ESA21
Environmental Science Activities for the 21st Century

Trees and Carbon

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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. Because all organisms are made of substances, it is equally important that we understand how chemicals are used and transported through an ecosystem. This exercise will help contribute to our understanding of the movements of compounds in ecosystems.

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.

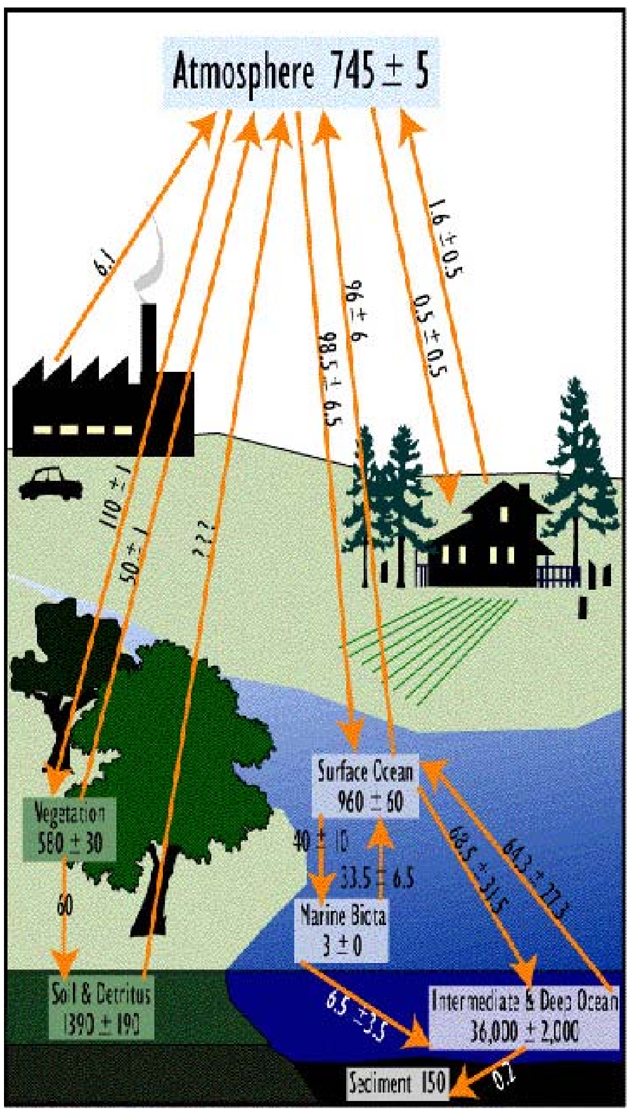
Carbon Cycle: Example

In this and other activities, 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 below 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^{o} F); because of this carbon dioxide concentration (plus a small amount of other greenhouse gases), it has a temperature of 740 K (about 900^{o}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^{o} F, instead of the 60 of 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^{o} 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

$6\ CO_2 + 6\ H_2O$ + sunlight ---> $C_6H_{12}O_6 + 6\ O_2$

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 kg of dried tree) x (.45 kg of C/1 kg of dried tree) x (44 amu of CO_2/12 AMU of C) = 1.65 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.

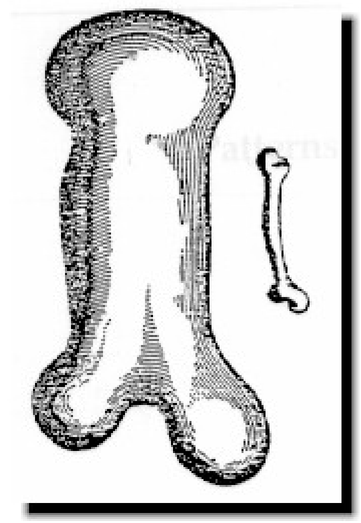
In this activity, we are going to estimate how much carbon is sequestered in an acre of forest land. In order to do this, all that we need to know, given the information above, is how much dried wood is in an acre of forest. To get this information, we will first need to know something about how organisms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

Allometry

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 Galilee 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 two in all directions), its mass would increase by a factor of eight (the volume depends on the product of all three dimensions).

However, its bones' strength would only increase by a factor of four 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 sizes 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.

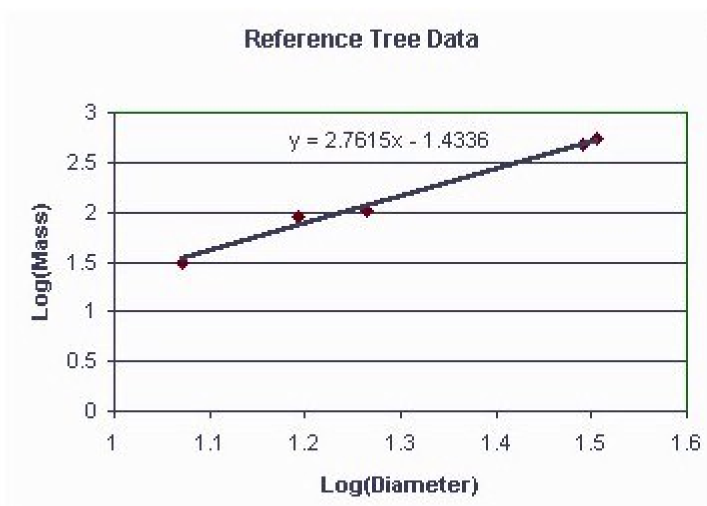
Allometric Equation: Carbon

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, Kloeppel, et al[1] 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.

Case Study: Campus Housing Construction at Kennesaw State University (KSU)
In September 2001, previously forested land on the campus of Kennesaw State University in suburban Atlanta was cleared to begin the process of construction of several units of campus housing. The clearcutting of 15 acres of forest provided an opportunity to verify the equations presented in this activity. Before the cut trees were ground up into mulch, we were able to sample 5 representative trees (three pines and two 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[1]. 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

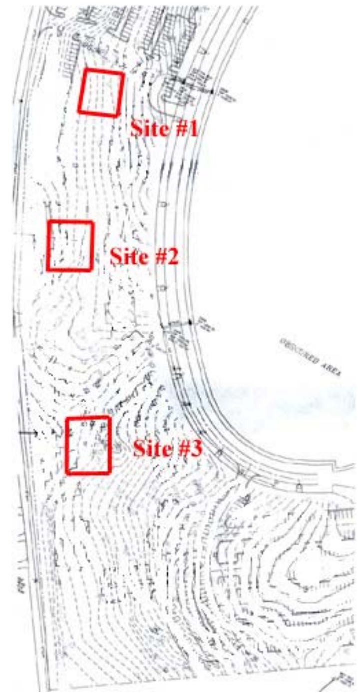
$$\log_{10}M = -1.25 + 2.66 \log_{10}D$$

[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 below), a 10 meter by 10 meter square was randomly selected, and all trees with a diameter of 2 cm or greater within that square were measured.

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

With this data, and the equation

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

you can estimate the amount of aboveground biomass in a 10m x 10m plot (100 m^2) of forested land. Given that 1 acre = 4047 m^2, 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.

ESA 21: Environmental Science Activities

Activity Sheet
Trees and Carbon

Name:

Instructor:

Using the equation and the table of data below, calculate the aboveground biomass of the trees in the three sites sampled. The first value has been provided.

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

DATA SET: VERSION A

Site #1			Site #2			Site #3		
Tree	Diameter (cm)	Biomass (kg)	Tree	Diameter (cm)	Biomass (kg)	Tree	Diameter (cm)	Biomass (kg)
Pine	22	209	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	
Total			Total			Total		

ESA 21: Environmental Science Activities

Activity Sheet
Trees and Carbon

Name:

Instructor:

Using the equation and the table of data below, calculate the aboveground biomass of the trees in the three sites sampled. The first value has been provided.

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

DATA SET: VERSION B

Site #1			Site #2			Site #3		
Tree	Diameter (cm)	Biomass (kg)	Tree	Diameter (cm)	Biomass (kg)	Tree	Diameter (cm)	Biomass (kg)
Pine	22	209	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	17		Pine	12	
Pine	43		Sweet Gum	5		Pine	22	
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		Birch	3		Hickory	12	
Birch	4		Maple	4		Hickory	5	
						Birch	2	
Total			Total			Total		

ESA 21: Environmental Science Activities

Activity Sheet
Trees and Carbon

Name:

Instructor:

Using the equation and the table of data below, calculate the aboveground biomass of the trees in the three sites sampled. The first value has been provided.

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

DATA SET: VERSION C

Site #1			Site #2			Site #3		
Tree	Diameter (cm)	Biomass (kg)	Tree	Diameter (cm)	Biomass (kg)	Tree	Diameter (cm)	Biomass (kg)
Pine	22	209	Pine	11		Pine	36	
Pine	16		Pine	35		Pine	31	
Pine	29		Pine	39		Pine	25	
Pine	24		Pine	7		Pine	12	
Pine	32		Sweet Gum	8		Pine	22	
Pine	12		Sweet Gum	5		Pine	25	
Pine	43		Sweet Gum	12		Pine	17	
Pine	28		Dogwood	7		Sweet Gum	15	
Pine	39		Dogwood	5		Sweet Gum	11	
Sweet Gum	7		Dogwood	11		Sweet Gum	9	
Sweet Gum	3		Dogwood	7		Sweet Gum	38	
Dogwood	3		Hickory	11		Dogwood	17	
Dogwood	8		Hickory	6		Hickory	12	
Birch	7		Hickory	8		Birch	2	
Birch	4		Birch	3		Birch	2	
			Maple	4				
Total			Total			Total		

Calculations:

(a.) Calculate the mean biomass per 100 m^2 for the three plots _____________ kg/100 m^2

(b.) Convert biomass per m^2 to biomass per acre. Since 1 acre = 4047 m^2, multiply the mean biomass per 100 m^2 by 40.47. _____________ kg/acre

(c.) To calculate the amount of carbon stored in the plant tissues, multiply the average biomass per acre by 0.45, since studies have shown that about 45% of the biomass of a tree is carbon. _____________ kg C/acre

(d.) While carbon per acre is a useful measurement, most studies of carbon cycling quantify carbon flux as carbon dioxide, not carbon. To determine the amount of CO_2 that the trees removed from the atmosphere, multiply the carbon per acre value by 3.67. This value is the mass conversion factor for carbon to carbon dioxide. _____________ kg CO_2/acre

This is an important value, as it shows how much carbon dioxide is sequestered in an acre of forest, and how much would be released to the atmosphere if the trees from an acre were cut and then burned or allowed to decay (mulched). We will return to this value later in the module when you determine your personal CO_2 emissions from energy usage, and see how many acres of forest would be needed to "store" your carbon dioxide.

Analysis:

(a.) Let's now calculate the amount of CO_2 that could be stored on the land occupied by your residence, if it were forested. Choose either the single-family home or apartment sections below. If neither of these categories exactly describes your residence, choose the one that is most appropriate. You will need the conversion factors for square feet and square miles to acres, so they are listed below.

1 $mile^2$ = 640 acres   1 acre = 43, 560 ft^2

Single-family home:
Measure the area of your home's lot that is not covered by large trees. If you are unsure of the size of your lot in acres, measure its length and width in feet, calculate the square footage, and convert to acres using the factor above.

Do the same for your entire subdivision. If you don't know its total acreage, reset the odometer on your car and measure the length and width of the subdivision in miles using tenths of miles from the odometer. Multiply these values together to get the square miles, and then convert to acres using the factor above. Subdivisions are rarely square or rectangular, so you may have to make some estimations and judgment calls in this process.

Apartment complex:
Measure your apartment building's length and width in feet, calculate the square footage, and convert to acres using the factor above. Then divide this value by the number of apartments in the building to determine the each apartment's "share" of the area.

Do the same for the entire apartment complex. If you don't know its total acreage, measure it in miles (as described in section (a.) above) or feet, whichever is most appropriate. Calculate the complex's area in square miles or feet, and then convert to acres.

Using the "Carbon dioxide stored/released per acre" value from your calculations of the KSU sites, calculate the amount of CO_2 that would have been removed from the atmosphere and stored in plant tissues if your lot/apartment and subdivision/apartment complex were forested land. List your answers below.

	Single-family home		**Apartment**	
	Lot	**Subdivision**	**Apartment**	**Complex**
CO_2 stored/released (kg/acre)				

(b.) It is estimated that the greater Atlanta area (where KSU is located) loses 50 acres of trees per **day** to development. If we assume that the cut trees are burned or mulched, how much CO_2 will this release into the atmosphere in a **year**? __________________ kg CO_2

Does this information cause you to consider buying a smaller lot for your next home? Does it change the way you would landscape your current or future home?