The Global Water and Nitrogen Cycles

"The foremost critical natural resource issue facing humanity is freshwater. ... No more fresh water will exist on earth than there was 2,000 years ago when the population was 3% of its current size."

(R. Robarts & R. Wetzel, SIL News V. 29, Jan 2000)

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Global Water Cycle

The water cycle contains the largest chemical flux on earth. Water distributes heat around the globe and thus creates climate, and water is the single most important factor regulating land-plant productivity worldwide. Without water life would not exist (perhaps on ANY planet), and despite the fact that 70% of the earth's surface is covered with water, that water is salty and can't be used for drinking, agriculture, or industry. Only about 0.014% of the water at earth's surface is useable by plants, humans, and other animals.

In attempting to understand element cycles as part of the major functioning of ecosystems, it is useful to follow a specific "approach". This general approach was followed in the previous lecture on the carbon cycle, and it can be used to help understand any element cycle. It consists of 3 parts and is formally outlined below:

- 1st - **Accounting**: Accounting tells you ***"where things are"***, or the distribution of the element in different pools within the ecosystem.
- 2nd - **Cycling**: Cycling tells you ***"where things are going"***, and how fast they are moving from different pools in the ecosystem.
- 3rd - **Controls**: Determining the controls tells you ***"how does the system function, and what factors drive the cycling"***.

Using this approach of gaining knowledge about each of these three components enables you to answer the question of **"*How will things change?*"**. Gaining this kind of a **predictive understanding** of ecosystems, or of communities or populations, is the most important goal in basic scientific research. So, let's start with the **Accounting** in our examination of the global water cycle.

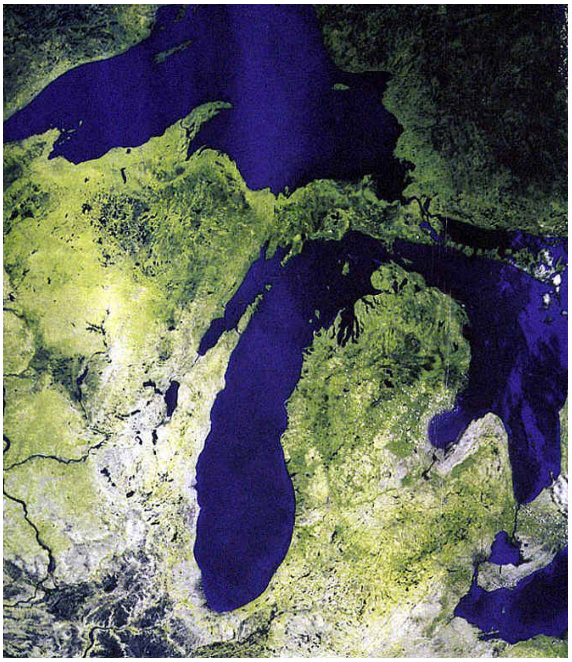


Figure 1. *The Laurentian Great Lakes.*

Accounting for Water

(distribution of water in $km^3 \times 10^6$)

Rocks (not usable)	**25,000**
Oceans (97.4% of usable water)	**1,350**
Ice	**27.5**
Groundwater	**8.2**
Lakes and Rivers	**0.025**
Atmosphere (vapor)	**0.013**

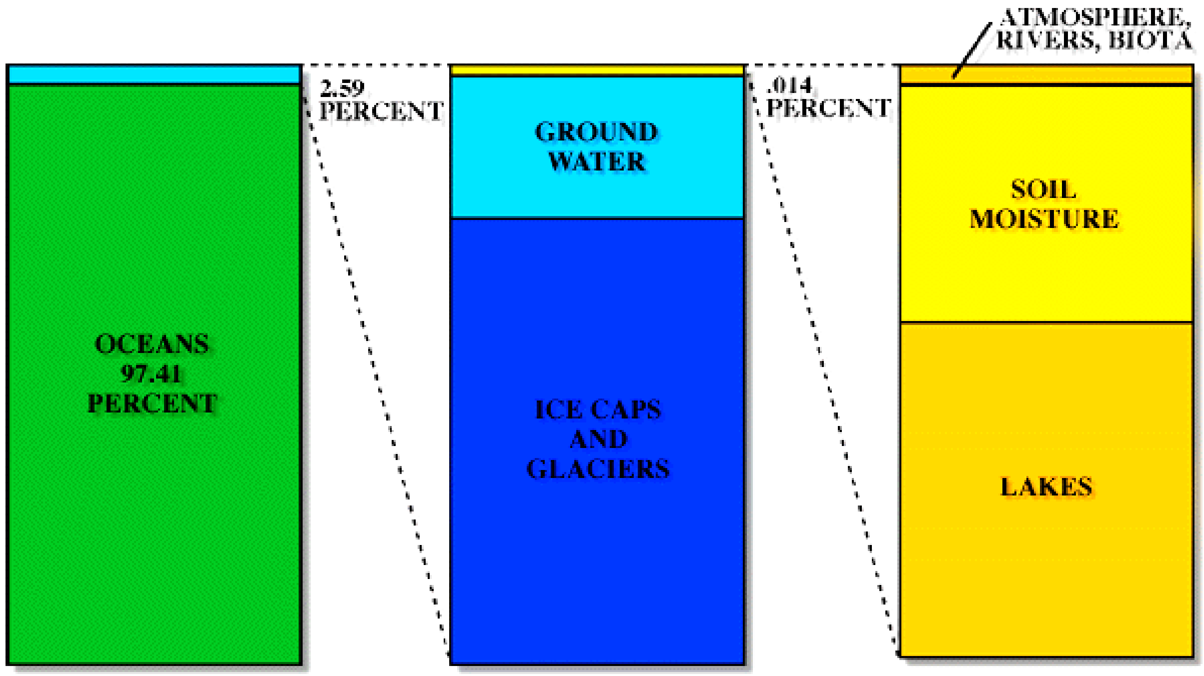


Figure 2. *The distribution of water at the earth's surface.*

As you can see from the Table and from *Figure 2*, most of the water on earth is tied-up in rocks and unavailable. Of the water that is at the surface of the earth and available for cycling, only a very small percentage is fresh water. Of that fresh water, about 20% is contained solely in the Laurentian Great Lakes in North America (*Figure 1*), and another 20% is contained in a single lake in Siberia, Lake Baikal.

Cycling

There are 4 major pathways of cycling in the global water cycle (*Figure 3*): *precipitation, evaporation, vapor transfer* from ocean to land, and *return flow* in rivers and groundwaters from land to oceans. The following gives the flux of these different pathways:

1. Total precipitation = 0.5 x 10^6 km^3 / year (~0.385 over oceans, 0.111 over land)
2. Evaporation from ocean = 0.425 x 10^6 km^3 / year
3. Ocean Residence Time, Rt = (1,350 10^6 km^3) / (0.425 10^6 km^3/yr)

   = 3,176 years

4. Atmospheric water residence time (As part of your learning about the water cycle, please take a moment to calculate the atmospheric water residence time.)

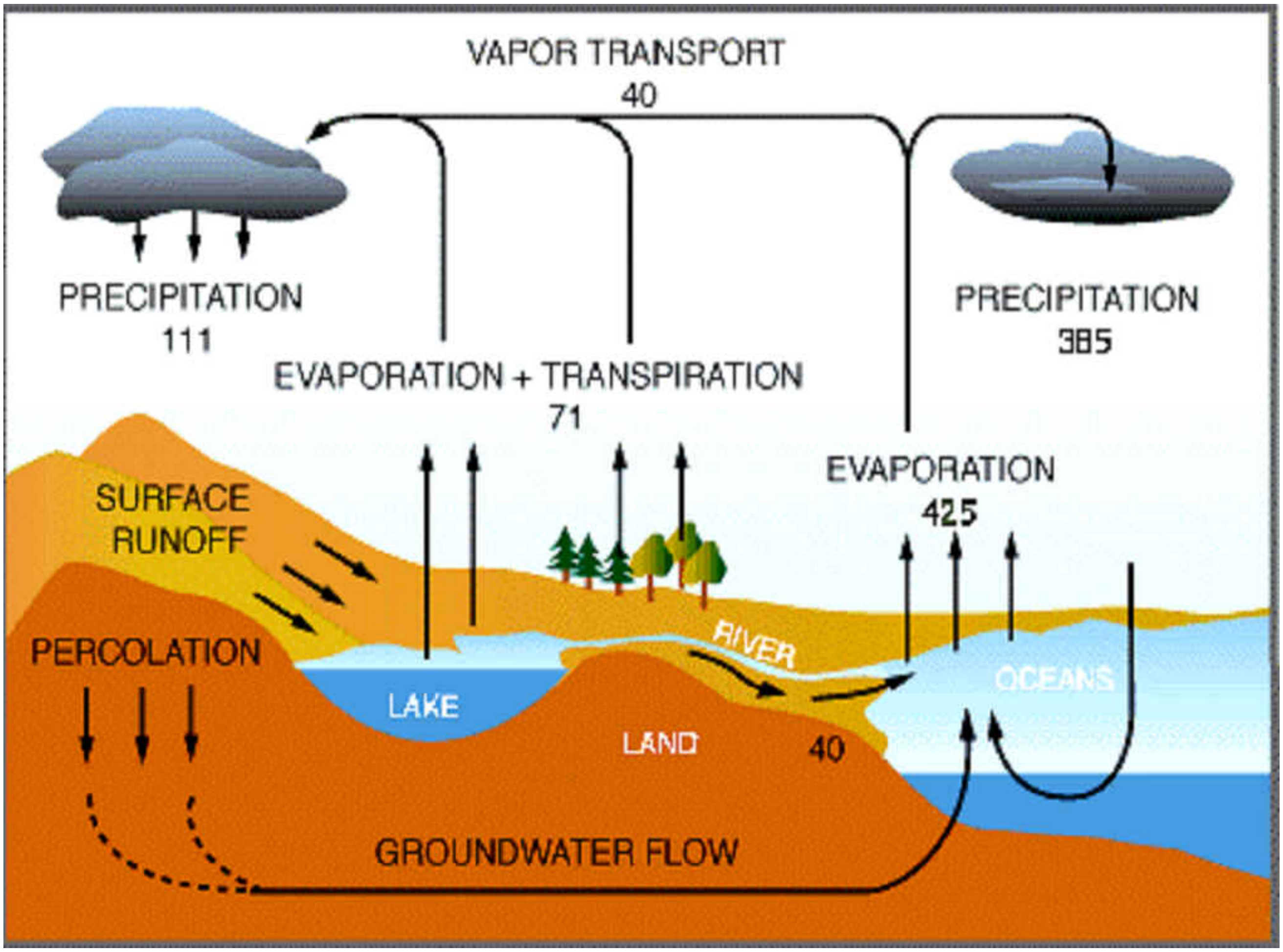


Figure 3. *The Global Water Cycle - Pathways and Fluxes. (Values in 10^3 km^3/yr).*

Controls

There are several major controls on the water cycle, including **human consumption**, **temperature increases**, and **land use changes**.

(A). <u>Human consumption</u>. The consumption of water by humans has increased dramatically since the industrial revolution, and today water is a critically lacking resource in certain areas such as deserts and semi-deserts. In addition to this local vulnerability, it is quite likely that water shortages due to human consumption will occur at the regional scale in the near future. For example, the southwestern United States (in all seriousness) has proposed to "buy" water from the Great Lakes states and build a pipeline from Lake Michigan -- so far Michigan, Wisconsin, and other nearby states and Canadian provinces have declined such offers.

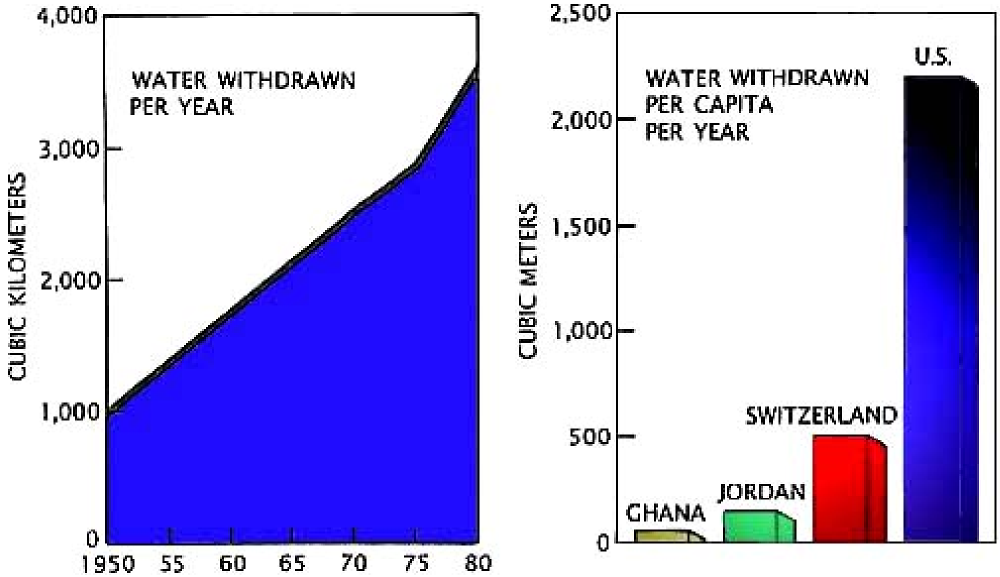


Figure 4. *Rates of water withdrawn from surface and groundwater sources, and consumption per individual for representative countries.*

(B). <u>Temperature</u>. The second major control on the cycling of water on earth is temperature. Increasing temperature increases the rates of evaporation and ice melting, and causes sea level to rise. Severe droughts, like in the Sahel in Africa, are caused by small changes in the geographical distribution of water that are in turn caused by changes in temperature. In *Figure 5* below there are some examples of the effect that increased global temperatures have had on glaciers in recent years.

1. **Glacier melting** in the French Alps and Alaska. The engraving on the upper left from 1848 shows a glacier filling much of the valley, while the photograph on the right from ~1965 shows the tremendous retreat of the glacier. This situation of recent retreat of ice sheets has occurred and is documented in many parts of the world. For example, in Alaska Exit Glacier (lower left) has retreated from where the photographer was standing to its current location within the last 100 years, and a coastal glacier (right) used to fill the entire valley to the sea.

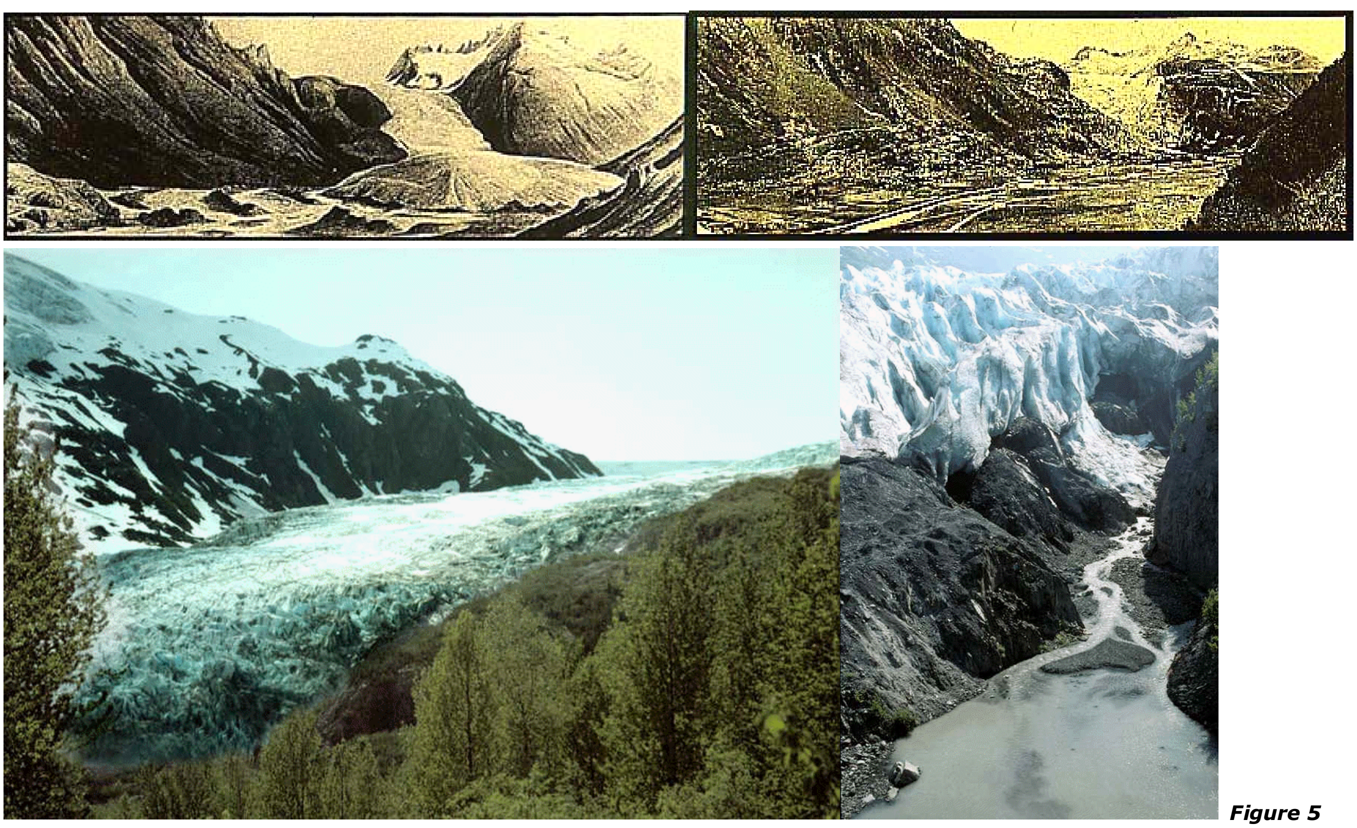
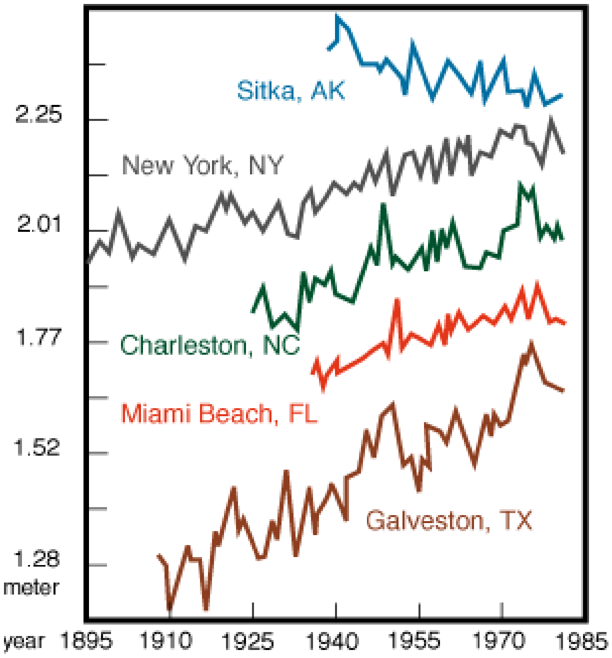


Figure 5

2. **Sea level rise.** Sea level has been rising in the world in recent years. *Figures 6 and 7* below show first how large these changes have been in various parts of the world, and second how much of this increase is due simply to the thermal expansion of water as temperature Increases. Figure 8 shows the effect of a rise of 4.7 m in sea level on Florida. Note that while 4.7 m may seem like a large increase, during the last glaciation sea level was a full 100 m lower than it is today; with that time perspective, a change of 4.7 m does not seem so large.



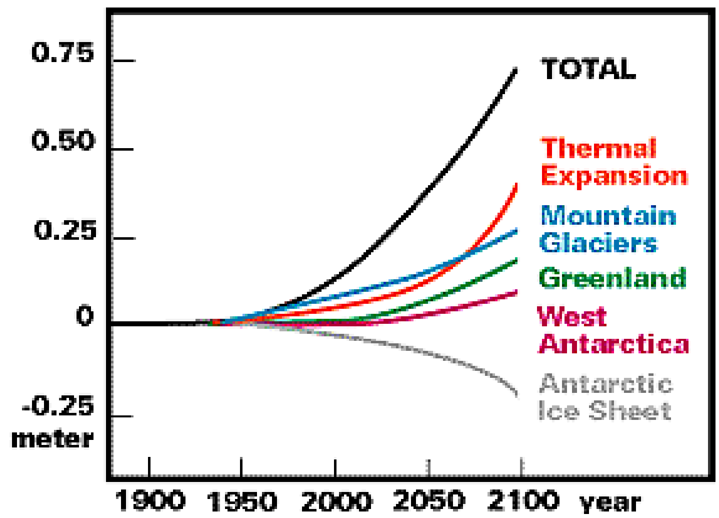
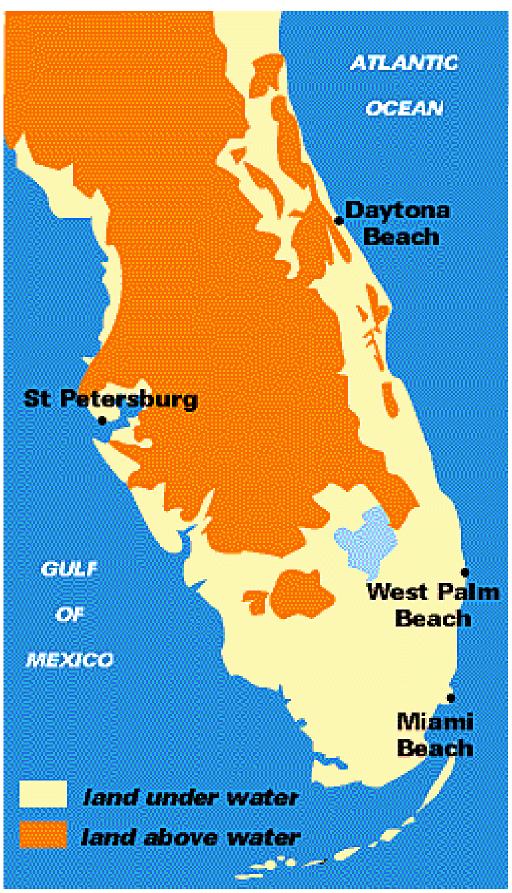
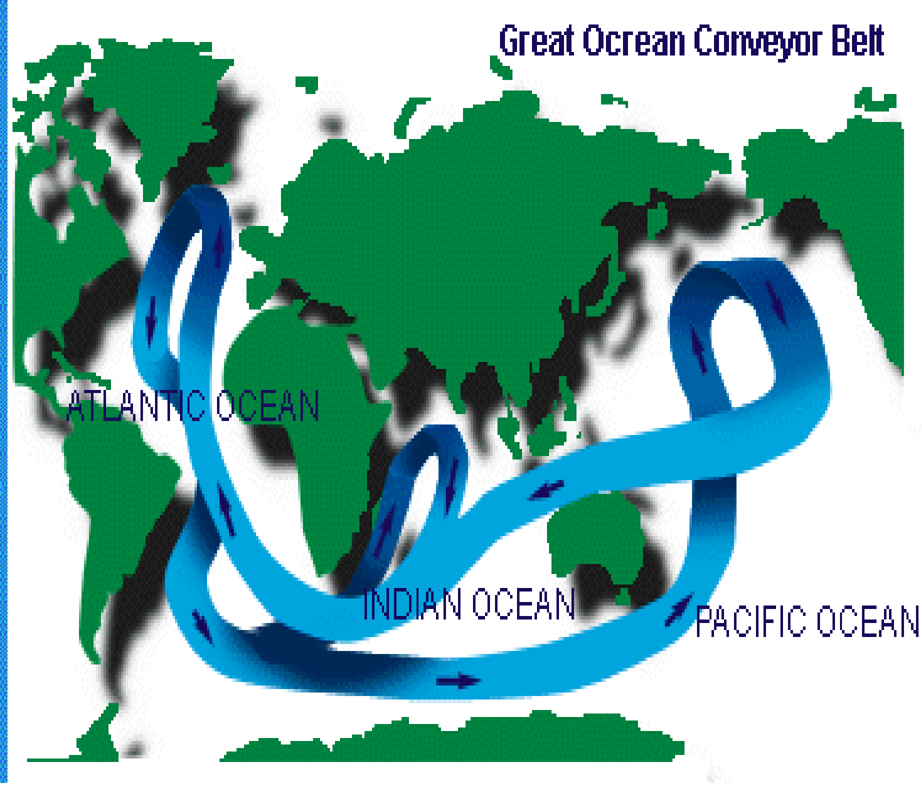


Figure 6 & 7 (above). *Sea level rise and impacts of temperature (above).*

Figure 8 & 9 (below). *Impact of sea level rise on low-lying areas of Florida (left). The conveyor belt circulation (right) of the ocean may be altered by increasing freshwater inputs to the Arctic ocean.*

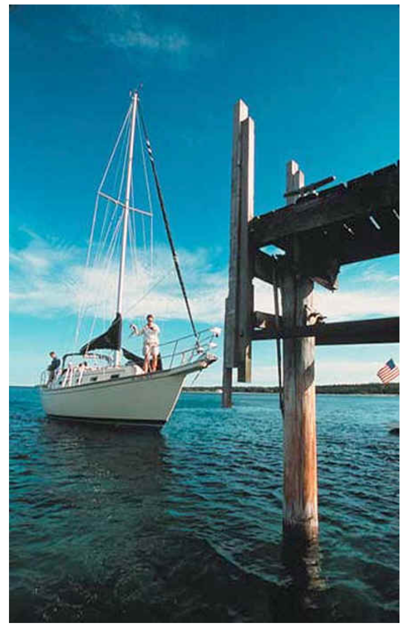




3. **River flows.** As more and more of the ice caps on land melt, there will be an increased river flow of

freshwater from land to the ocean, and especially to the Arctic ocean. This flow of water will place a less dense, freshwater "cap" on the surface water of the ocean, and could prevent sinking of cold, salty water ("deep water formation") that drives ocean currents (*Figure 9 above*; *see lectures on ocean circulation for review of this topic*).

4. **Interactions in the hydrological cycle.** One of the important aspects of the hydrological cycle is how temperature will interact with other factors. For example, in 2000 the lake levels in the Laurentian Great Lakes were extremely low, and these low levels had a great impact on shipping and recreation (see pictures below). However, that year the precipitation and temperature were about average, and initially it was unclear just why the lake levels were so low. Based on your knowledge of the main factors involved in the hydrological cycle, can you suggest what might have occurred to cause the lake levels to be so low? (This will be discussed in lecture).



(C). Land use changes. Currently most of the land use changes on earth, such as deforestation, are at a local scale. However, it may soon become important at regional scales and for the entire globe in the future. For example, in a study done at Hubbard Brook in New Hampshire, run-off increased by up to 400% after deforestation. Nutrient cycles are strongly linked to hydrologic cycle, and so nutrient export was also increased. These increases are only temporary, however, and the likely end result of such land use changes is that precipitation will be decreased (this will be discussed in more detail in the upcoming lecture on the Tropical Rainforest), and soils will become less fertile. This illustrates one of the key points about element cycles, which is that they are most often linked and it is difficult to study them in isolation. In this example, we found that the water cycle strongly controls the nutrient cycling due to the transport of nutrients in runoff. In the next section we will examine the nitrogen cycle specifically as an example of a global cycle of an important nutrient.

The Global Nitrogen Cycle

The cycling of nitrogen is different from the cycling of water in at least one important area, which is that the **"forms"** of nitrogen are more varied than the form of water, which is always H_2O and in either a liquid, gas, or solid form. The nitrogen cycle is complex then in part because of the many chemical forms of N such as: Organic-N; NO_3; NH_4; and the gases N_2, N_2O, NO + NO_2 (=NOx). *Figure 10* below gives an overview of the global nitrogen cycle.

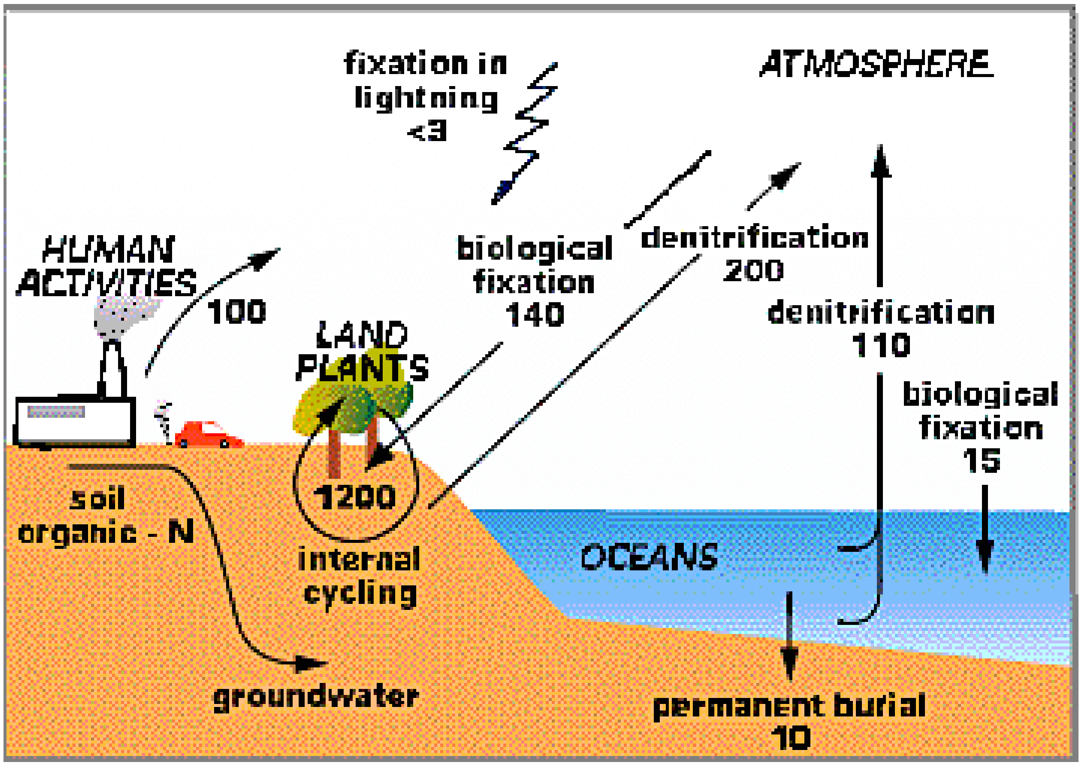


Figure 10. *The Global Nitrogen Cycle*

Accounting

Just as we did for the water cycle, or first step in understanding the nitrogen cycle is to examine the distribution of N on earth. The Table below gives the distribution of N in x10^{15} grams. Notice that the largest pool of available N is in the atmosphere.

Rocks and sediments	**190,400,120 (deep, unavailable)**
Atmosphere	**3,900,000**
Ocean	**23,348**
Soils	**460**
Land plants	**14**
land animals	**0.2**
In the Atmosphere:	
N_2	**3,900,000**
N_2O	**1.4**
NOx	**0.0006 (less than 1 billionth %)**

Cycling

The pathways and the reactions involved in the nitrogen cycle are also more complicated than in the water cycle due, again, to the fact that there are different chemical forms. The major pathways are shown in *Figure 10*, and these pathways can be linked to specific chemical reactions that are listed below and shown in *Figure 11*.

1. N_2 to organic-N; called **"N-fixation"** (plants and humans)
2. Organic-N to NH_4^+; **"mineralization"** (by bacteria and fungi)
3. NH_4^+ to NO_3^- , producing NO and N_2O; **"nitrification"** (by bacteria)
4. NO_3^- to N_2 , producing N_2O; **"denitrification"** (by bacteria)
5. NO_3^- & NH_4^+ to organic-N; **"photosynthesis"** (uptake by plants)

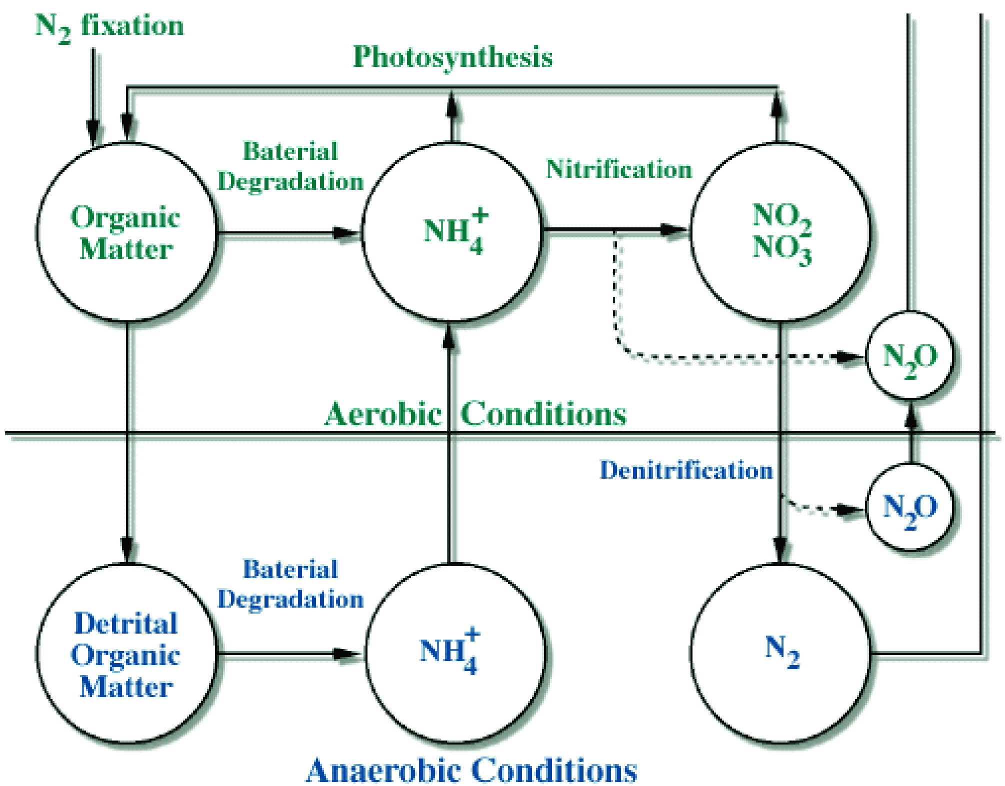


Figure 11. *The processes controlling the conversion of one form of nitrogen into another form. There are aerobic processes (with oxygen) at the top of the figure, and anaerobic processes (w/o oxygen) at the bottom of the figure. Notice that the chemical conversions begin with the fixation of N_2 gas from the atmosphere by N-fixation, and end with the return of N_2 gas to the atmosphere by denitrification.*

Nitrogen Fluxes (with respect to the atmosphere). Given the information above, we can calculate some of the fluxes of various nitrogen chemical species and their residence times in the atmosphere.

1. N_2 output from the atmosphere = 158 x 10^{12} g / year (N-fixation)

   * $\mathbf{R_T}$ of N_2 = 24.68 million years

2. NO_x output from atmosphere = 60 x 10^{12} g / year

* R_T of NO_x = 0.01 yr = 3.6 days

- **Note** that small pool sizes of an element often mean that the component is converted to something else quickly, or, that it is very "reactive". Large pool sizes are difficult to ***"disturb"***; an example is the pool of N_2 gas in the atmosphere.

Controls

There are very many "controls" on the overall nitrogen cycle, but in this lecture we will focus on the controls that are related directly to a major environmental problem on earth, which is acid rain. The general way in which acid rain is formed is given in *Figure 12* below.

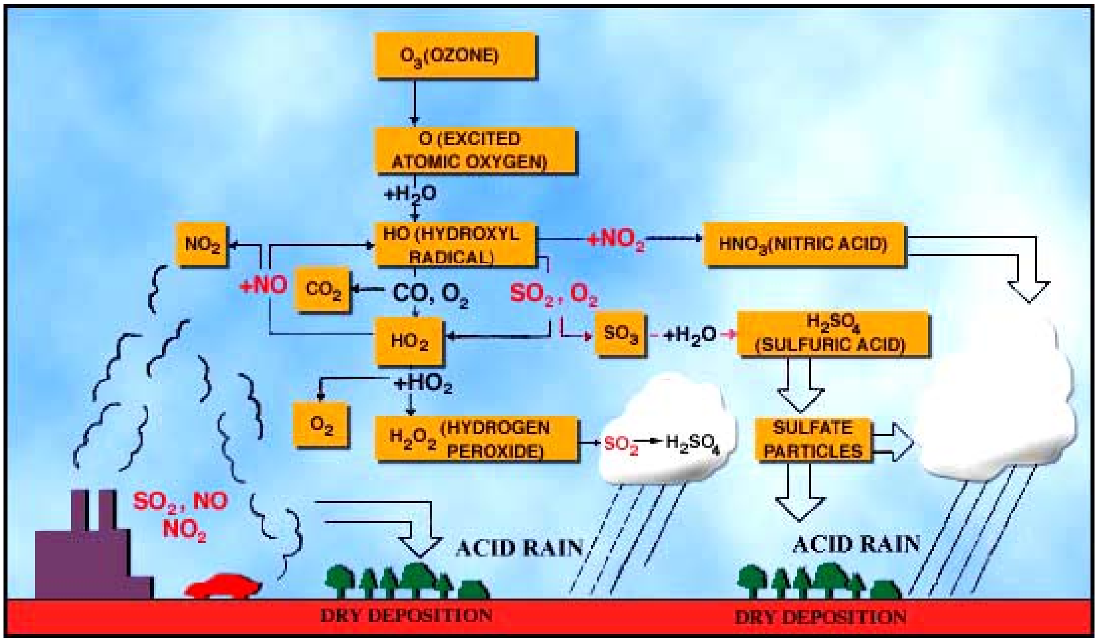


Figure 12. *Diagram of the pathways and reactions leading to the formation of acid rain in our atmosphere.*

- NO_x - produced by combustion of fossil fuels and by industry. Important in forming acid rain.

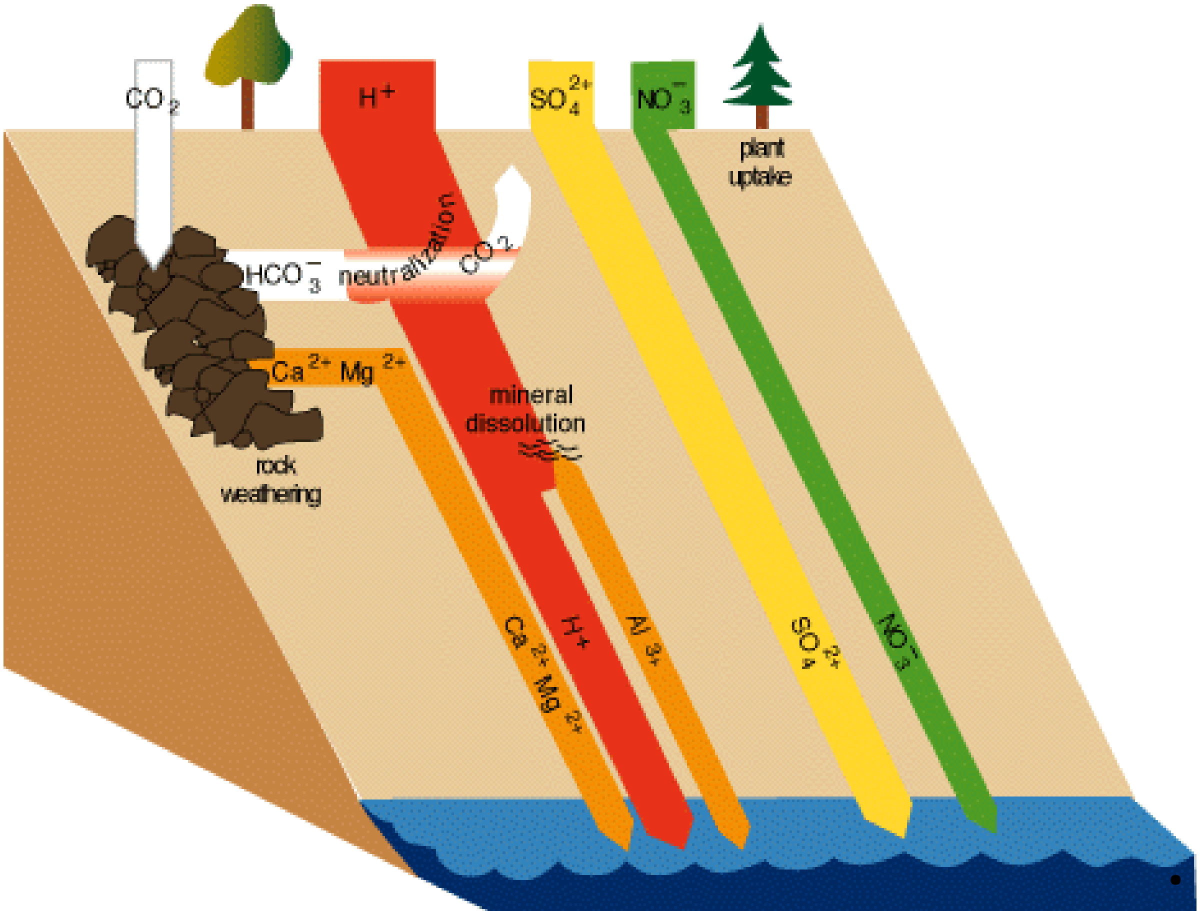
  1. $NO + O_3$ (ozone) = NO_2
  2. $NO_2 + OH = HNO_3$ = "nitric acid"
  3. In water, HNO_3 dissociates (breaks apart) to give H^+ and NO_3^- (note that the charges must balance, so there is one positive and one negative charged ion after the dissociation.)

- The Second important reaction involved with acid rain is the formation of sulfuric acid in the atmosphere.

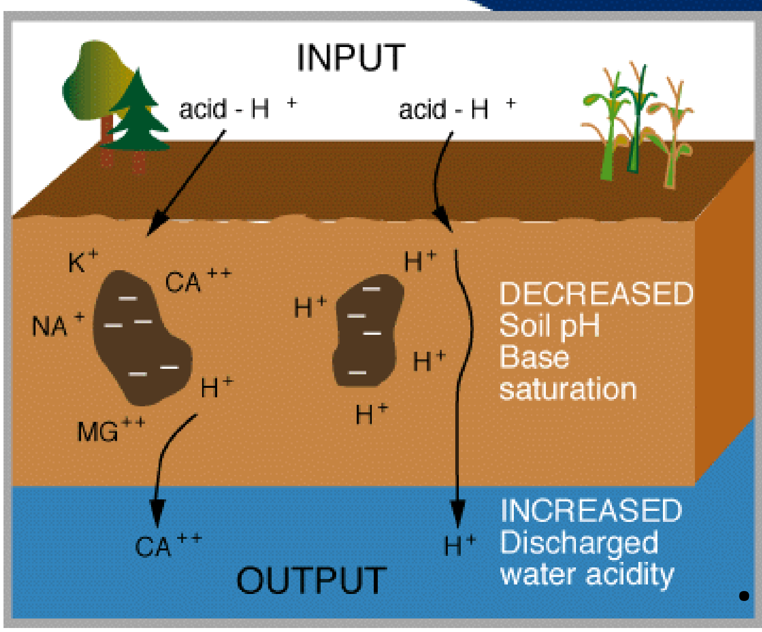
1. H_2SO_4 dissociates in water to give 2 H^+ and SO_4^{2-} .

Effects of acid rain

It is important to learn and understand that most biogeochemical questions must be solved by combining information about several element cycles. This is because most element cycles interact strongly with surrounding elements, and so for example to help solve the problems of acid rain we must first understand the controls on the elements that interact. The two Figures below (13 and 14), illustrate some of these interactions.



Figures 13 and 14 (left and below). *Chemical reactions of acid rain components in soils.*



The important aspects of these figures can be summarized as follows:

- The buffering capacity of soils is limited by the amount of **"base saturation"** in the soils. Base saturation reflects the amount of base cations such as calcium and magnesium (positively charged) that are found attached to mineral grains in the soils. The higher the base saturation the more **buffering capacity** the soil has to adsorb H^+ ions. H+ is neutralized by weathering reactions in the soil and in plants. H^+ is a small ion that is very reactive, and it displaces other positively charged elements such as base cations on the clays that form mineral grains in the soil. Thus the acid is neutralized in the soil, and the base cations that were exchanged are washed out of the soil and into streams and lakes. *Figure 15* below shows how the base saturation has changed in soils since industrial times.
- What effects does acid rain have?
    - Plants, trees, and buildings can be damaged.
    - As pH drops, aquatic life is negatively affected.

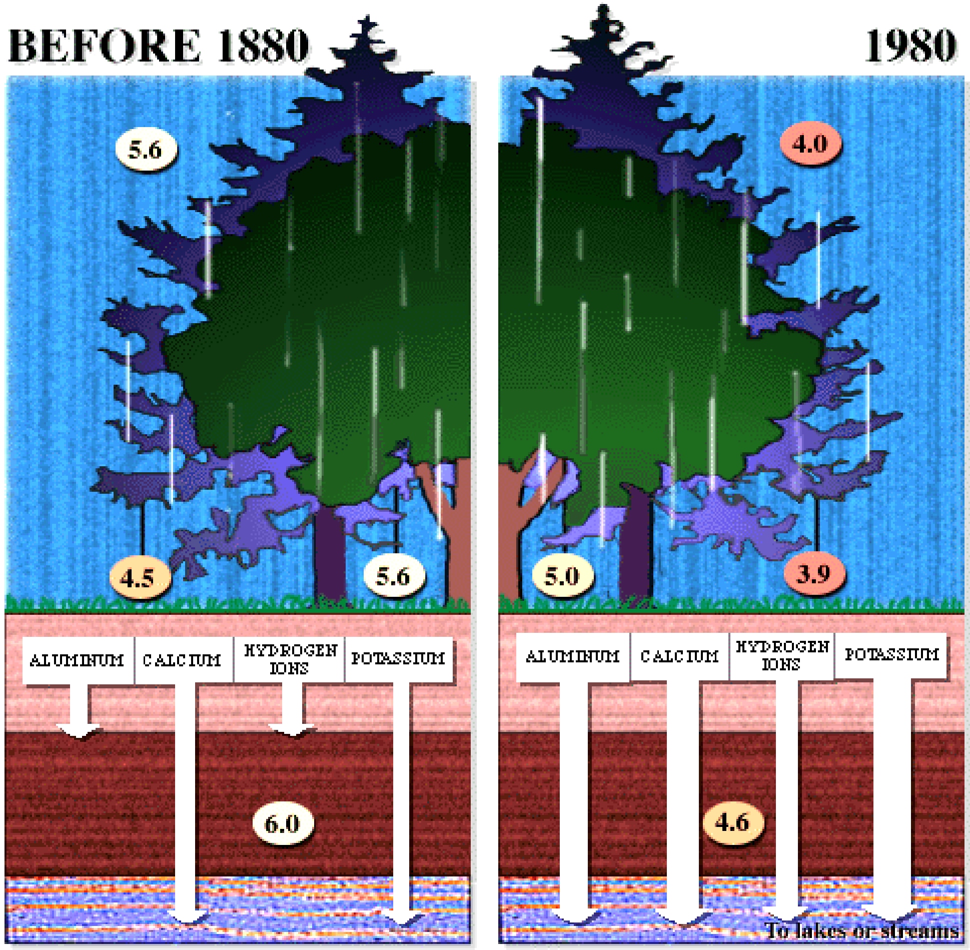


Figure 15. *Diagram of the situation in a typical forest before acid rain (~1880) and after acid rain has become important. Note that on the right panel the soils are now releasing aluminum and hydrogen ions, and the pH of the exported water is very acid (pH = 4.6).*

By measuring the buffering capacity of soils, you can determine regions of sensitivity to acid rain, as is shown below in the map of the United States.

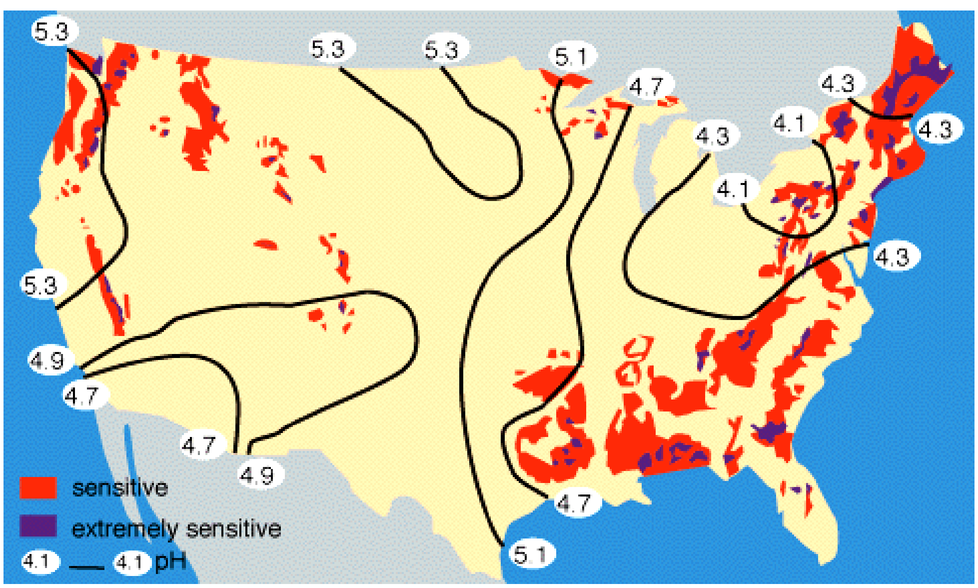


Figure 16. *Regions of sensitivity to acid rain in the United States. Also shown are the isopleths of the pH of precipitation; for example, all of the eastern U.S. currently has an average pH of rainfall between 4-5, where "neutral" rainwater has a pH of ~6.*

Summary

- The cycling of elements is a major aspect of how ecosystems function. Most of our major environmental problems of today involve perturbations of critical element cycles such as water, nitrogen, or carbon.
- The hydrological cycle is influenced or controlled by temperature, land-use changes, and human consumption.
- Acid Rain is an important consequence of the nitrogen and sulfur cycles. Acid rain is produced by the interactions of other elements in the atmosphere, and the impacts of acid rain are controlled by many other element cycles on land and in the water.
- The main take-home message for today's lecture is:

"ELEMENT CYCLES INTERACT" and they cannot be studied in isolation.

Review and Self Test

- Review of main terms and concepts in this lecture.
- Self-Test for this lecture.