosphere) to another (plants). Over time, these plants die and decay, are harvested by humans, or are burned either for energy or in wildfires. All of these processes are fluxes that can cycle carbon among various pools within ecosystems and eventually releases it back to the atmosphere. Viewing the Earth as a whole, individual cycles like this are linked to others involving oceans, rocks, etc. on a range of spatial and temporal scales to form an integrated global carbon cycle (Figure 2).

Global Carbon Cycle

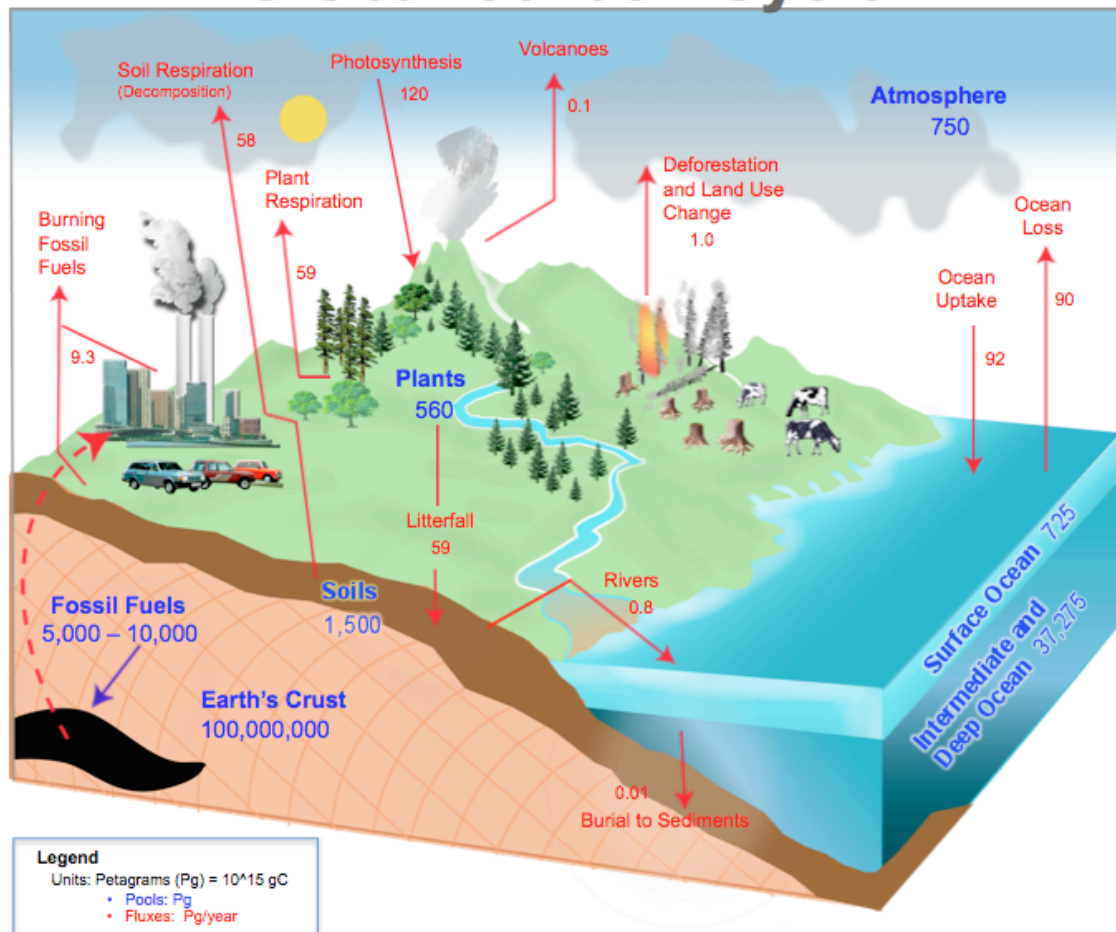


Figure 2. A simplified diagram of the global carbon cycle. Pool sizes, shown in blue, are given in petagrams (Pg) of carbon. Fluxes, shown in red, are in Pg per year.

On the shortest *time scales*, of seconds to minutes, plants take carbon out of the atmosphere through photosynthesis and release it back into the atmosphere via respiration. On longer time scales, carbon from dead plant material can be incorporated into soils, where it might reside for years, decades or centuries before being broken down by soil microbes and released back to the atmosphere. On still longer time scales, organic matter¹ that became buried in deep sediments (and protected from decay) was slowly transformed into deposits of coal, oil and natural gas, the fossil fuels we use today. When we burn these substances, carbon that has been stored for millions of years is released once again to the atmosphere in the form of carbon dioxide (CO₂).

The carbon cycle has a large effect on the function and well being of our planet. Globally, the carbon cycle plays a key role in regulating the Earth's climate by controlling the concentration of carbon dioxide in the atmosphere. Carbon dioxide (CO₂) is important because it contributes to the *greenhouse effect*, in which heat generated from sunlight at the Earth's surface is trapped by certain gasses and prevented from escaping through the atmosphere. The greenhouse effect itself is a perfectly natural phenomenon and, without it, the Earth would be a much colder place. But as is often the case, too much of a good thing can have negative consequences, and an unnatural buildup of greenhouse gasses

can lead to a planet that gets unnaturally hot.

In recent years CO₂ has received much attention because its concentration in the atmosphere has risen to approximately 45% (as of 2017) above natural background levels and will continue to rise into the near future. Scientists have shown that this increase is a result of human activities that have occurred over the last 150 years, including the burning of fossil fuels and deforestation. Because CO₂ is a greenhouse gas, this increase is believed to be causing a rise in global temperatures. This is the primary cause of climate change and is the main reason for increasing interest in the carbon cycle.

The Earth's carbon reservoirs naturally act as both sources, adding carbon to the atmosphere, and sinks, removing carbon from the atmosphere. If all sources are equal to all sinks, the carbon cycle can be said to be in equilibrium (or in balance) and there is no change in the size of the pools over time. Maintaining a steady amount of CO₂ in the atmosphere helps maintain stable average temperatures at the global scale. However, because fossil fuel combustion and deforestation have increased CO₂ inputs to the atmosphere without matching increases in the natural sinks that draw CO₂ out of the atmosphere (oceans, forests, etc.), these activities have caused the size of the atmospheric carbon pool to increase. This is what has been responsible for the present buildup of CO₂ and is believed to cause the observed trend of increasing global temperatures. How far will CO₂ levels rise in the future? The answer depends both on how much CO₂ humans continue to release and on the future amount of carbon uptake and storage by the Earth's natural sinks and reservoirs. In short, it depends on the carbon cycle.

POOLS, FLUXES AND A WORD ABOUT UNITS

In order to understand how carbon is cycled and how atmospheric CO₂ will change in the future, scientists must carefully study the places in which carbon is stored (pools), how long it resides there, and processes that transfer it from one pool to another (fluxes). Collectively, all of the major pools and fluxes of carbon on Earth comprise what we refer to as the global carbon cycle.

1. We often refer to carbon occurring in “organic” versus “inorganic” forms. This is a simple way of grouping different forms of carbon into biologically derived compounds (complex substances produced only by the growth of living organisms) and mineral compounds that can be formed in the absence of biological activity (but can sometimes be formed with the assistance of living things, as in the case of sea shells). Organic compounds includes such things as sugars, fats, proteins and starches and are contained in both living organisms and the material that remains after their death and partial decomposition (including the organic matter in soils as well as the deposits of coal and oils we refer to as fossil fuels). Note that complete decomposition of organic matter results in a return to mineral forms, often as CO₂. Mineral forms of carbon include carbonates contained in rock and seawater as well as CO₂ itself.

As you might imagine, the actual global carbon cycle is immensely complex. It includes every plant, animal and microbe, every photosynthesizing leaf and fallen tree, every ocean, lake, pond and puddle, every soil, sediment and carbonate rock, every breath of fresh air, volcanic eruption and bubble rising to the surface of a swamp, among much, much else. Because we can't deal with that level of complexity, scientists often describe the carbon cycle by lumping similar objects or environments into simpler groups (forest, grassland, atmosphere, ocean) and focusing only on the processes that are most important at the global scale (Figure 2). As you might imagine, part of the trick is understanding just what those processes are.

The following section is a brief overview of some of the important pools and fluxes in the global carbon cycle (and note that, in our discussion, we will use the terms pool, stock and reservoir interchangeably). But first, it's worth taking a moment to consider the numbers and units scientists often deal with. Because the quantities of carbon in the Earth's major carbon pools can be quite large, it is inconvenient to use familiar units such as pounds or kilograms. Instead, we use other units, such as Petagrams, that are better suited for expressing large numbers. For example, a Petagram (Pg), also known as a Gigaton (Gt), is equal to one quadrillion (1,000,000,000,000,000 or 10^{15}) grams! Because there are a thousand grams in a kilogram, and a thousand kilograms in a tonne (also known as a metric ton), we can see that a Petagram is equal to a trillion (1,000,000,000,000) kilograms or a billion (1,000,000,000) tonnes. For those who prefer pounds, knowing that one kilogram is equal to 2.205 pounds tells us that one Petagram equals about 2.2 trillion pounds. In all cases, expressing this as 1 Pg is much simpler than working with that many zeros. Now we will consider carbon stored on Earth in four main reservoirs.

CARBON POOLS

Depending on our goals, the Earth's carbon pools can be grouped into any number of different categories. Here, we will consider four categories that have the greatest relevance to the overall carbon cycle. Keep in mind that any of these pools could be further divided into a number of subcategories, as we will occasionally discuss.

The Earth's Crust: The largest amount of carbon on Earth is stored in sedimentary rocks within the planet's crust. These are rocks produced either by the hardening of mud (containing organic matter) into shale over geological time, or by the collection of calcium carbonate particles, from the shells and skeletons of marine organisms, into limestone and other carbon-containing sedimentary rocks. Together all sedimentary rocks on Earth store 100,000,000 PgC (Petagrams of carbon). Recalling that 1 Pg is equal to a trillion kilograms and over two trillion pounds, this is clearly a large mass of carbon! Another 4,000 PgC is stored in the Earth's crust as hydrocarbons formed over millions of years from ancient living organisms under intense temperature and pressure. These hydrocarbons are commonly known as fossil fuels.

Oceans: The Earth's oceans contain 38,000 PgC, most of which is in the form of dissolved inorganic carbon stored at great depths where it resides for long periods of time. A much smaller amount of carbon, approximately 1,000 Pg, is located near the ocean surface. This carbon is exchanged rapidly with the atmosphere through both physical processes, such as CO₂ gas dissolving into the water, and biological processes, such as the growth, death and decay of plankton. Although most of this surface carbon cycles rapidly, some of it can also be transferred by sinking to the deep ocean pool where it can be stored for a much longer time.

Atmosphere: The atmosphere contains approximately 750 PgC, most of which is in the form of CO₂, with much smaller amounts of methane (CH₄) and various other compounds. Although this is considerably less carbon than that contained in the oceans or crust, carbon in the atmosphere is of vital importance because of its influence on the greenhouse effect and climate. The relatively small size of the atmospheric C pool also makes it more sensitive to disruptions caused by an increase in sources or sinks of C from the Earth's other pools. In fact, the present-day value of 750 PgC is substantially higher than that which occurred

before the onset of fossil fuel combustion and deforestation. Before these activities began, the atmosphere contained approximately 560 PgC and this value is believed to be the normal upper limit for the Earth under natural conditions. In the context of global pools and fluxes, the increase that has occurred in the past several centuries is the result of C fluxes to the atmosphere from the crust (fossil fuels) and terrestrial ecosystems (via deforestation and other forms of land clearing).

Terrestrial Ecosystems: Terrestrial ecosystems contain carbon in the form of plants, animals, soils and microorganisms (bacteria and fungi). Of these, plants and soils are by far the largest and, when dealing with the entire globe, the smaller pools are often ignored. Unlike the Earth's crust and oceans, most of the carbon in terrestrial ecosystems exists in organic forms. In this context, the term "organic" refers to compounds produced by living things, including leaves, wood, roots, dead plant material and the brown organic matter in soils (which is the decomposed remains of formerly living tissues).

Plants exchange carbon with the atmosphere relatively rapidly through photosynthesis, in which CO₂ is absorbed and converted into new plant tissues, and respiration, where some fraction of the previously captured CO₂ is released back to the atmosphere as a product of metabolism. Of the various kinds of tissues produced by plants, woody stems such as those produced by trees have the greatest ability to store large amounts of carbon, because wood is dense and trees can be large. Collectively, the Earth's plants store approximately 560 PgC, with the wood in trees being the largest fraction.

The total amount of carbon in the world's soils is estimated to be 1500 PgC. Measuring soil carbon can be challenging, but a few basic assumptions can make estimating it much easier. First, the most prevalent form of carbon in the soil is organic carbon derived from dead plant materials and microorganisms. Second, as soil depth increases the abundance of organic carbon decreases. Standard soil measurements are typically only taken to 1m in depth. In most cases, this captures the dominant fraction of carbon in soils, although some environments

Box 1: Fossil Fuels

Fossil fuels are the transformed remains of ancient organisms: terrestrial plants and drifting plankton that once lived in oceans and lakes. The necessary processes of burial and chemical transformation require millions of years and conditions today aren't nearly as ideal as they were during the carboniferous era, when most fossil fuel deposits formed. Today, most organic material is broken down at the Earth's surface through decomposition, although organic matter can build up in oxygen-poor environments, such as wetlands, or is buried by sediments in lake and ocean basins. Over millions of years of accumulation and burial, the organic material undergoes a chemical change, resulting in what we now recognize as fossil fuels and a variety of intermediate substances.

All of the energy fossil fuels contain was initially captured by plants during photosynthesis and has become concentrated in various solid or liquid forms. The most common forms are petroleum, coal and natural gas, but other hydrocarbon deposits have also been recognized (oil shale, tar sands, and gas hydrates). Combustion of fossil fuels releases a great deal of energy, which is why they have been used in transportation, manufacturing, home heating and electricity generation. Globally, fossil fuels account for approximate three-quarters of total energy production. The primary product of this hydrocarbon combustion is carbon dioxide.

have very deep soils where this rule doesn't apply. Most of the carbon in soils enters in the form of dead plant matter that is broken down by microorganisms during decay. The decay process also releases carbon back to the atmosphere because the metabolism of these microorganisms eventually breaks most of the organic matter all the way down to CO₂.

CARBON FLUXES

The movement of any material from one place to another is called a flux and we typically think of a carbon flux as a transfer of carbon from one pool to another. Fluxes are usually expressed as a *rate* with units of an amount of some substance being transferred over a certain period of time (e.g. g cm⁻² s⁻¹ or kg km² yr⁻¹). For example, the flow of water in a river can be thought of as a flux that transfers water from the land to the sea and can be measured in liters per second, cubic meters per minute or cubic kilometers per year.

A single carbon pool can often have several fluxes both adding and removing carbon simultaneously. For example, the atmosphere has inflows from decomposition (CO₂ released by the breakdown of organic matter), forest fires and fossil fuel combustion and outflows from plant growth and uptake by the oceans. The size of various fluxes can vary widely. In the previous section, we briefly discussed a few of the fluxes into and out of various global C pools. Here, we will pay more careful attention to some of the more important C fluxes.

Photosynthesis: During photosynthesis, plants use energy from sunlight to combine CO₂ from the atmosphere with water from the soil to create carbohydrates (notice that the two parts of the word, *carbo-* and *-hydrate*, signify carbon and water). In this way, CO₂ is removed from the atmosphere and stored in the structure of plants. Virtually all of the organic matter on Earth was initially formed through this process. Because some plants can live to be tens, hundreds or sometimes even thousands of years old (in the case of the longest-living trees), carbon may be stored, or *sequestered*, for relatively long periods of time. When plants die, their tissues remain for a wide range of time periods. Tissues such as leaves, which have a high quality for decomposer organisms, tend to decay quickly, while more resistant structures, such as wood can persist much longer. Current estimates suggest photosynthesis removes 120 PgC/year from the atmosphere and about 610 PgC is stored in plants at any given time.

Plant Respiration: Plants also release CO₂ back to the atmosphere through the process of respiration (the equivalent for plants of exhaling). Respiration occurs as plant cells use carbohydrates, made during photosynthesis, for energy. Plant respiration represents approximately half (60 PgC/year) of the CO₂ that is returned to the atmosphere in the terrestrial portion of the carbon cycle.

Litterfall: In addition to the death of whole plants, living plants also shed some portion of their leaves, roots and branches each year. Because all parts of the plant are made up of carbon, the loss of these parts to the ground is a transfer of carbon (a flux) from the plant to the soil. Dead plant material is often referred to as litter (leaf litter, branch litter, etc.) and once on the ground, all forms of litter will begin the process of decomposition.

Soil Respiration: The release of CO₂ through respiration is not unique to plants, but is something all organisms do, including microscopic organisms living in soil. When dead

organic matter is broken down or decomposed (consumed by bacteria and fungi), CO₂ is released into the atmosphere at an average rate of about 60 PgC/year globally. Because it can take years for a plant to decompose (or decades in the case of large trees), carbon is temporarily stored in the organic matter of soil.

Ocean—Atmosphere exchange: Inorganic carbon is absorbed and released at the interface of the oceans' surface and surrounding air, through the process of diffusion. It may not seem obvious that gasses can be dissolved into, or released from water, but this is what leads to the formation of bubbles that appear in a glass of water left to sit for a long enough period of time. The air contained in those bubbles includes CO₂ and this same process is the first step in the uptake of carbon by oceans. Once in a dissolved form, CO₂ goes on to react with water in what are known as the carbonate reactions. These are relatively simple chemical reactions in which H₂O and CO₂ join to form H₂CO₃ (also known as carbonic acid, the anion of which is called carbonate, or CO₃⁻). The formation of carbonate in seawater allows oceans to take up and store a much larger amount of carbon than would be possible if dissolved CO₂ remained in that form. Carbonate is also important to a vast number of marine organisms that use this mineral form of carbon to build shells.

Carbon is also cycled through the ocean by the biological processes of photosynthesis, respiration, and decomposition of aquatic plants. In contrast with terrestrial vegetation is the speed at which marine organisms decompose. Because ocean plants don't have large, woody trunks that take years to breakdown, the process happens much more quickly in oceans than on land—often in a matter of days. For this reason, very little carbon is stored in the ocean through biological processes. The total amount of carbon uptake (92 Pg C) and carbon loss (90 PgC) from the ocean is dependent on the balance of organic and inorganic processes.

Fossil fuel combustion and land cover change: The carbon fluxes discussed thus far involve natural processes that have helped regulate the carbon cycle and atmospheric CO₂ levels for millions of years. However, the modern-day carbon cycle also includes several important fluxes that stem from human activities. The most important of these is combustion of fossil fuels: coal, oil and natural gas. These materials contain carbon that was captured by living organisms over periods of millions of years and has been stored in various places within the Earth's crust (see Box 1: Fossil Fuels). However, since the onset of the industrial revolution, these fuels have been mined and combusted at increasing rates and have served as a primary source of the energy that drives modern industrial human civilization. Because the main byproduct of fossil fuel combustion is CO₂, these activities can be viewed in geological terms as a new and relatively rapid flux to the atmosphere of large amounts of carbon. At present, fossil fuel combustion represents a flux to the atmosphere of approximately 9 PgC/year.

Another human activity that has caused a flux of carbon to the atmosphere is land cover change, largely in the form of deforestation. With the expansion of the human population and growth of human settlements, a considerable amount of the Earth's land surface has been converted from native ecosystems to farms and urban areas. Native forests in many areas have been cleared for timber or burned for conversion to farms and grasslands. Because forests and other native ecosystems generally contain more carbon (in both plant tissues and soils) than the cover types they have been replaced with, these changes have

resulted in a net flux to the atmosphere of about 1 PgC/year. In some areas, regrowth of forests from past land clearing activities can represent a sink of carbon (as in the case of forest growth following farm abandonment in eastern North America), but the net effect of all human-induced land cover conversions globally represents a source to the atmosphere.

Geological Processes: Geological processes represent an important control on the Earth's carbon cycle over time scales of hundreds of millions of years. A thorough discussion of the geological carbon cycle is beyond the scope of this introduction, but the processes involved include the formation of sedimentary rocks and their recycling via plate tectonics, weathering and volcanic eruptions.

To take a slightly closer look, rocks on land are broken down by the atmosphere, rain, and groundwater into small particles and dissolved materials, a process known as weathering. These materials are combined with plant and soil particles that result from decomposition and surface erosion and are later carried to the ocean where the larger particles are deposited near shore. Slowly, these sediments accumulate, burying older sediments below. The layering and burial of sediment causes pressure to build, which eventually becomes so great that deeper sediments are turned into rock, such as shale. Within the ocean water itself, dissolved materials mix with seawater and are used by marine life to make calcium carbonate (CaCO_3) skeletons and shells. When these organisms die, their skeletons and shells sink to the bottom of the ocean. In shallow waters (less than 4km) the carbonate collects and eventually forms another type of sedimentary rock called limestone.

Collectively, these processes slowly convert carbon that was initially contained in living organisms into sedimentary rocks within the Earth's crust. Once there, these materials continue to be moved and transformed through the process of plate tectonics, uplift of rocks contained in the lighter plates and melting of rocks in the heavier plates as they are pushed deep under the surface. These melted materials can eventually result in emission of gaseous carbon back to the atmosphere through volcanic eruptions, thereby completing the cycle. Without this geological recycling, the carbon that becomes bound up in rocks would accumulate and remain there forever, eventually depleting the sources of CO_2 that are vital to life. The recycling of carbon through sedimentary rocks is an important part of our planet's long-term (over millions of years) ability to sustain life. Without it, the carbon that becomes bound up in rocks would accumulate and remain there forever, eventually depleting the sources of CO_2 that are vital to plants. However, because the geological cycle moves so slowly, these fluxes are small on an annual basis and have little effect on a human time-scale.

CARBON BUDGETS: THE BALANCE BETWEEN SOURCES & SINKS

The Earth's carbon cycle is in a constant state of motion. Through processes that take place over seconds, days, years and millennia, carbon is constantly being transferred between all the various pools discussed above. But what does this mean for the size of any given pool? The fact that carbon moves into and out of the Earth's land, atmosphere and oceans doesn't, on its own, mean that these pools are changing. In fact, if the amount of carbon moving into a given pool is matched by an equal amount of carbon moving out, the pool size remains constant. If this condition were true for all carbon pools, the global carbon cycle would be said to be in a state of dynamic equilibrium; "*dynamic*" because the carbon itself is moving, and "*equilibrium*" because the equal size of all inputs and outputs keeps

the system in balance. The size of all carbon pools remains unchanged.

When scientists examine whether any system is in a state of change or in one of equilibrium, they typically begin by constructing a budget. Just as in the constructing of a financial budget, a carbon budget is simply a list all pools along with estimates of their size and of all the fluxes that constitute inputs and outputs. Presently, a budget of the Earth's carbon cycle shows that it is far from being in a state of balance. While random variation in natural processes such as climate and forest fires often results in some degree of imbalance on an annual basis, the very large imbalance in today's carbon cycle is due to the processes of fossil fuel combustion and land cover change, as discussed earlier. And this brings us to an interesting question scientists are presently trying to answer. Although CO₂ is indeed building up in the atmosphere, the rate at which it is accumulating is less than the rate at which it is being emitted and the difference is difficult to account for through present estimates of uptake by the land and oceans. The primary hypothesis scientists are exploring is that carbon uptake by forests and other ecosystems is larger than has been estimated and that carbon accumulation in plants and soils has kept the atmosphere from increasing at an even greater pace. But if this is correct, why are present estimates too low and where in the world's ecosystems is the missing carbon going? This mystery has sparked a great deal of research on ecological aspects of the carbon cycle and is an underlying driver for much of the work students involved in the GLOBE Carbon Cycle Project are investigating.

GLOSSARY

Anthropogenic emissions: Human-made materials (gases, particles, vapors, chemical compounds, etc.) that come out of smokestacks, chimneys, and vehicle tailpipes.

Atmosphere: The mixture of gases surrounding the Earth. The Earth's atmosphere consists of about 79.1% nitrogen (by volume), 20.9% oxygen, 0.036% carbon dioxide and trace amounts of other gases. The atmosphere can be divided into a number of layers. The layer nearest the Earth is the troposphere, which reaches up to an altitude of about 8 km (about 5 miles) in the Polar Regions and up to 17 km (11 mi.) above the equator. The stratosphere, which reaches to an altitude of about 50 km (31 mi.), is above the troposphere. The mesosphere, which extends up to 80-90 km (48-54 mi.), is above the stratosphere, and finally, the thermosphere, or ionosphere, is the layer that forms a poorly defined border with outer space. There is relatively little mixing of gases between layers.

Carbon cycle: The exchange of carbon between its four main reservoirs—the atmosphere, terrestrial biosphere, oceans, and sediments. Each of these global reservoirs may be subdivided into smaller pools, ranging in size from individual communities or ecosystems to the total of all living organisms.

Carbon dioxide (CO₂): A colorless, odorless non-combustible gas that is present in the atmosphere. It is formed by the combustion of carbon and carbon compounds (such as fossil fuels and biomass), by respiration of animals and plants, by the gradual oxidation of organic matter in the soil, and by chemical processes that occur with certain geological components.

Carbon sequestration: The uptake and storage of carbon. Trees and plants, for example, absorb carbon dioxide, release the oxygen and store the carbon.

Carbon sink: A carbon reservoir that takes in and stores (sequesters) more carbon than it releases. Carbon sinks can serve to partially offset greenhouse gas emissions. Forests and oceans are both large carbon sinks.

Carbon source: A reservoir or component of the carbon cycle that releases more carbon than it absorbs. Anthropogenic emissions are a source of carbon.

Climate: The average weather, usually taken over a 30 year time period, for a particular region and time period. Climate is not the same as weather, but rather, it is the average pattern of weather for a particular region. Weather describes the short-term state of the atmosphere. It is often challenging to differentiate between weather and climate patterns.

Climate change: The long-term fluctuations in temperature, precipitation, wind, and other aspects of the Earth's climate. Although it refers to temperature fluctuations in either direction, as well as other climate variation, the media often uses it interchangeably with the term global warming. Scientists use the term both in reference to natural and anthropogenic change.

Decomposition: The breakdown of matter by bacteria and fungi. It changes the chemical composition and physical appearance of the materials. It is the process by which carbon

is released from decaying biological matter.

Deforestation: The transformation of forested lands to non-forest uses. This is often cited as one of the major causes of human-induced climate change for two reasons. In the case of slash and burn clearing, the burning and decomposition of plant matter releases carbon dioxide. Also, deforestation removes trees that once consumed and stored carbon dioxide from the atmosphere. Deforestation is a type of land–use change.

Fossil fuel: Any hydrocarbon deposit such as petroleum, coal, or natural gas that can be burned for heat or power.

Flux: The rate of exchange between reservoirs.

Global warming: A popular term used to describe the increase in average global temperatures due to the greenhouse effect. It is often used interchangeably with the term climate change.

Greenhouse effect: A popular term used to describe the roles of water vapor, carbon dioxide, methane, and other gases (greenhouse gases—GHG) in keeping the Earth's surface warmer than it would be otherwise.

Greenhouse gases (GHG): Those gases, such as water vapor, carbon dioxide, tropospheric ozone, nitrous oxide, and methane, which allow solar radiation to pass through to the Earth, but block outgoing longwave radiation. Their action is compared to that of glass in a greenhouse.

Soil carbon: Soil is a major component of the terrestrial biosphere pool in the carbon cycle. Organic soil carbon estimates, rather than total soil carbon, are generally quoted. The amount of carbon in the soil is a function of historical vegetative cover and productivity, which in turn is dependent upon climatic variables.