

# ESA 21: ENVIRONMENTAL SCIENCE EXERCISES

## Biogeochemical Cycles: Trees and Carbon

### Chemical Cycles

#### Introduction

To understand the environment, it is important to understand how organisms and their surroundings interact. Since all organisms use energy, we need to understand how energy can be used and transferred. This was the purpose of our last module, which studied what factors limit how energy can flow. Because all organisms are made of substances, it is equally important that we understand how chemicals are used and transported through an ecosystem. Over the next three weeks, we will do just this.

The transport and transformation of substances in the environment are known collectively as biogeochemical cycles. These global cycles involve the circulation of elements and nutrients that sustain both the biological and physical aspects of the environment. For example, all known organisms on this planet depend on water to sustain them. They are constantly cycling water, consuming it on a regular basis either by itself or with nutrients, while expelling water (with waste products) at the same time. Besides being critical for the biosphere, water is also an extremely important part of the physical environment. When water vapor condenses to form clouds, more of the Sun's rays are reflected back into the atmosphere, usually cooling the climate. Conversely, water vapor is also an important greenhouse gas in the atmosphere, trapping heat in the infrared part of the spectrum in the lower atmosphere. Water is also involved in other biogeochemical cycles. The hydrologic cycle intersects with almost every other element cycles, as well as some of the geological cycles such as the sedimentary cycle.

### Carbon Cycle

#### Example

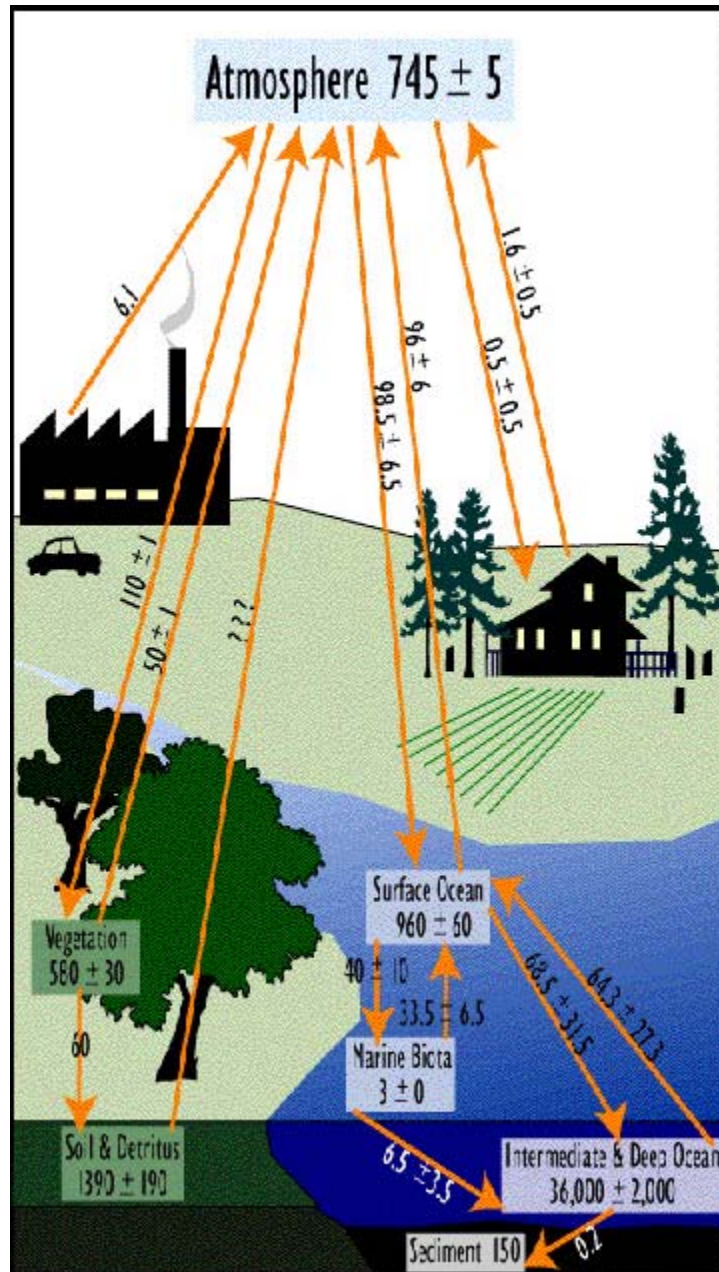
Over the next three weeks, we are going to study how carbon cycles through our ecosystem and how mankind affects this cycle. It is important that we understand how carbon cycles through the ecosystem for two reasons. The first of these reasons is that all organic material contains carbon. From the smallest vitamin molecule all the way up to the long polymer chains of proteins and DNA, carbon provides the basis of all organic compounds.

The second reason why we need to understand the carbon cycle is because of its effect on the physical environment. Carbon, in the form of carbon dioxide, is released as a waste product of oxidation. This means that it is released during the combustion of fossil fuels, as well as the respiration of organisms. As we will see later, this can have a tremendous effect on our climate, since carbon dioxide is a greenhouse gas.

Carbon has two phases in the carbon cycle: gaseous and solid. Its gaseous phase is mostly in the form of carbon dioxide, but it can also be found in compounds like methane and carbon monoxide. Carbon dioxide can be taken out of the atmosphere by photosynthesis in plants, which convert the carbon into a solid form (sugars) that can be stored or put back into the air during respiration. It can also be removed from the atmosphere by being absorbed by water, where it becomes available to water plants for photosynthesis as well as being available to form compounds such as calcium carbonate (chalk) or to be put back into the atmosphere when the water gets warmer.

As we can see, the carbon cycle has reservoirs where it is stored as a solid. The diagram at the right shows some of these. In a cycle that has reached equilibrium, the rate at which carbon is removed from storage is equal to the amount that is being taken out of the atmosphere. The reason why many people

are concerned about the carbon cycle is because mankind's intervention has caused this system to go grossly out of equilibrium. By burning fossil fuels, mankind has upset the balance of the cycle and greatly increased the rate at which carbon is returning to the gaseous phase. Is this a problem? In order to understand why it might be a problem, we need to understand more about the properties of carbon dioxide.



## Greenhouse Effect

### Global Warming

The effect of infrared re-radiation being absorbed in the atmosphere is called the "Greenhouse Effect" since it mimics what happens in a real greenhouse. There, the radiation is trapped by glass window panes, which are optically opaque in the infrared region of the spectrum. Since the infrared radiation does not pass through the glass, it remains in the greenhouse and keeps the inside temperature warmer than the outside temperature (the same effect keeps the inside of your car warm even on a cold sunny day).



The science behind this effect in the atmosphere is fairly well understood. Certain gases, such as water vapor, carbon dioxide, and methane, are able to absorb infrared radiation very well. The Earth re-radiates absorbed sunlight back into outer space mostly in the infrared range of the electromagnetic spectrum. When these gases are present in the atmosphere, they will absorb this energy before it gets back into space, and thereby heat the atmosphere. We see this in action everyday, both on our planet and on others in the Solar System. For example, Venus has an atmosphere that contains almost a million times the concentration of carbon dioxide (a greenhouse gas) as our atmosphere. If Venus were to have no atmosphere, its average temperature would be about 230 K (-45 °F); because of this carbon dioxide concentration (plus a small amount of other greenhouse gases), it has a temperature of 740 K (about 900 °F). A similar, but smaller, effect is seen on Mars and other planets that contain greenhouse gases. Without the greenhouse gases that we have on Earth, it is estimated that our average daily temperature would be about -10 °F, instead of the 60 °F that it is.

While water vapor has the greatest contribution to atmospheric heating due to the greenhouse effect here on Earth, most of the attention in this area lately has been focused on carbon dioxide. The reason for this is that the levels of carbon dioxide have increased from about 292 ppm (parts per million) to over 360 PPM over the last 100 years. This increase in concentrations has corresponded to the same time period over which we have seen the average tropospheric temperature increase about 1 °C. The correlation between these two events, plus our knowledge of how greenhouse gases work, has led many to hypothesize that the Earth will continue to get warmer as we release more and more greenhouse gases into the atmosphere.

## Carbon Sequestering in Trees

### Carbon Reservoirs

In burning fossil fuels as an energy source, we are taking stored carbon and putting it back into the atmosphere at a rate that is greater than it is being taken out. This causes means that the amount of carbon dioxide in the atmosphere is increasing, and will continue to do so until the difference in these two rates disappears. One way to bring this about would be to greatly curtail the rate at which burn fossil fuels. Many people do not like this idea, as it would mean a great change in our lifestyle. Another proposed method would be to speed up the rate at which carbon is removed from the atmosphere. One way of doing this would be to plant more trees.

During photosynthesis, trees convert carbon dioxide and water into sugar molecules and oxygen through a series of oxidation and reduction reactions. The overall equation for the photosynthetic process may be expressed as



Some of this sugar is stored, while most of it gets used by the tree for other purposes such as energy and structure. For instance, a great deal of the sugar is linked together to form cellulose which provides the structure for the tree.

If we look at this sugar from a mass standpoint, we see that a large fraction of it is due to the carbon. The fact that carbon has an atomic mass of 12, hydrogen has an atomic mass of 1, and oxygen has an atomic mass of 16 means that  $72/180 = 40\%$  of the mass of the sugar molecule comes from carbon. Taking into account the other types of molecules that are found in a tree (proteins, lipids, etc.), we find that about 45% of the dry mass (not including the water) of a tree comes from carbon. In other words, a 100 kilogram log of a tree that has been completely dried contains about 45 kilograms of stored carbon.

While each kilogram of dried tree is storing .45 kilograms of carbon, it is removing more than a kilogram of carbon dioxide from the atmosphere. This is because each carbon dioxide molecule contains two oxygen atoms. Using the data from above, this means that each carbon dioxide molecule has an atomic mass of  $12 + 2(16) = 44$ , of which only 12 are due to the carbon. Therefore, for each atom of carbon stored in a tree, 44 atomic mass units of carbon dioxide is removed from the atmosphere. This means that each kilogram of dried tree corresponds to

$$(1 \text{ kg of dried tree}) \times (.45 \text{ kg of C/1 kg of dried tree}) \times (44 \text{ amu of CO}_2/12 \text{ AMU of C}) = 1.65 \text{ kg of CO}_2$$

This large of an amount gives the idea of using trees to remove carbon from the atmosphere a lot of validity. However, it should also be pointed out that this equation works in reverse. When a tree is burned or allowed to decay completely, the carbon in the tree is put back into the atmosphere as carbon dioxide. Worldwide, we are actually losing forest, and this relationship shows why we should be concerned.

In this week's activity, we are going to estimate how much carbon is sequestered in an acre of forest land. In order to do this, all that we need to know, given the information above, is how much dried wood is in an acre of forest. To get this information, we will first need to know something about how organisms grow.

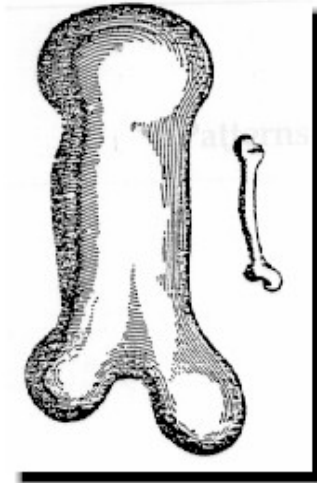
## Allometry

### Definition

One way to estimate how much carbon is in an acre of forest is clearcut one acre of forest, measure the weight of all organic material harvested, and then analyze the material for the percentage of carbon in it. While it would give a very precise estimate, it is not a very ecologically-friendly way to study nature. A less harmful way to carry out this estimate is to develop an allometric equation that will allow you to estimate the mass of a tree from a few simple measurements of it, and then to apply this equations to the trees in a forest. The term allometry is defined as "the measure and study of relative growth of a part in relation to an entire organism or to a standard". It is based upon a principle first describe by Galileo Galilei in the 1630's about how the proportions of an organism must change as it gets bigger.

Galileo noted that the strength of a bone was related to its cross-sectional area, while the mass of an organism was related to its volume. Because of this, he correctly noted that an organism could not grow in a linear fashion forever. If it did grow linearly, then it would increase the same percentage in all directions. This would mean that its volume, and hence its mass, would increase at a rate that was much faster than its bone structure could handle. For instance, if the organism was to double in size (increase by a factor of 2 in all directions), its mass would increase by a factor of 8 (the volume depends on the product of all three dimensions). However, its bones' strength would only increase by a factor of 4 since the cross sectional area of the bone only depends on the square of the diameter of the bones. Thus, he posited that the diameter of the support structure of an organism must increase at a faster rate than its height increases, or else the bone would crack under the pressure.

Galileo's illustration of the same bone (femur) from animals of different sizes. Whereas the lengths of the bones differ by about 2.5 times, the width of the bones differ over tenfold.



Instead of growing linearly, most organisms grow at different rates for different parts of the body. The relationship between the size of any two parts of an organism can be written as

$$y = bx^{a/c}$$

where  $a$  is the growth rate of  $y$ ,  $c$  is the growth rate of  $x$ , and  $b$  is a proportionality constant that relates the two ( $y = b$  when  $x=1$ ). This equation can also be expressed in its logarithmic form

$$\log_{10}y = \log_{10}b + (a/c) \log_{10}x$$

While this equation looks rather nasty, it is very powerful. What it allows one to do is to calculate some aspect of an organism by measuring some other variable of the organism. This is important to be able to do, as the variable that you want to measure might not be able to be measured without killing the organism, as we mentioned above in our example of measuring the mass of a tree. With the correct formula, we should be able to "measure" the mass of a tree by merely measuring the diameter of the tree trunk at its base.

## Allometric Equation

### Carbon

Determining the allometric equations to use for estimating the amount of carbon sequestered in a forest has been getting a lot of interest in the last decade as countries debate global warming and the effects of deforestation. One way for us to proceed would be to use the equations developed by other researchers on similar forests. For instance, Martin, Kloeppe, et al<sup>1</sup> calculated a set of average equations for deciduous trees in the southern Appalachian mountains that relate the diameter of the tree at a height of 1.4 meters to various parameters like the dry mass of the stem, the dry mass of the stem, bark, and branches, and the total biomass of the tree excluding roots. If we were to use these equations, we would not have to develop our own equations, which would require that we sacrifice a few trees.

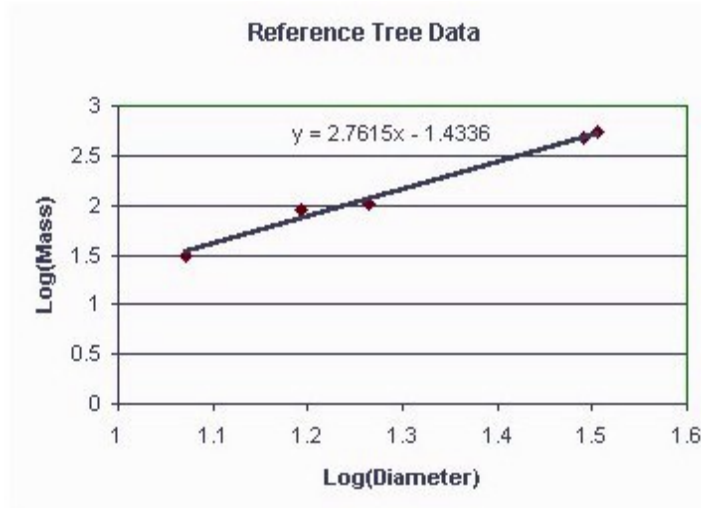


One of the reference plots before trees were clear cut for the construction.

The recent construction of apartments on the campus of KSU and the clearcutting of the 15 acres of forest, though, have provided us the opportunity to verify these equations. Before the trees were ground up into mulch, we were able to sample 5 representative trees (3 pines and 2 sweet gums) from this location. Measurements of the circumferences of the stems of the trees were made at multiple heights, allowing for the volume of the stems to be calculated. Wood samples were taken for age analysis and density measurements. The wood samples were dried, and the densities were measured. Using the density and volume measurements, the total mass of the stem of the trees was found.

Tree	Diam. at 1.4 m	Stem Mass	Age
Pine #1	15.5 cm	89 kg	35 yrs
Pine #2	32 cm	544 kg	54 yrs
Pine #3	31 cm	467 kg	51 yrs
Sweet Gum #1	18.5 cm	102 kg	37 yrs
Sweet Gum #2	12 cm	31 kg	26 yrs

Now that we have the masses of the stems and the diameters of the trees at 1.4 m, we can develop our own allometric equation relating these two and see how it compares to that developed by Martin, et al<sup>1</sup>. If we plot this data on a log-log plot, we get



This data shows a relationship between the diameter of the tree at 1.4 meters and the stem mass of

$$\log_{10}M = -1.43 + 2.76 \log_{10}D$$

where M is the dry mass of the tree above ground in kilograms and D is the diameter of the tree in centimeter at 1.3 meters above ground level. This compares very well to the results of Martin, et al of

$$\log_{10}M = -1.44 + 2.69 \log_{10}D$$

for the same relationship, given the error bars on the data.

The fact that our reference data for stem mass and diameter so closely matches that of Martin, et al provides some evidence that the trees in our forest are similar to those in their forest. This makes sense since the area where their data was collected was at a location that is only about 100 miles from our site. Since our data is so similar, we are justified in using their equation that relates the diameter at 1.4 meters with total biomass of the tree (excluding roots) in our estimate. This equation is

$$\log_{10}M = -1.25 + 2.66 \log_{10}D$$

1 "Aboveground biomass and nitrogen allocation of ten deciduous southern Appalachian tree species", Martin, Kloeppel, Schaefer, Kimbler, and McNulty, *Can J. For. Res.* 28: 1648-1659 (1998).

## Forest Data

### Carbon Analysis

Now that we have verified the equation that we will use for estimating the amount of biomass in a tree, we are ready to begin our calculation for the amount of carbon sequestered in an acre of forest. To do this, we sampled the same forest from which we took out reference trees at three different locations. At each of the three locations (shown in the figure to the right), a 10 meter by 10 meter square was randomly laid out, and the trees within that square were measured. The trees that were measured had to be more than 2 centimeters in diameter.

Site #1		Site #2		Site #3	
Tree	Diam. (cm)	Tree	Diam. (Cm)	Tree	Diam. (Cm)
Pine	22	Pine	11	Pine	36
Pine	16	Pine	35	Pine	21
Pine	29	Pine	39	Pine	23
Pine	24	Pine	7	Pine	31
Pine	32	Pine	9	Pine	25
Pine	12	Sweet Gum	8	Pine	12
Pine	43	Sweet Gum	17	Pine	22
Pine	28	Sweet Gum	5	Pine	25
Pine	39	Sweet Gum	12	Pine	17
Sweet Gum	7	Dogwood	7	Sweet Gum	15
Sweet Gum	3	Dogwood	5	Sweet Gum	11
Sweet Gum	21	Dogwood	11	Sweet Gum	9
Dogwood	3	Dogwood	7	Sweet Gum	38
Dogwood	8	Hickory	11	Dogwood	17
Birch	7	Hickory	6	Hickory	12
Birch	4	Hickory	8	Hickory	5
		Birch	3	Birch	2
		Maple	4	Birch	2
				Birch	2



Map of the KSU dorm site. Trees were sampled in the three locations denoted by the red squares

KSU [Map](#) of housing sites

**Internet Addresses of Linked Sites:**

*KSU Map Page:* <http://www.kennesaw.edu/maps/ksu.html>

With this data, and the equation

$$\log_{10}M = -1.25 + 2.66 \log_{10}D$$

one can estimate the amount of aboveground biomass in a 10m x 10m plot (100 m<sup>2</sup>) of forested land. Given that 1 acre = 4047 m<sup>2</sup>, these same calculations can be expanded to estimate the amount of aboveground biomass in an acre of forest.

While this exercise was originally done using the data above, additional data sets have been derived from the original set to provide variety in the calculations. Use the data set assigned by your instructor, and if your instructor does not assign a particular data set, use data set #1. Complete only one activity sheet - the one for your data set.