

Carbon in the Geobiosphere

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1. Project Description

The goal of this project was to quantify the abundance and flow of carbon among the major reservoirs on Earth and to identify the forms of carbon and processes responsible for the storage, flow, and transformation of carbon. The primary resource for this project is the first few chapters of the book, "Carbon in the Geobiosphere". The approach was to read the book, search other books and internet sources, and use Excel and PowerPoint to generate tables, charts, and diagrams to evaluate and illustrate the characteristics of the global carbon cycle for this brief draft progress report. Additional work will precede the next revision.

2. Background

The issue of carbon in the atmosphere is of great contemporary interest because, unlike the dominant atmospheric gases of nitrogen and oxygen, small amounts of greenhouse gases like carbon dioxide and methane transmit most of the incident sunlight but trap portions of the long wavelength infrared energy radiated by the Earth's warm surface, elevating the surface temperature of the planet and affecting the weather and the abundance, diversity, and distribution of life on Earth.

Carbon is present as a small fraction of the atmosphere, oceans, and solid Earth, typically a few hundred ppm. It is a major element in biota (typically 10% or more) and was abundant in the atmosphere billions of years ago. A combination of physical, chemical, and biological processes contributed to the historical transfer of carbon from the atmosphere to biota, soils, and sediments. These processes continue to determine the flow rates of carbon among the major reservoirs that store carbon today. These reservoirs include the atmosphere, ocean, terrestrial and marine biota, soils on land, sediments, and crust, all of which are components of the geobiosphere.

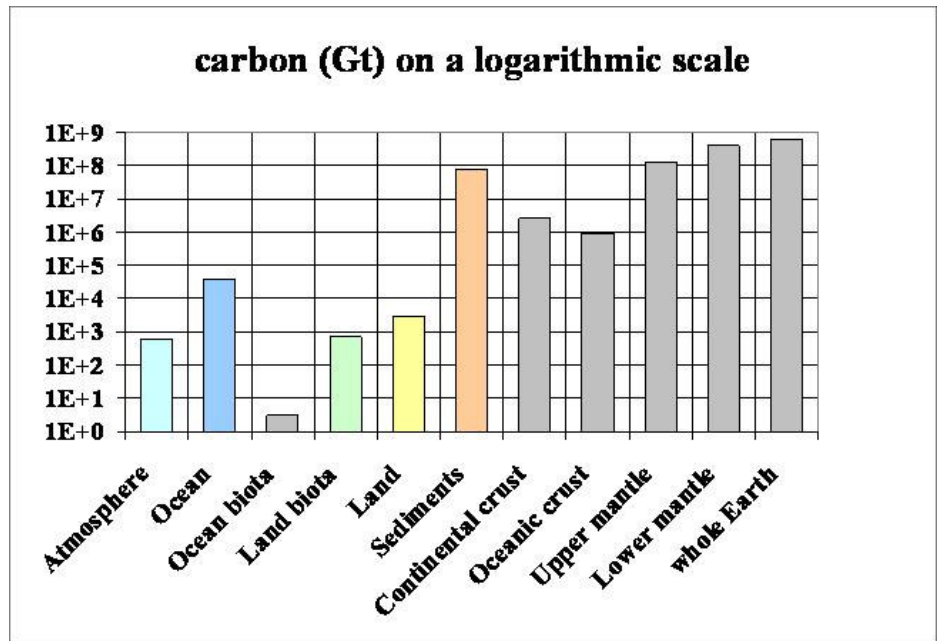
3. Abundance and Distribution of Carbon in the Geobiosphere

The first table and the logarithmic chart show the estimated amounts of carbon in Gigatons in each of the major reservoirs of the Earth including the Earth as a whole. Seventh eighths of the carbon on Earth is in the mantle, but one eighth is stored in sediments. The continental and oceanic crusts contain about 0.5% of the Earth's carbon.

reservoir	carbon (Gt) estimates	carbon as fraction of total mass
Atmosphere	600	0.00012
Ocean	38430	0.00003
Ocean biota	3	0.10000
Land biota	705	0.34199
Land	2890	0.00012
Sediments	77,800,000	0.00039
Continental crust	2,576,000	0.00012
Oceanic crust	920,000	0.00039
Upper mantle	132,000,000	0.00014
Lower mantle	400,249,221	0.00014
whole Earth	613,587,849	0.00010

About 60 ppm of the Earth’s carbon resides in the atmosphere, oceans, land, and biota, about 90% of which is in the soil on the land. The carbon in the atmosphere is almost entirely in the form of carbon dioxide, with small amounts of the highly potent greenhouse gas methane. Early in the Earth’s history, carbon was as much as 10,000 times more abundant and was in the form of carbon dioxide and methane. In the current industrial age, carbon dioxide has risen by about 30% and is continuing to rise.

The column showing carbon as a fraction of the total mass of each reservoir indicates that carbon typically composes about 0.1% of a reservoir, with a somewhat greater concentration in the sediments and thin ocean crust. The ocean and land biota concentrate carbon as a result of photosynthesis, particular the phytomass of land plants which have significant reservoirs of carbon stored mostly in cellulose and other woody fibers. Ocean biota store very little carbon – marine life is predominately short lived microscopic organisms (photosynthetic bacteria and algae) that fix a lot of carbon which ultimately flows into other reservoirs as we shall see in the next section.



The second table provides a more detailed accounting of the forms of carbon in the other four surface reservoirs.

The ocean, not including its previously discussed biota, is a major reservoir of available carbon in the geobiosphere. About 97% of the carbon in the ocean is dissolved inorganic carbon, DIC, mostly carbon dioxide. Most of the remaining 3% is dissolved organic carbon, DOC, including materials originating in both living and dead organisms. About 0.1% of the carbon is particulate organic carbon, POC.

As previously mentioned, the primary difference between land biota and ocean biota is the enormous amount of carbon stored in land plants, an amount exceeding the pre-industrial carbon dioxide in the atmosphere. Without the evolution of long lasting plant fibers, the carbon in land biota would be approximately 100 times smaller. In fact land plants also have important relationships with bacteria, fungi, and animals, so the significance of phytomass cannot be overstated.

reservoir	carbon (Gt) estimates	carbon as fraction of total mass
Ocean	38430	0.00003
Dissolved inorganic (DIC)	37400	0.00002
Dissolved organic (DOC)	1000	0.00000
Particulate organic (POC)	30	0.00000
Land biota	705	0.34199
Phytomass	700	0.35000
Bacteria and fungi	3	0.10000
Land Animals	1.5	0.05000
Land	2890	0.00012
Soil humus	1920	0.00008
Dead organic matter, litter, peat	250	0.00001
Inorganic soil (CaCO ₃)	720	0.00003
Sediments	77,800,000	0.00039
Carbonate sediments	65,300,000	0.00032
Organic matter sediments	12,500,000	0.00006

The land itself stores four times as much carbon as the land biota and most of it came from land biota. Inorganic soil contains carbon in the form of CaCO₃ whose abundance is comparable to the carbon in phytomass or the atmosphere. The other three fourths is almost 90% soil humus (a stable form of decomposed organic matter from plants and animals) and about 10% dead organic matter that is in the process of decaying.

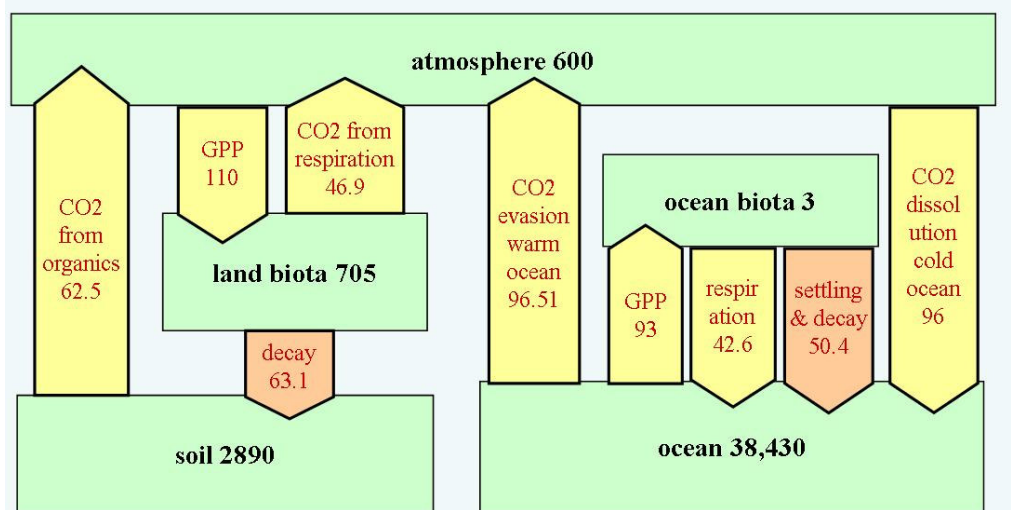
Sediments contain an enormous reservoir of carbon – 100,000 times as much as the atmosphere. This carbon slowly cycles through the other reservoirs because the surface of our planet is geologically active. Sediments are the burial ground of both carbonates and organic matter, the former being five times more abundant than the latter and resulting from a mixture of physical, chemical, and biological processes.

The last column reveals that pound for pound phytomass has the greatest concentration of carbon of any reservoir.

4. Flows of Carbon Within the Geobiosphere

What are the processes and rates of flow of carbon into and out of these reservoirs? How long does a typical carbon atom reside in a reservoir before it flows to the next reservoir in the global carbon cycle? The major flows of carbon in the geobiosphere are associated with the consumption of atmospheric and oceanic carbon dioxide for the production of organic matter by photosynthesizers and the subsequent consumption and decomposition of organic matter, most of which is recycled to carbon dioxide. There is a climate related flow of carbon dioxide from the atmosphere to cold waters and back to the atmosphere by warm waters.

The diagram shows the reservoirs (green boxes) of carbon in the geobiosphere that participate in the major carbon fluxes. The flows are represented by arrows, yellow if CO₂ is involved, tan for dead and decaying organic matter. The reservoirs are in gigatons of carbon and the flows are in gigatons of carbon per year and all numbers are based on a pre-industrial planet, several centuries or several thousand centuries ago. Most of the values used are from the



Major Carbon Fluxes

primary reference source, but some values are based on other sources. Carbon dioxide flows from the atmosphere when plants absorb it for gross primary production and some of it returns when plants respire. The difference between the gross primary production and respiration is the net primary production, NPP. Carbon dioxide returns to the atmosphere when organic matter in the soil is decomposed. The carbon previously entered the soil as land biota died, was consumed by organisms, and decayed into litter humus.

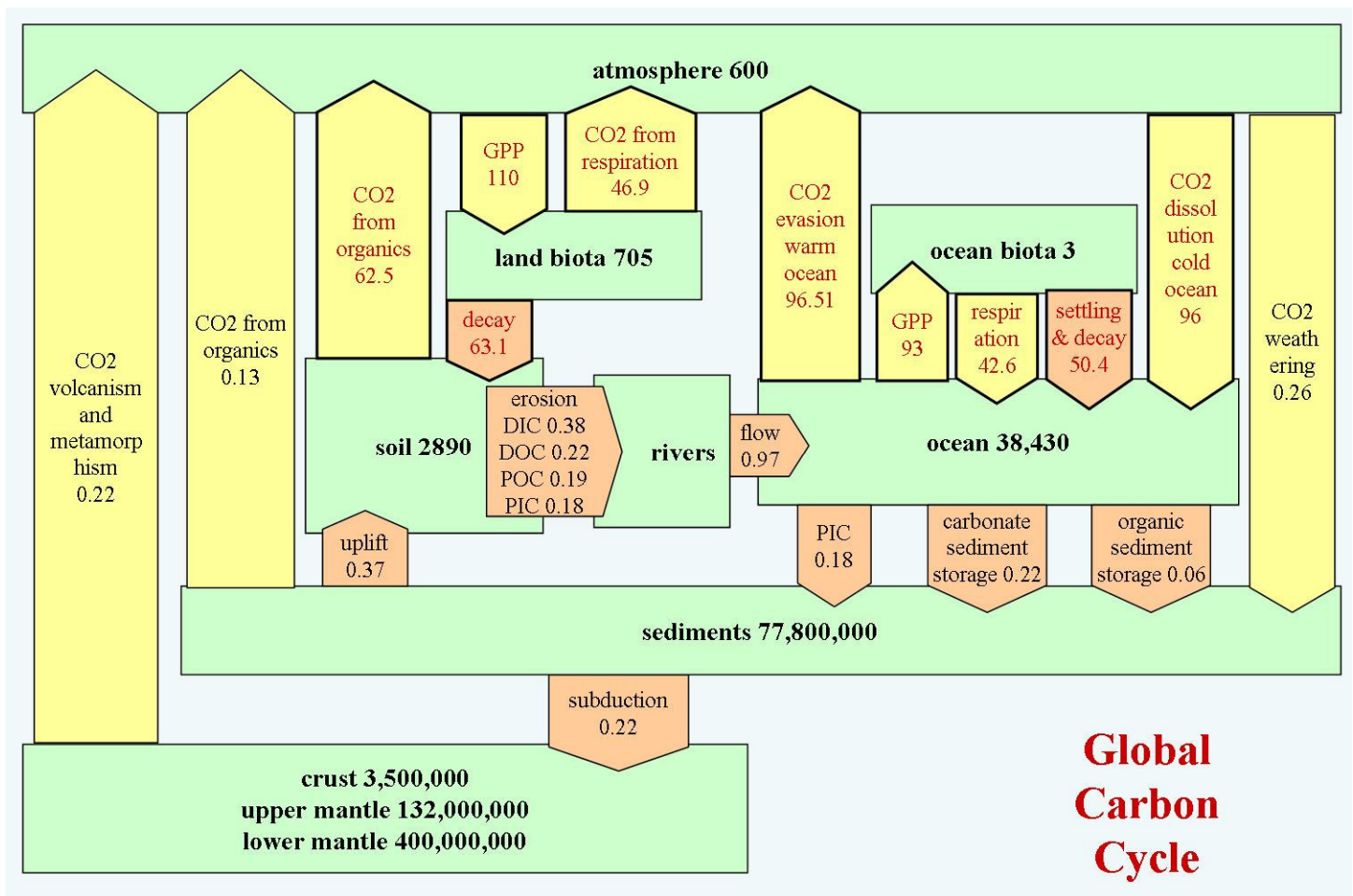
Carbon dioxide does not flow directly from the atmosphere to ocean biota. Carbon dioxide is dissolved in cold ocean surface waters and is emitted by warm ocean surface waters. Ocean biota absorbs carbon dioxide from the ocean as represented by the GPP arrow and it returns through respiration as well as settling and decay.

The fluxes are not in balance for the land and ocean biota but are not quite in balance for the other reservoirs because the diagram does not show the smaller fluxes involving rivers, sediments, and the Earth's crust, none of which exceeds one gigaton of carbon per year. The land based cycle seems on balance to remove carbon dioxide from the atmosphere as expected, but the ocean based cycle seems to have a net outflow of carbon dioxide to atmosphere, contrary to the claims of many sources that photosynthesis in marine organisms reduces atmospheric carbon dioxide, partially offsetting anthropogenic carbon output (not shown).

A more complete diagram includes the previous reservoirs and major flows (which are still highlighted with dark red text in arrows with thicker perimeter lines), but also shows the smaller flows associated with rivers, sedimentary deposits, and the crust. The major flows involve fast processes associated with the biological carbon cycle while the small flows involve slow processes associated with the geological carbon cycle. Some smaller flux values were selected to be consistent with zero net flux in each reservoir as would be expected if no reservoirs are growing or shrinking. The subject of net flux will be addressed by a later table. Note that the size of the carbon flux does not necessarily correlate with the size of the reservoir. The difference is related to the drastic variations in residence time of different reservoirs, which will be discussed later.

Carbon dioxide also cycles through sediments as continental rocks are weathered by carbon dioxide and water in the atmosphere and form sediments and they return as organic matter in the sediments release carbon dioxide during decomposition.

Carbon in a variety of forms erodes from soil and flows via rivers to the ocean. Carbon also flows directly into sediments by weathering and is returned by uplift. Sediments also erode and dissolve in rivers before flowing into the ocean. Sediments also collect carbon from oceans and deposit them in the crust which are recycled into the atmosphere as carbon dioxide emissions from volcanism and metamorphism.



The diagram identifies seven inflows and outflows associated with sediment cycles. The cycle involving the crust is characterized by subduction inflows and outflows of carbon dioxide to the atmosphere related to volcanism, metamorphism, and other thermal processes. For completeness, the diagram includes the vast reservoir of carbon in the Earth's mantle, but does not identify specific carbon cycles in the mantle. The mantle tends to cycle by convection on a time frame of several hundred million years.

5. Analysis of Residence Time

The underlying assumptions are that reservoirs are components of a complex system through which carbon flows. Unfortunately the reservoirs are more than components; they are complex systems in which carbon is

stored in several forms, the carbon undergoes processes within a reservoir that changes its forms, and the inflows and outflows are in several forms. Some insight can be made with a zeroth order model of homogeneous reservoirs in which the first carbon to flow in is also the first carbon to flow out, but ultimately the forms of the carbon need to be taken into account.

What is the residence time for carbon in each reservoir? We have made some estimates, but perhaps inorganic flows should be analyzed separately from organic flows. The table summarizes the estimates.

My definition of residence time is the ratio of the total mass of carbon in a reservoir to the mass outflow per year. In other words, the residence time is the amount of time it would take for all of the carbon in a reservoir to flow out of it at the current rate of total outflow through one particular outlet if the reservoir had no inflows. The definition does depend on certain assumptions, such as whether GPP and respiration are treated separately or lumped together as NPP. The latter treatment results in a lower flux and longer residence time. This treatment affects the atmosphere, ocean, and all of the biota.

The residence time of carbon in the atmosphere that is recycled by net primary production of land biota is 600/63.1 or 9.5 years. The residence time of carbon in land biota recycled by decay to the soil is 705/63.1 or 11.2 years. Residence time of soil to the atmosphere by decay is 2890/62.5 or about 46 years. Residence time of carbon in ocean biota decaying back to the ocean is 3/50.4 or 0.06 years. Ocean residence time by evasion of CO₂ to the atmosphere is 38430/96.51 or nearly 400 years. These numbers barely change when including the smaller outflows included below. Carbon residence time in sediments recycled by geologic movement is 77800000/0.59 or about 130 million years and in the crust by volcanism is 3500000/0.22 or about 16 million years.

6. Net Flux per Reservoir now and in the past

We have assumed that the reservoirs of carbon are neither growing nor shrinking. This is certainly true over most short time intervals in the pre-industrial past. But we know that reservoirs do change slowly over time and may even change rapidly under extreme conditions such as climate catastrophes, extraterrestrial impacts, and innovative evolutionary developments. The development of large land plants during the Phanerozoic era provided an opportunity for the land biota to increase its carbon storage, particularly in the form of cellulose and other woody fibers. These fibers eventually collected in soil and sediment reservoirs, beginning an era of coal formation. The evolution and distribution of bacteria and fungi capable of decomposing these fibers altered their accumulation in soil and sediments, ending an era of rapid accumulation of fossil fuel deposits in sediments.

net flux per reservoir (Gt/year)		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Reservoir	Carbon Flux Gt/year	atmosp here	land biota	ocean biota	soil (land)	ocean	sedim ents	crust	
GPP from atmosphere to land biota	110	-110	110						0
GPP from ocean to ocean biota	93			93		-93			0
respiration from land biota to atmosphere	46.9	46.9	-46.9						0
respiration from ocean biota to ocean	42.6			-42.6		42.6			0
Volatilization from soil organic matter to atmosphere	62.5	62.5			-62.5				0
decay of land biota to soil	63.1		-63.1		63.1				0
decay of ocean biota to ocean	50.4			-50.4		50.4			0
Weathering of CO ₂ from atmosphere to sediments	0.26	-0.26					0.26		0
dissolution from atmosphere to ocean	96	-96				96			0
evasion to atmosphere from ocean	96.51	96.51				-96.51			0
DIC (river outflow to ocean)	0.38				-0.38	0.38			0
DOC (river outflow to ocean)	0.22				-0.22	0.22			0
POC (river outflow to ocean)	0.19				-0.19	0.19			0
PIC (river outflow to ocean and on to sediments)	0.18				-0.18		0.18		0
Oceanic sediment long-term storage of Carbonates	0.22					-0.22	0.22		0
Oceanic sediment long-term storage of Organic matter	0.06					-0.06	0.06		0
CO ₂ from organics from sediments to atmosphere	0.13	0.13					-0.13		0
subduction	0.22						-0.22	0.22	0
Volcanism, etc. from land to atmosphere	0.22	0.22						-0.22	0
Uplift	0.37				0.37		-0.37		0

7. Future Projects & Recommendations

The most difficult parts of this project involved understanding which reservoirs are involved in which fluxes and trying to fine tune the fluxes to produce a balanced zero net flux in each reservoir. Historically, reservoirs grow and shrink over time and the zero net flux model is nothing more than a useful simplifying assumption.

There are several questions raised by the tables of storage and flows of carbon into and out of Earth's reservoirs. First, are the values accurate and do they agree with other reports? Second, should we specify the reservoirs in more detail, distinguishing between cold and warm surface waters and deeper oceans? Are the inflows and outflows in balance or do the carbon reservoirs grow or shrink? How long did it take for the reservoirs to acquire their initial carbon masses and how long to grow or shrink to current levels? How much carbon did the reservoirs contain in earlier eras and what fluxes and physical, chemical, and biological processes were typical then?

We recommend that future projects investigate the abundance, distribution, and flow of carbon among the major reservoirs on Earth at several periods spanning the nearly five billion year history of our planet. Clues include the rise of oxygen in the atmosphere, the uptake of oxygen by other reservoirs including iron formations, the rise of land phytomass, and the rise of buried carbon.

We also recommend an analysis of the abundance, distribution, and flow of other volatiles such as water, oxygen, chlorine, sulfur, and phosphorus among the major reservoirs on Earth from both a contemporary perspective and across the span of planetary history.

8. References – books, journals, websites

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