The Carbon Question

DRAFT VERSION 1
Prepared for review and field-testing

In order to make connections between science and education that can impact how science is taught and learned, a collaborative program at the NASA Goddard Institute for Space Studies was created to involve climate researchers, students, and teachers in the Institute on Climate and Planets. It is designed to foster joint investigations concerning actual research problems related to climate change and to enhance classroom learning and teaching with lessons motivated by this educational experience. *The Carbon Question* is an important part of this experience.

By the Institute on Climate and Planets
A curriculum project of the NASA Goddard Institute for Space Studies
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Introduction

The Carbon Question Research Education Module

The Carbon Question module and accompanying Research Projects are designed to open up the world of scientific research in carbon investigations to students. The learning experience can be described as a pathway from introductory, inquiry-driven lessons that develop students' conceptual understandings about carbon and basic research skills to the knowledge and skills they will need to participate in any of the culminating research projects.

Our approach is called *research education*. This is founded in the idea that one of the best ways for students to appreciate how critical scientific knowledge develops is to get involved in the research process. Whether they are employing scientific methods to discover what is already known or contributing to active original research, students involved in research education gain tools and approaches for solving problems that can be applied to any discipline. Most importantly, they learn to think objectively and reason about the world they live in.

Along the learning pathway, students encounter fundamental science questions relevant to areas of particular interest in climate and carbon research such as:

1. What components of an ecosystem are affected by climate change?
2. How well do we know the terrestrial carbon budget i.e. forest trees and soils?
3. How do we measure terrestrial carbon stores to help us quantify carbon budget components in order to help us find the missing carbon sink?
4. How are humans influencing the carbon cycle and contributing to climate change?

Learning activities and science content addressed in the module are meant to enrich earth science, biology, and living environment curriculum and instruction, offering practical and interesting lessons that will help students meet national and state science standards. Technology and instrumentation are emphasized throughout the module, enabling students to appreciate how various scientific tools are used to improve our understanding of how Earth works in general and ecosystems in particular.

The module concludes with various research projects. By getting involved in one or more of the projects, students will become a part of a greater scientific effort to quantify terrestrial carbon storage and ultimately, to complete our understanding of the global carbon cycle as it relates to climate.

All of the investigations in this curriculum module are motivated by research topics that matter to scientists. The goal is to capture students' fascination with the world around them and encourage them to get involved in meaningful and thoughtful environmental studies.

Introduction

A Real World Problem: Studying Carbon

Why is carbon important?

Carbon and the importance of carbon storage in the global carbon budget have become issues of great scientific interest and public debate in the last decade. Concern and curiosity are linked to evidence that levels of carbon in Earth's atmosphere are increasing. Scientists and policymakers have debated to what extent this change in atmospheric carbon may be contributing to climate change and whether or not human activities are contributing to changes in the carbon budget and in climate. Although climate change is a controversial topic, the general scientific consensus is that climate patterns around the world are changing (IPCC, 2001).

Scientists know that the Earth's climate system is governed, in part, by the global carbon cycle. Because carbon affects temperature, it also affects atmospheric pressure, ocean circulation and weather and storm patterns. In this way, carbon and climate affects vegetation growth patterns and agricultural yields (WRI, 2001) and other aspects of the ecosystem that are extremely relevant to humans. However, there are many aspects of the carbon cycle that need to be better understood.

The storage of carbon in vegetation and soils in all the different ecosystems around the world is still not quantified which makes it difficult for scientists to balance the global carbon budget and to make predictions about the effects of future climate change.

Where is carbon found? How is it stored?

Carbon is contained in most living organisms, as part of proteins, carbohydrates and fats. Heterotrophic organisms release carbon dioxide when they respire. Autotrophs, including plants, use and release carbon dioxide in photosynthesis and respiration although they use and store more carbon than they respire. When organisms die, bacteria and decomposers break down the organic carbon molecules and release the carbon atoms as carbon dioxide. Carbon, in its various chemical forms, naturally cycles through the atmosphere, the terrestrial biosphere and the oceans, three components that are commonly referred to as carbon 'reservoirs'. Forests store carbon in vegetation, detritus, soil, black carbon residue from fire and harvestable products (Schulze *et al.*, 2000).

Because so many organisms and materials contain carbon, the total amount of carbon contained in the world, in one of the world's biomes, in an ecosystem or even in a single habitat is difficult to quantify.

Figure 1 shows a representation of the global carbon cycle. It shows that some carbon is stored in Earth's reservoirs and some carbon is always flowing between and within three reservoirs, the atmosphere, the ocean and the land. Efforts to quantify the carbon stored in all of the reservoirs are underway. Quantifying the carbon land storage component is especially difficult due to the diversity of ecosystems on Earth.

Different tree species and soil types hold different amounts of carbon. They also decompose at different rates. Decomposition, carried out by various microbes, results in the release of carbon to the atmosphere. The microbes respire as we do, taking in oxygen and releasing carbon dioxide. So, understanding the terrestrial carbon reservoir means that we have to understand what is growing on Earth today as well as how fast it will decay and, through microbial decomposition, how fast the carbon held in trees and soils will return to the atmosphere in the future.

Figure 1: Diagram of the Carbon Cycle

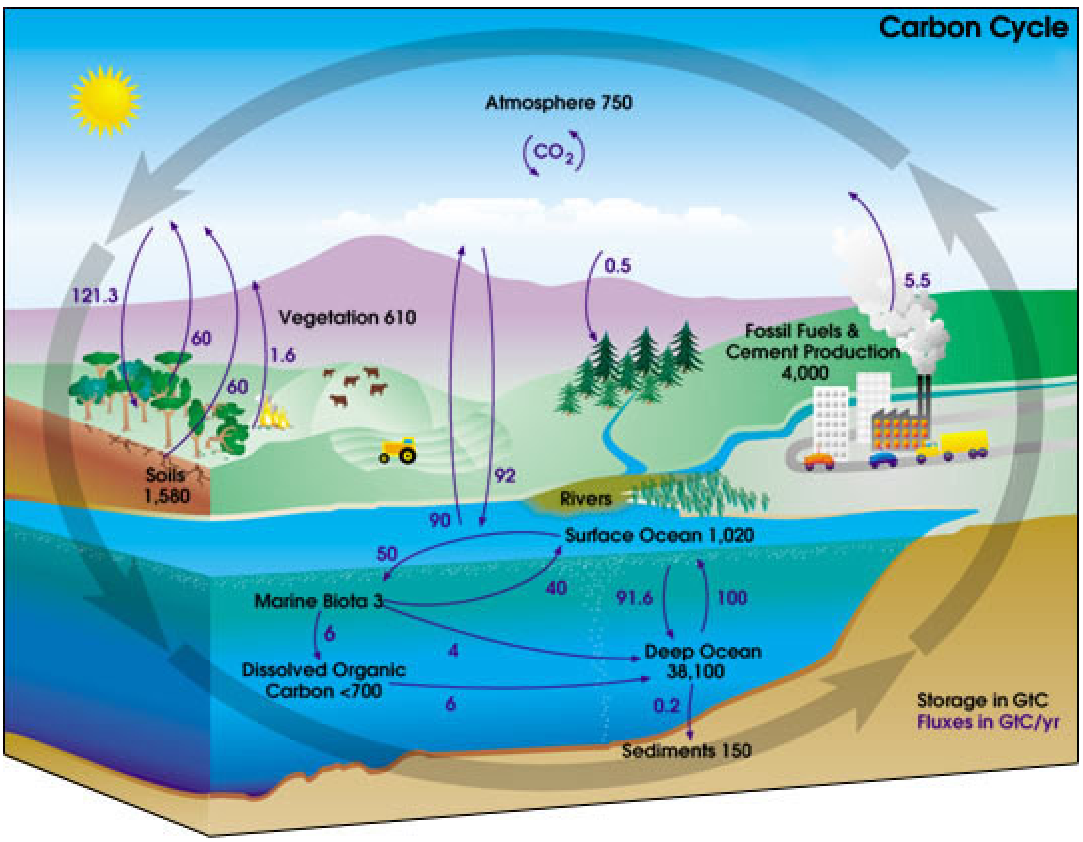


Image from: http://earthobservatory.nasa.gov/Library/CarbonCycle/carbon_cycle4.html, Courtesy of NASA Earth Science Enterprise.

What's the connection between Carbon and Climate?

Carbon dioxide, water vapor, nitrous oxide, methane and certain other carbon-based molecules are considered to be Greenhouse Gases. This means that they exist in the atmosphere and allow energy from the sun to pass through the atmosphere and warm the Earth's surface but they trap energy that is re-emitted from the Earth. The gases re-release the energy back toward the Earth, thereby warming the surface. This is known as the Greenhouse Effect. Carbon and other Greenhouse Gases in the atmosphere help to keep the temperature of the planet's surface warm enough to support abundant life.

Plants are just one example of organisms that need a warm atmosphere in order to grow. Under favorable conditions (sufficient light, water and nutrients), plants photosynthesize. They use energy from the sun and water and carbon dioxide to manufacture sugars and oxygen. Therefore, photosynthetic organisms remove carbon dioxide from the atmosphere and help to keep the carbon budget in balance.

The Earth system and the many eco-systems it supports are sensitive systems. That means that a change in one component of the system, whether it is biotic or abiotic, has an impact on other components of the system. A small perturbation in atmospheric carbon is not an isolated event and it may have long-range and large-scale impacts.

What about Carbon and Climate in the Past?

Changes in the carbon budget have occurred many times throughout Earth's history. This point has led some people to believe that recent global climate change and increasing atmospheric carbon levels are part of a natural cycle and not related to human activities. It is true that, although the Earth system is sensitive to change, it is also quite resilient which means that it has withstood tremendous environmental change without completely shutting down.

A record was obtained from an ice core in Vostok, East Antarctica that shows a more than 400,000-year-long record of fluctuating atmospheric carbon dioxide levels (Petit *et al.*, 1997, 1999). Interesting changes occurred in the carbon cycle during glacial times when glaciers covered vast areas of the Earth's surface. Earth can, and has, returned to supporting many kinds of life forms after each glacial period.

As you can see in Figure 2 below, even on very long timescales, atmospheric carbon and temperature appears to have a close relationship.

Figure 2: 400,000+ Years of Carbon Dioxide and Temperature History

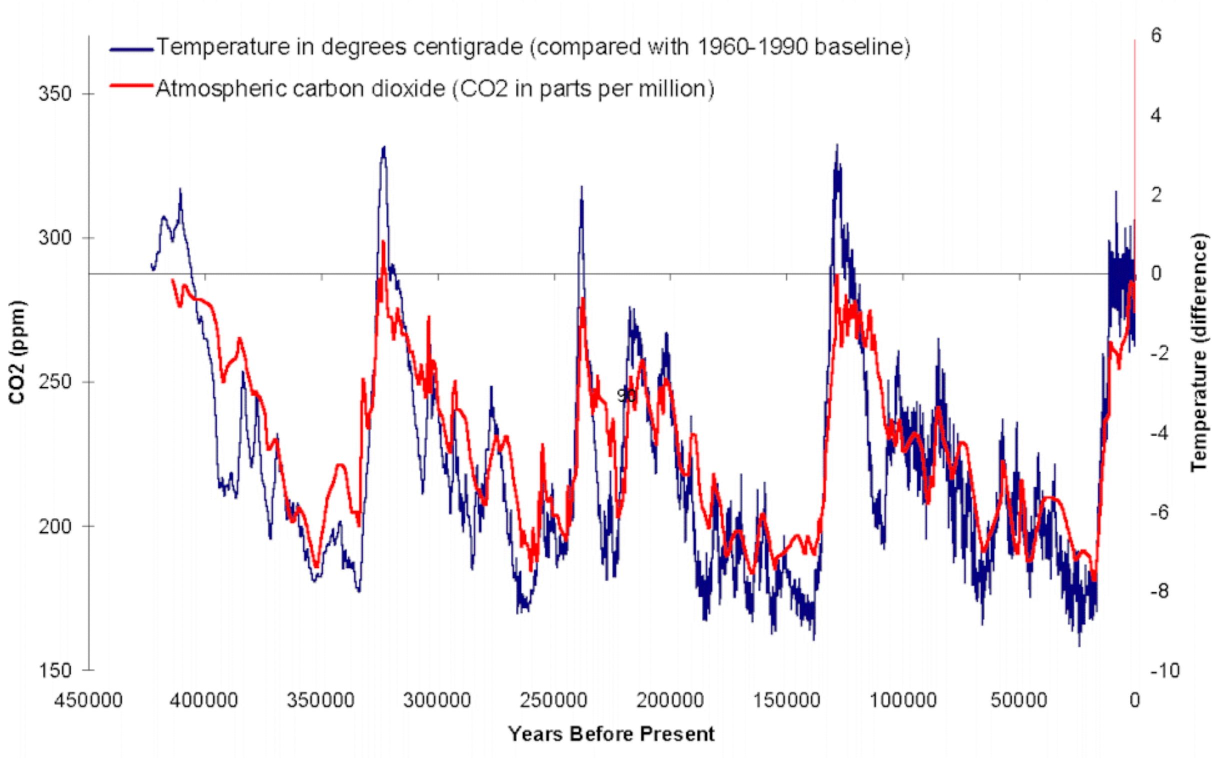


Image from http://www.brighton73.freeserve.co.uk/gw/paleo/400000yrfig.htm. Data from Keeling and Whorf, 2004; Etheridge *et al*., 1996, 1998; Petit *et al*., 1997, 1999.

Scientists have discovered that global climate has been changing at an unprecedented rate since the Industrial Revolution when new technologies invented or discovered by humans led to increased carbon emissions into the atmosphere. Activities, such as fossil fuel combustion, which convert carbon that has been long-stored in coal, gas and petroleum to carbon dioxide, have continued to alter the global carbon budget since the Industrial Revolution. Research suggests that such activities have caused a 30% increase in atmospheric carbon dioxide since 1998 (IPCC, 2000).

An Important Carbon Discovery – The Keeling Curve

In 1957, a scientist by the name of Charles David Keeling began taking continuous measurements of atmospheric carbon at Mauna Loa, Hawaii. He was the first person to document that levels of atmospheric carbon are increasing. There is a scientific consensus that global temperatures are increasing along with carbon dioxide. Human activities such as deforestation, fossil fuel burning and land-clearing for agriculture, among others, may be contributing to these global trends. Take a look at Figure 3 which shows the results of Keeling's work at Mauna Loa.

Figure 3: The 'Keeling Curve'

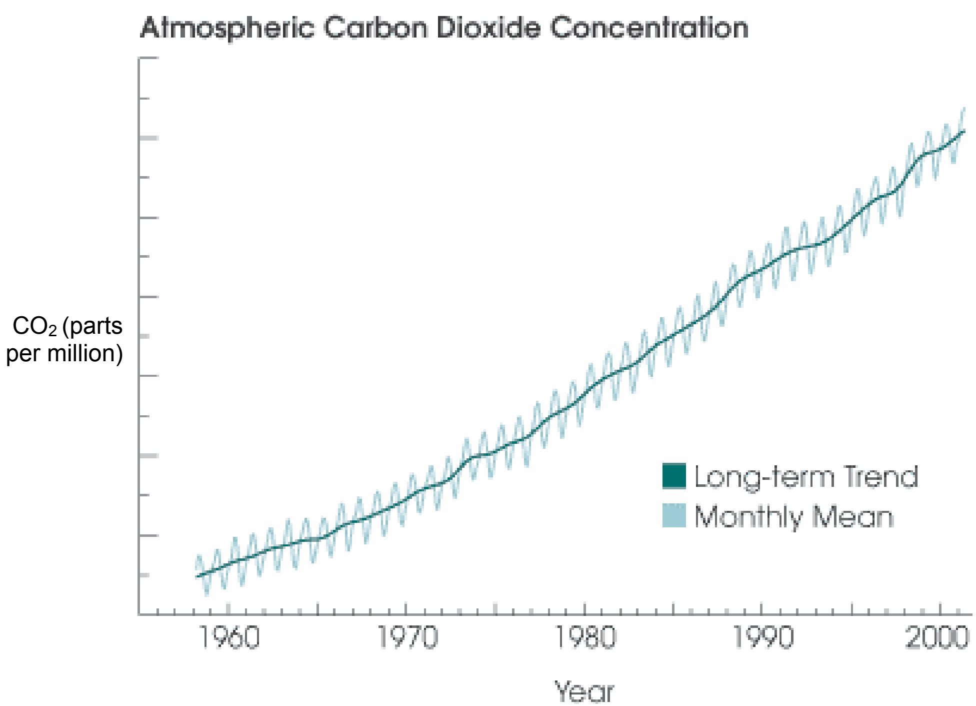


Image from http://earthobservatory.nasa.gov/Library/CarbonCycle/carbon_cycle3.html. Graph by Robert Simmon, based on data from the NOAA Climate Monitoring & Diagnostics Laboratory.

What overall trends are seen in Keeling's graph? Notice that the graph representing the monthly mean oscillates (moves up and down) while the long-term trend shows a gradual increase. The monthly average values indicate that carbon concentrations in the atmospheric reservoir vary. Why does the amount of carbon dioxide in the atmosphere change? One clue is to look at how often it goes up and down. Think about seasonal changes in our ecosystems. If you live in the northern hemisphere, the ecosystem looks different during the summer than during the winter. How is this difference in ecosystem appearance linked to carbon dioxide in Earth's atmosphere? Why do scientists consider Keeling's data, which was collected at a single location in Hawaii, representive of atmospheric carbon in the entire northern hemisphere?

In the northern hemisphere, photosynthesis increases during a certain time of year. During which season does it increase? Based on the conditions that plants require in order to photosynthesize, can you think of reasons why photosynthesis increases during a particular season? What affect does this have on atmospheric carbon? Take another look at Keeling's curve and try to explain what it shows knowing what you now know about the role of vegetation in carbon cycling.

Scientists are building a consensus about how Keeling's carbon dioxide curve may be linked to global warming. When human activities contribute to the amount of Greenhouse Gases in the atmosphere, we are enhancing the natural Greenhouse Effect. The increase in Earth's surface temperature reveals this trend. Although the change in temperature since the 1800's is not noticeable to most humans (0.6 degrees Celsius), the warming has already begun to have an effect on other living organisms. The habitat ranges of some species have begun to shift as a result, putting some populations in danger of extinction (Krajick, 2004).

What Impact Have Humans had on Carbon?

Are the skeptics correct in asserting that any climate change we see today is due purely to natural climate fluctuations? Alternatively, are others correct in asserting that human activities are causing climate change? Or is the answer somewhere between these two opposing views? Most scientists today agree that the carbon release due to fossil-fuel combustion and deforestation does play a part in the increasing atmospheric carbon dioxide of the last 45 years, as measured by Keeling at Mauna Loa.

One of the great challenges for climate scientists is to figure out how the carbon cycle and Earth's ecosystems would be functioning if humans and our activities were absent. Scientists are attempting to look at historical records (through ice cores, marine cores, tree rings and vegetation history) that indicate the natural variability in the carbon cycle and in global climate. The challenge of this investigation is that it is impossible to go back in time to gather all the data we need to monitor all the natural fluctuations in atmospheric carbon and in climate. Researchers have turned to models to help them simulate what might have happened in the past. But nature is infinitely more complicated than computer models and it has been very difficult to include the degree of complexity necessary to give realistic climatic conditions for both the past and the future.

Scientists estimate that between one-third and one-half of Earth's land surface has been transformed or affected by human activities (Vitousek *et al.*, 1997). In order to illustrate the impacts that humans have on ecosystems, (Vitousek *et al.*, 1997) created a flow chart (see Figure 4). If you follow the many paths from Human Population at the top of the diagram, you see that humans are connected in various ways to carbon, climate change, enhanced greenhouse effects and biological diversity.

Figure 4: Flow chart illustrating the impact of humans on ecosystems

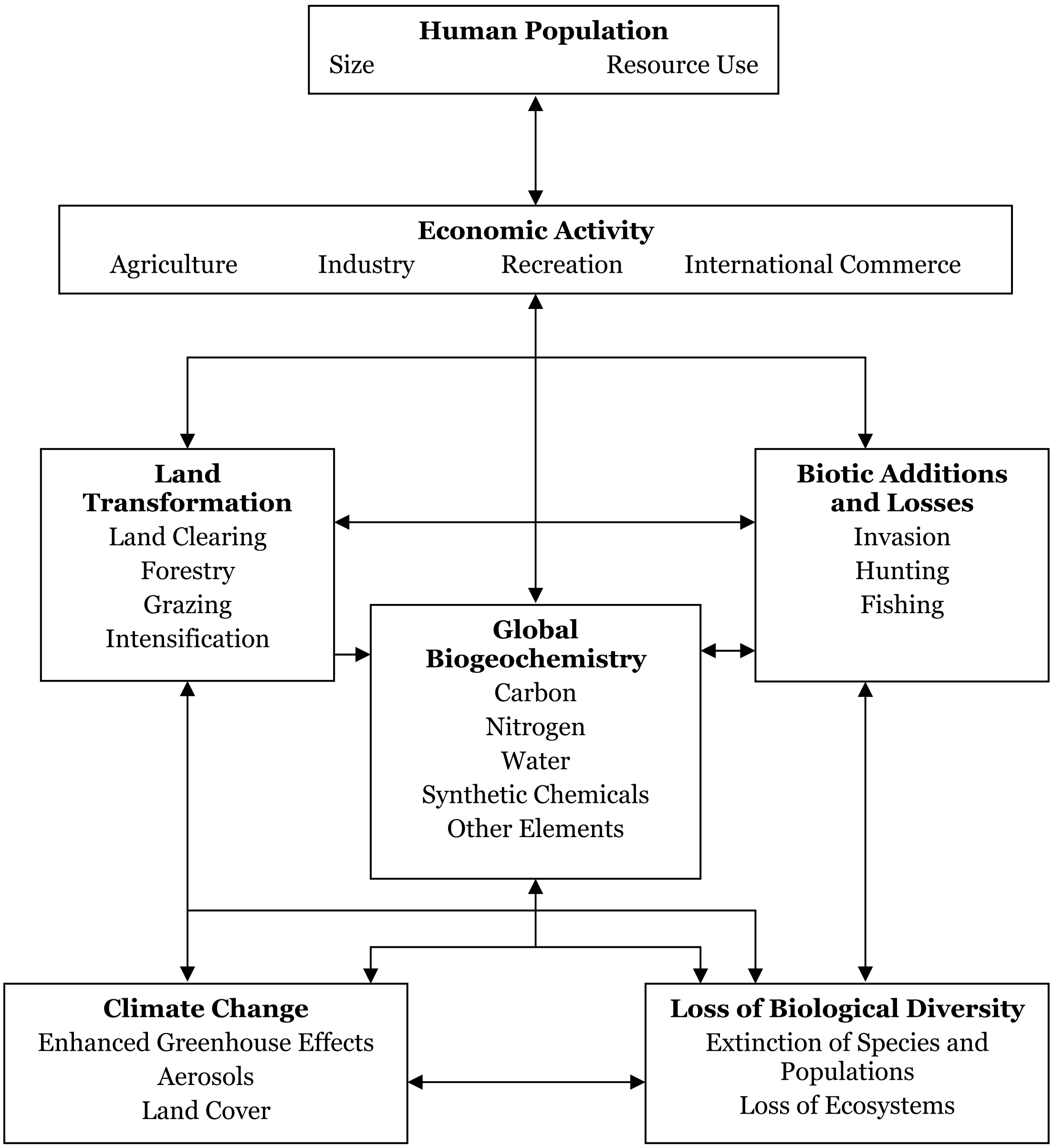


Chart modified from Vitousek *et al*., 1997.

With this flow chart in mind, consider what impact humans might have on carbon and climate in the long run. Take a look at Figure 5 below which predicts how global human population will grow in the future and you may come to the conclusion that human activities will likely increase. If humans are already impacting the carbon budget, what will happen in the future as our population grows? How do you think a better understanding of humans' affect on the global carbon budget help us to make better decisions about human activities such as deforestation, industrial emissions and clearing land for agriculture?

Figure 5: World Population Data and Projection

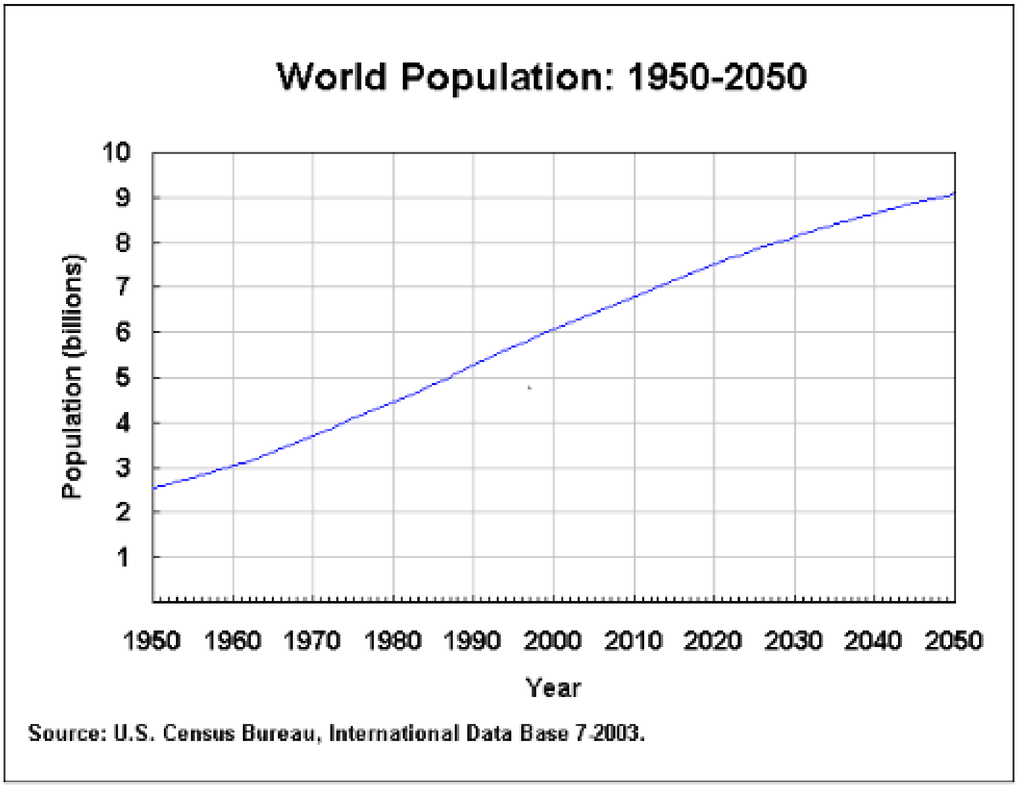


Image from http://www.census.gov/ipc/www/img/worldpop.gif

What have scientists been studying? What is The Missing Carbon Sink?

In order to understand how the carbon budget is balanced, scientists have made great efforts to quantify carbon storage and carbon flowing between the land, atmosphere and ocean reservoirs. They use various techniques to make their measurements.

More than 10 years ago, scientists reported in the journal *Science*, that atmospheric carbon measurements and computer models suggested that the terrestrial biosphere (vegetation and soils) was taking up atmospheric carbon dioxide and acting as a terrestrial carbon sink (Tans *et al.*, 1990). Further investigation led researchers to focus on the importance of carbon reservoirs in northern temperate regions. More than a decade later, in another *Science* article, a group of researchers agreed that although land, especially land in the northern hemisphere in temperate regions, plays an important role in the carbon cycle, the size, distribution and cause of the land sink is uncertain (Pacala *et al.*, 2001).

In order to contribute to the scientific effort to quantify and to find the missing sink, scientists at the Woods Hole Research Center developed the following equation. It summarizes the global carbon budget for the 1980s. They took the numbers that were available: the amount of atmospheric carbon increase, the amount of oceanic carbon increase and the known amounts of carbon released through fossil fuel emissions and land use change. They were left with an unbalanced equation…until they added the missing carbon sink. They calculated that the missing sink was somewhere between 0.6 and 3 billion metric tones of carbon per year in the 1980s.

Atmospheric increase	=	Emissions from fossil fuels	+	Net emissions from changes in land use	–	Oceanic uptake	–	Missing carbon sink
3.3(±0.2)	=	5.5(±0.5)	+	1.6(±0.7)	–	2.0(±0.8)	–	1.8(±1.2)

Units are PgC = Petagrams of Carbon = 1 billion metric tons, Equation from http://www.whrc.org/science/carbon/carbon.htm

An article was published in *Global Change Biology* in 2003 that addressed uncertainty about the sink by comparing estimates of northern mid-latitude land carbon sinks made by several different scientists. The article suggested that the land sink can be explained partly by the *age* of the forest ecosystem (including past land management and disturbances like pest outbreaks and fire) and partly by *atmospheric conditions* that have increased the ability of these forests to take up carbon (such as the increase in forest growth or 'fertilization' associated with higher atmospheric carbon levels) (Houghton, 2003).

Scientists and policymakers have been unable to find consensus on what, if any, action should be taken to combat carbon emissions. It has become increasingly clear that there is a need for extensive and precise monitoring of the quantity of carbon moving out of geologic reservoirs and into and between the atmosphere, ocean and terrestrial biosphere (vegetation and soils).

In order to explain the existence of a 'carbon sink', scientists have explored factors as diverse as plant physiology and the activity of microbes, to CO_2 fertilization, nitrogen deposition and changes in climate. However, new theories about the role of northern temperate forests are continually being proposed. Houghton (2002) suggests that the ability of forests to sequester carbon may be strongly influenced by land management practices (such as conversion of agricultural land to forest, fire suppression and tree planting) and ecosystem disturbances that affect the age structure of forests. Forest age influences rates of photosynthesis, respiration and mortality. Unfortunately, Houghton's research does not include detailed analysis of the role played by soil in forest carbon storage. Soil carbon is not often measured and included in forest carbon inventories even though it has been suggested that forest soils might play a large role in the global carbon cycle (Körner, 2003). A general lack of soil carbon quantification studies provides additional impetus for soil carbon inventories to be done in northeastern U.S. forests where scientists are already focusing missing sink research.

Myneni *et al.* also support the idea that management has a large impact on global terrestrial carbon storage in forests (2001). Further, they suggest that the variability in forest management practices implies uncertainty about the future of biomass carbon sinks. Linking the carbon cycle and climate variability with human activities may provide crucial information for ensuring the future of Earth's ecosystems.

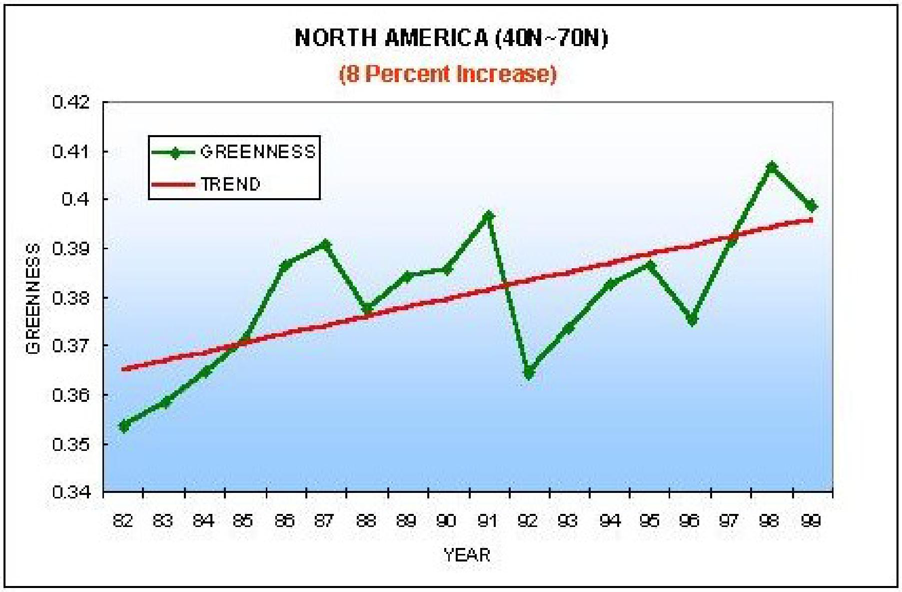
In a Perspectives article in the journal *Science* (2003), Körner suggests that terrestrial biomes and soil humus store three times the amount of carbon as the atmosphere contains. Körner recommends that studies of terrestrial storage should include long-term monitoring, not just short-term inventories. He argues that tree growth and soil sequestration are long-term, ongoing processes that are always included in carbon studies but that carbon losses due to age- or pest-related mortality, logging, fire, wind throw, etc. are all short-term, rapid processes that may be missed by short-term studies.

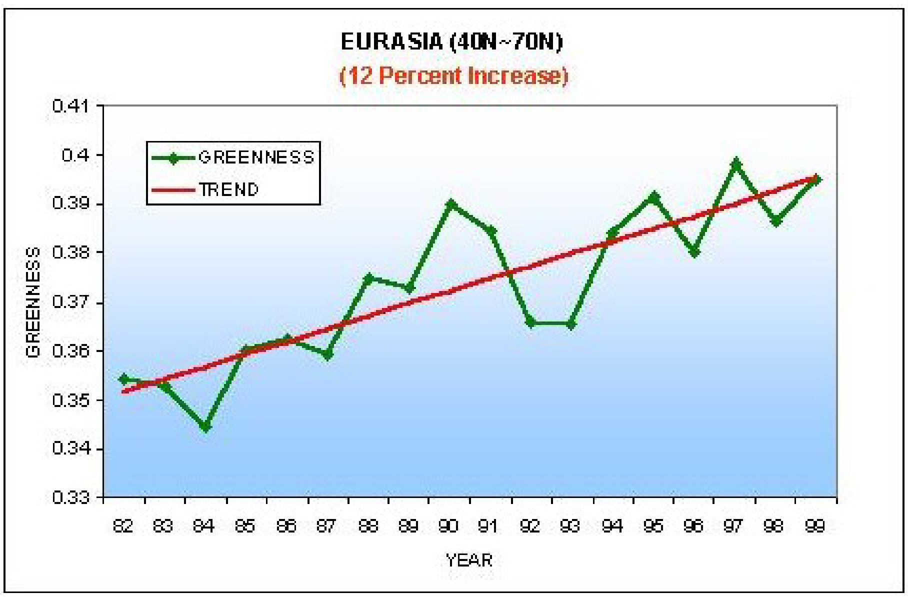
Schimel *et al.* (2000) also suggest that inter-annual variability in terrestrial carbon storage can affect conclusions about the importance of forests. In their study, they modeled the annual carbon sink in the U.S. and found that it ranged from <0.1 Pg of carbon net efflux to >0.2 Pg of carbon net influx or storage. A yearly variation of more than 100% could lead researchers to the wrong conclusions about storage and also indicates the need for long-term studies.

Recently, researchers have begun using satellite images and remote sensing to detect patterns of deforestation, reforestation and afforestation. Satellites can detect areas on Earth that are becoming greener, indicating an increase in vegetated surface therefore implying areas of increasing carbon dioxide uptake. Researchers at Boston University's Climate and Vegetation Research Group have used maps of Earth to determine 'percentage greenness.'

These images can be viewed at http://cybele.bu.edu/greenergh/data.nt.html. Temperate regions in North America and Eurasia have been 'greening' over the past two decades as indicated by Figure 6a/b. In the future, satellite images combined with forest carbon monitoring and measuring in the field will provide scientists will a better understanding of the global carbon budget components and, more specifically, terrestrial carbon reservoirs.

Figure 6a/b: Percent Greenness Revealed through Remote Sensing





Images from http://cybele.bu.edu/greenergh/mag.nt.html. Myneni, R., Climate and Vegetation Research Group, 2001.

There is still much to learn about forest ecosystems and, to make things more complicated, there is large natural ecological variation between and within forested ecosystems. Part of the problem with studying climate is the fact that, by definition, climate is a long-term phenomenon and short-term studies, at best, can only capture trends in the year-to-year changes in weather patterns.

Some components of forests are storing more carbon while others are releasing carbon to the atmosphere. The variations are due to differences in age, species composition, land use history, disturbance history and inter-annual climate variability, as well as different measurement techniques and a lack of standard ecosystem classification i.e. separating forest from scrubland. These variations have led to very different results in carbon studies, often depending on where researchers take their measurements. Many skeptics use these data variations as evidence that carbon cycle and climate change research are too uncertain. Further, they suggest that if the underlying science is uncertain, it is impossible to prove that humans are influencing global climate change at all.

Locating the mysterious stored carbon can help facilitate scientific and political consensus about climate change. In addition, we will better understand how to manage and conserve ecosystems that are buffering us from higher atmospheric carbon. The best way to determine if temperate forested landscapes are responsible for the missing carbon sink is to go out and measure the amount of carbon sequestered in them. Students, teachers and scientists alike can contribute to the carbon storage quantification effort.

Research at the NASA GISS Institute on Climate and Planets

Starting in the summer of 2000, a research team consisting of a group of New York City high school students and their teachers, led by NASA research scientist Dr. Dorothy Peteet, set out to tackle the challenge and contribute to the global effort to locate the missing carbon sink.

Under the guidance of Dr. Peteet, the researchers quantified the carbon sequestered in the trees and soils at lowland and upland sites in Cascade Brook Watershed, in Black Rock Forest near Cornwall, New York. You can see what the two different habitat types look like in the photographs in Figure 8 below. The results of the study have been provocative and are represented in the graph in Figure 7 below.

The team found that the bulk of the carbon stored in the ecosystem at Black Rock Forest was in the soil, rather than in the trees (Figure 7). This was despite the fact that Black Rock Forest's soils are thin and rocky and therefore thought to be a small carbon reservoir. In addition, contrary to current thinking about soil moisture and carbon content, more of the soil carbon was found in soil samples taken from the dry, upland site than in the samples from the moist, lowland site. These findings confirm the need for more data from northern temperate forest soils. The data also suggests that the importance of soils in the carbon cycle may be under-estimated at present. A summary of the research project can be viewed at http://icp.giss.nasa.gov/research/ppa/2002/carbon/

Figure 7: Results from ICP's Study at Black Rock Forest in Two Habitats

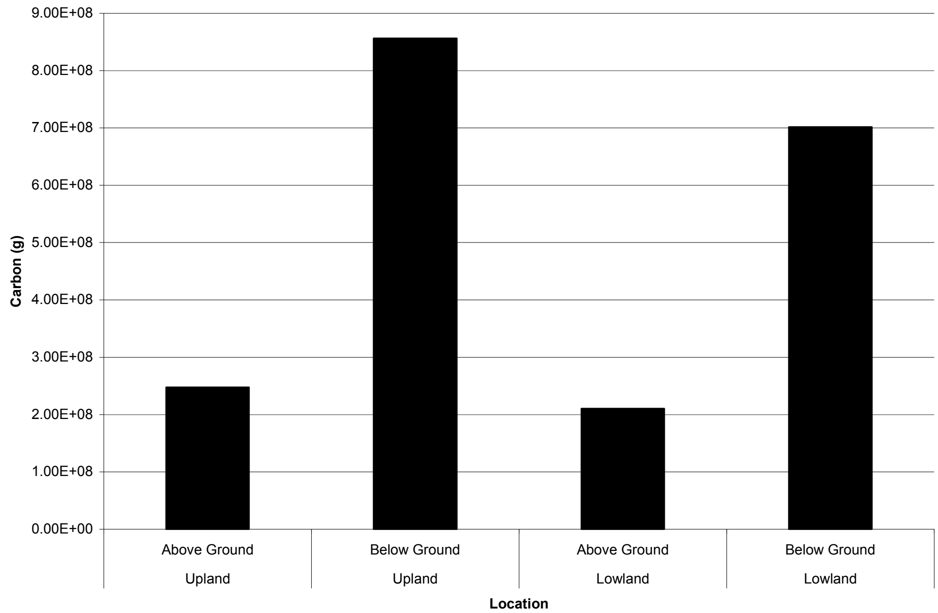


Figure 8: Photographs of a lowland and an upland ecosystem in Black Rock Forest

Lowland Upland

Photos taken by Kirsten Sauer, Columbia University.

References

The complete list of references used in *The Carbon Question* is available at the module's main web page located at http://icp.giss.nasa.gov/education/modules/carbon/