Curriculum Units by Fellows of the Yale-New Haven Teachers Institute
2010 Volume III: Geomicrobiology: How Microbes Shape Our Planet

Microbial Influence on Earth's Systems

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by Charlene Woodland

Introduction

> "When we try to pick out anything by itself,
> we find it hitched to everything else in the Universe." [1]

Earth is virtually a closed system; with little matter being added from meteorites that survive their passage through the mesosphere. Given this fact, the matter that does exist on Earth must perpetually cycle. The general view of cycling on Earth, is of inorganic substances moving. We often refer to the rock cycle and the water cycle, with both examples devoid of biological intervention. Every level of all matter cycling involves interaction with the biotic world, however unseen. Microbes may not be large enough to see with the unaided eye, but they are there assisting in every aspect of the dynamic Earth. This unit will cover the basics of biogeochemical cycling, its importance, an explanation of microbes and their influence on nutrient cycling, followed by a more detailed description of the most referenced cycles; the carbon, nitrogen, phosphorus, and sulfur cycles.

Earth's Origin

Earth: The third planet from the Sun. Its blue and green hues verified by Apollo 17 when they landed on the moon in 1972. It is the only "known" planet to contain life, as we know it. This oblate spheroid with its varying layers of solid and molten rock spins about its axis approximately 1000 miles per hour, while orbiting the Sun at about 67,000 miles per hour [2]. Earth is overwhelmed with life, from the microscopic bacillus to the gigantic blue whale. But how? But why? What makes this planet so unique, different from the other eight in our solar system? In order to understand how Earth became the habitable planet that it is today, we have to go back.

Way, way back to the beginning of the story, to the conception of Earth.

In the far reaches of space existed a single condensed point of matter. About fourteen billion years ago this point of matter exploded shooting protons, electrons, neutrons, positrons, neutrinos, and photons everywhere. As this superheated mass began to cool the subatomic particles began to join one another forming neutral atoms [3] . These neutral atoms continued to coalesce to eventually form the Sun and the planets. About 4.5 billion years ago, as Earth was finalizing its accretion, a Mars-sized body collided with it. The intense heat from the impact transformed Earth into a molten body of rock. The pieces that dislodged from Earth and what remained of the body, combined to form the Moon [4] . As the Earth continued to form, the heavier elements sank and the lighter elements rose into the atmosphere. The lightest of all, hydrogen escaped into space, leaving behind an atmosphere abundant in carbon dioxide, sulfur dioxide, methane, ammonia, and water vapor. Earth's early atmosphere contained very little oxygen [4] . With all the pieces in place the planet now had everything it would need for the evolution of life to proceed.

Origin of Life

There are many theories of how life began on Earth. The "primordial soup" theory suggests that from Earth's inorganic molecules amino acids were formed. These amino acids gave way to more complex organic molecules which evolved. The "panspermia hypothesis" holds that life on Earth was seeded by molecules that arrived on Earth via meteorites. The chemoautotrophic hypothesis suggests that life began in the depths of the oceans at hydrothermal vents where hydrogen sulfide was the energy source. Whichever hypothesis is correct, one thing is certain; the oldest fossils found are the remains of microbes [5] .

The oldest fossils on Earth are around 3.8 billion years old. They are in the form of stromatolites, which are dome shaped rock structures. Through exhaustive research, scientists found evidence of the microorganism cyanobacteria, also known as blue-green algae. Cyanobacteria are self-feeding organisms that use inorganic molecules, such as carbon dioxide and light, in the metabolic process of photosynthesis. This discovery has helped to understand the transformation of Earth's carbon dioxide rich atmosphere into one with enough oxygen to support other life forms [6] .

So What Are Microorganisms Anyway?

A microbe or microorganism is any organism that is too small to be seen with the unaided eye. Single celled organisms like bacteria, fungi, protozoa, algae, and viruses are all examples of microbes [7] . Although their stature is small their numbers are immense . There is an average of 1 billion bacteria in a liter of ocean water [8] . Consequently, microbes make up most of Earth's biomass. Not much thought is given to these tiny creatures because of their small size. Scientists weren't even aware of their existence until Antoine van Leeuwenhoek developed a crude magnifying instrument which allowed him to see microbes in water and scrapings from his mouth [9] . Today, microscopes have developed greatly and although most microbes can be seen under one hundred times magnification the details are still obscure. Scientists employ the scanning electron microscope (SEM) and the transmission electron microscope (TEM), which both shoot high energy beams of electrons onto the specimen to get a better look [9].

Microbes are living organism if all prerequisites are met [7]. The biological definition of life includes five requirements. The first requirement is that the organism has a metabolism. Through its open system it can interact with its environment and take in chemicals and reorganize and rearrange them for biological function and eliminate the waste. The second is that the organism can grow or reproduce. The third is differentiation, through which the organism can produce new cell structures. The fourth is communication. The organism must have the ability to communicate and locate other like organisms. The communication is not restricted to audible signals, it can be chemical signals. The last requirement is evolution. The organism must be able to change characteristics and pass these down to their offspring. By this definition, the prokaryotes, Bacteria and Archaea are living organisms [7].

All life can be divided into three domains: The Bacteria, the Archaea and the Eukarya. Current scientific theory suggests that these three groups of life forms share a common ancestor, for now called the universal ancestor. As they diverged into their separate groups the Bacteria and Archaea, the prokaryotes, maintained their single-celled morphology, whereas the eukaryotes, aside from the protozoa, evolved into the multicelluar organisms we know today as plants, fungi, and animals [7].

Eubacteria and Archaea are very similar. Within both domains, single-cell structures include a cell wall, cell membrane, cytoplasm, chromosomes, ribosomes, plasmids, granules, capsules, and flagella. Both domains can thrive under aerobic and anaerobic conditions. Both can be found in all habitats on Earth, however the Archaea tend to occupy the extreme environments like hydrothermal vents [7].

Unlike the kingdoms Animalia and Plantae, both kingdoms of prokaryotes, the Eubacteria and the Archaea are classified by their metabolism. Microbes transform the molecules in their environment into chemicals that make up the cell, increasing its mass. This process is energy intensive and the cells must be able to obtain energy to forward the process. Some of these organisms obtain their energy from light like plants and the rest obtain energy by oxidizing chemical compounds. Microbes break down chemical compounds and release energy in a process called catabolism [10].

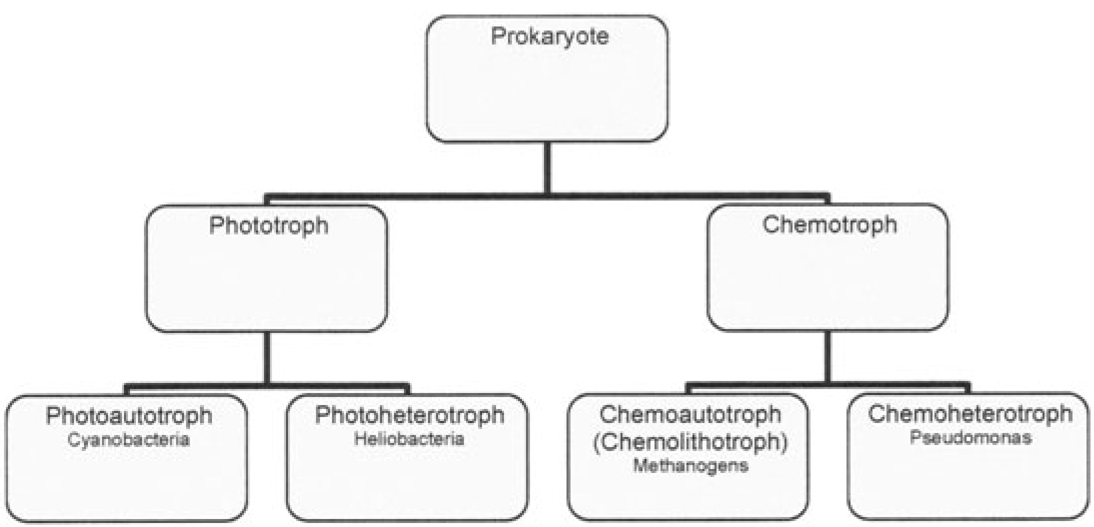

Figure 1.

All the names given the energy obtaining processes end in the suffix troph, from Greek, meaning feed. The organism's energy source is the starting point for its classification. An organism can obtain its energy from either a light source (phototroph) or a chemical source (chemotroph). From there the organisms are then divided into self-feeders (autotrophs) or heterotrophs (other-feeders) [10]. (See Figure 1.)

What are Biogeochemical Cycles?

The name in itself evokes a bit of confusion, but simply put "bio" represents the biological aspect, "geo" represents the geological aspect, and "chemical" represents the chemical reactions that occur [11]. These three aspects or factors work together to cycle matter.

A biogeochemical cycle is the pathway a nutrient takes throughout Earth's systems. These systems may include the biosphere, atmosphere, hydrosphere, and the lithosphere (geosphere). Nutrients move from one reservoir (pool) to the next, and then the next. This continuous cycle has no real beginning or end. The movement of a nutrient from one reservoir to the next is called flux. Flux is carried out over different time intervals and is termed the flux rate. Nutrients spend varying amounts of time in different reservoirs. The amount of time a nutrient spends in a given reservoir is its residence time (rt). For instance, carbon may reside in the lithosphere for millions of years, but spend less than 5 years in the atmosphere. A reservoir that receives more of a nutrient than it releases, is called a sink. A reservoir that releases more of a nutrient than it receives is called a source [5].

Why are Biogeochemical Cycles Important?

According to the law of conservation of mass, the mass of a closed system will remain constant over time. In other words; mass can neither be created nor destroyed, it can only be rearranged in space. Also, the First Law of Thermodynamics states that energy can neither be created nor destroyed only transformed from one form to another. With Earth being virtually a closed system, all mass and energy on Earth must rearrange itself. This is done by cycling through the various spheres.

The cycling of nutrients is more than just an explanation for where mass comes from and where it goes, it is the conduit by which all life on Earth receives its nutrition. As the nutrients cycle through the various reservoirs they change from inorganic to organic molecules, due to redox reactions, making them useful to living organisms [12].

Biogeochemical Cycles

It is important to note that although the following cycles are explained individually they all work together.

Carbon Cycle

Carbon is sixth element on the periodic table. In its pure form, carbon can be found in nature as diamonds, graphite, and coal, depending on its crystalline structure which is dependent on its cooling rate. Carbon is the basis for all organic life and is found in tissues, bones, carbohydrates, lipids, and proteins [5].

Carbon exists in all spheres; the atmosphere, the lithosphere, the hydrosphere, and the biosphere. Carbon has its longest residence time in the lithosphere, so the rocks would be considered a primary sink for carbon. Second to the lithosphere, carbon has a long residence time in the oceans, its second largest sink [13].

Carbon in its inorganic form, carbon dioxide (CO_2), exists in the atmosphere. Although it is less than a tenth of a percent of total atmospheric gases, it is a primary greenhouse gas and even small increases in its amounts cause a positive feedback, increasing the warming potential of the atmosphere [14].

Most carbon dioxide is removed from the atmosphere by photoautotrophic organisms, such as marine organisms like Prochlorococcus [15], a type of cyanobacteria, and higher order plants, for photosynthesis. During photosynthesis, phototrophs that are also autotrophs and able to make their own biomass from CO_2, they combine six carbon dioxide molecules and 6 water molecules, in the presence of light, to form one carbohydrate and six oxygen molecules ($6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$). The carbohydrate that is produced is used by other organisms higher on the food chain, to make ATP, the energy used by living organisms. From this point, the carbon cycle can go one of two ways, either the plant is consumed by a primary consumer or it dies [16].

When a plant is consumed by a primary consumer, the carbohydrates are used as fuel for that organism. One process by which an organism uses this energy is aerobic respiration. The chemical reaction involves one carbohydrate and six oxygen molecules to produce six carbon dioxide molecules, six water molecules and energy ($C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 38ATP$). It is just the opposite of photosynthesis [17]. The energy obtained is used to build tissue and do work. From here the cycle can repeat itself, from a primary consumer to a secondary consumer, then to a tertiary consumer, and then to decomposition.

Decomposition begins once an organism has died. The remaining biomass is degraded through anaerobic, aerobic, and fermentation processes initiated by various microorganisms. This process is carried out by the microorganisms oxidizing organic carbon to create carbon dioxide and methane. Methane is also produced by microorganisms that reduce CO_2 using hydrogen. Carbon dioxide and methane are then released into the environment. Some of this is stored in the lithosphere and the rest released into the atmosphere as CO_2 [13].

Microorganisms complete the cycle. Without them the carbon stored in the biomass that winds up in the various reservoirs would stay there and the CO_2 in the atmosphere would eventually be depleted, halting photosynthesis and eventually all organisms that depend on energy from the Sun and photosynthetic primary producers would die. However, it is important to note that there exist many organisms that live beneath the surface and receive their energy from chemicals like sulfur from hydrothermal vents that would carry on.

Nitrogen Cycle

Nitrogen is the seventh element on the periodic table. It exists in its elemental state in the atmosphere in the form of N_2 gas, dinitrogen. Nitrogen is an essential part of DNA and RNA and therefore needed by all living organisms. Approximately 78 percent of the atmosphere is nitrogen and although organisms breathe in this gas they cannot use it in this form. It must be fixed into NH_4^+, NO_3^{--}, and organic nitrogen. Microorganisms are responsible for the majority of biological fixation of nitrogen [5]. Two organisms capable of fixing nitrogen are cyanobacteria and Trichodesmium. Nitrogen can also be fixed by lightening, by a few plants living in symbiotic relationships with microbes [18], and synthetically by humans.

The first step in making nitrogen available for biological use is nitrogen fixation. Nitrogen fixation occurs when hydrogen is added to nitrogen to form NH_3, ammonia. This process is accomplished by a small fraction of bacteria that complete the process in both aerobic (Azotobacter) and anaerobic (Clostridium) environments . These bacteria live in both terrestrial (in symbiosis with plants) and aquatic environments . In the soil, bacteria can fix nitrogen on their own, yielding small amounts of NH_3, or in conjunction with plant roots, yielding much larger amounts of NH_3. Nitrogen fixation is an energy intensive activity, so the bacteria that work with the plants make a better living. Rhizobium is one such group of bacteria that exists in a mutualistic relationship with legumes such as soybeans [13].

Once in the form of ammonia plants can use the nitrogen. Once the plant dies the bacteria then convert NH_3 into ammonium, NH_4^+, through a process called ammonia assimilation. The ammonium made is also available for plant use. Some of it is oxidized to nitrate, NO_3^{--}, through a process called nitrification [13].

The next step in the process is to reduce the nitrate back into N_2, dinitrogen. This process is called denitrification [13].

If the cycle just included plants, it would be complete, but many other organisms require nitrogen for life. Consumers, receive their nitrogen from eating microbial producers and plants. The nitrogen is either expelled through waste processes or returned to the soil to decompose. At this point the denitrification would begin [5].

Phosphorus Cycle

Phosphorus, the fifteenth element is another vital part of biological systems. Phosphorus is used in the formation of DNA, RNA, ADP, and ATP and occurs primarily as phosphate (PO_4^{3--}). Unlike the other elements phosphorus does not cycle through the atmosphere; however trace particles can be found in the air [5]. The primary sink for phosphorus is the lithosphere in the mineral apatite ($Ca_5(PO_4)_3OH$). Apatite is the mineral found in our bones and teeth [19].

The phosphorus that is trapped in the rocks can only be released (naturally) through weathering. Since weathering is a slow process, the amount of phosphorus available to plants is limited. Primary, secondary, and tertiary consumers, receive their phosphorus through the consumption of plants and lower level consumers. Either through waste or death and decay of an organism, organic phosphorus in biomass is returned to the soil where bacteria can turn it back into inorganic phosphorus [5].

Sulfur Cycle

Sulfur is the sixteenth element. It plays a vital role in the proper functioning of some amino acids, hormones, vitamins, and coenzymes. Sulfur cycles through all spheres. It's largest sinks are the lithosphere and the oceans, respectively [13].

Sulfur in the form of sulfur dioxide (SO_2) and hydrogen sulfide (H_2S) is released into the atmosphere by both natural and anthropogenic processes. Naturally, SO_2 and H_2S are released into the atmosphere through volcanic eruptions and bacterial activity. Humans emit these compounds through the combustion of fossil fuels. These compounds are released from the atmosphere by rain, where they then fall to the land or the oceans. In the oceans H_2S dissolves, bonds with iron and is precipitated out as pyrite (FeS_2). The $SO_{2,}$ dissolves, bonds with calcium and is precipitated out as gypsum ($CaSO_4$). On land these compounds find their way into the soil. Plants and microorganisms are able to use inorganic sulfur in the form of sulfate and reduce it internally in a process called assimilatory sulfate reduction. While inside the cell the sulfate is reduced to sulfite and then sulfide. The sulfide is then used to form the amino acid cysteine. The sulfur is eventually released from its organic form by another amino acid in a process called sulfur mineralization . With the help of microbes sulfur eventually winds up back in the rock as metal compounds or in the atmosphere as gaseous compounds where the cycle begins again [13].

In oxygenated environments, a group of chemolithoautotrophic bacteria, like Acidithiobacillus (this is the classic acid mine drainage microbe that oxidizes sulfur (and Fe^{2+}) in pyrite at low pH) and Sulfobacillus oxidizes sulfide to sulfate (SO_4^{2--}) at low . They use the energy produced by oxidizing sulfur to fix CO_2. In environments devoid of oxygen, but rich in light, photoautotrophic bacteria, like Chlorobium and Chromatium, more commonly known as green and purple sulfur bacteria respectively, are able to oxidize H_2S to SO_4^{2--}. Their environments include mud and shallow water. In these oxygen poor environments these microbes are able to use light and sulfur to fix carbon. They can be identified by their green or purplish color. Environments that contain these microbes, like marshes, are easy to identify by their black sediment and pungent rotten egg smell [13].

Conclusion

Microbes influence every aspect of the environment. They are involved in every biogeochemical cycle including the water cycle [20]. Studying the biogeochemical cycles from this vantage point gives students a much more comprehensive view of these processes.

At the closing of the unit an assessment that includes an essay section summarizing the cycles and a practical that has students identify various microbes at different microscope stations could be used. After assessing students on the above cycles, the natural segue would be into food webs and ecosystems. Covering the cycles first will fill in the gaps that traditional coverage of these topics generally have.

The following activities have been designed to reinforce the content and give students a first hand look at microbes in action. The first activity, Microbial Life in a Water Drop, is designed to make students aware of the lifeforms that they cannot readily see and often ignore. The second activity, Photosynthesis, gives them visual proof that microorganisms do in fact perform photosynthesis and helps them to grasp how these tiny organisms actually changed Earth's early atmosphere. The third activity, Nitrogen Fixing Bacteria, allows students to see how microbes live in a mutualistic relationship with plants to fix nitrogen. The fourth activity, Phosphate as a Limiting Factor, is designed to show students how phosphorus encourages algal growth and is a leads to eutrophication.

The equipment used in the following labs is basic lab equipment and should be available in any high school laboratory. The biological supplies can be obtained from a science supply company such as Carolina Biological Supply Company. Other supplies such as soil and dish detergent can be obtained at most local department stores.

This type of study also lends itself to outdoor explorations. Field trips to a marsh or beach can be incorporated to allow students to see bacterial activity in action. Having students collect the pond water for the first activity helps to solidify the knowledge that these organisms really come from the environment and that they were not just produced for the laboratory investigation.

Classroom Activities

Activity 1: Microbial Life in a Water Drop

In this activity students will view the microbial life in three water samples: pond/river, ocean and tap water. They will examine each slide carefully and tally up the organisms found. They will then compare and contrast the samples and formulate an explanation.

Time Needed

90 minutes for lab

Additional time for conclusion

Objectives

Identify the microbes in each sample of water.

Compare and contrast the microbial life in each sample.

Analyze results.

Discuss findings in writing.

Materials (per group of two)

Microscope

Two sets of gloves

Test tube rack

One test tube of each water type

One pipette for each sample

Three slides

Three coverslips

Procedure

1. Make a slide of each sample.
2. Place the sample under the microscope and scan the whole sample beginning with the lowest magnification.
3. Identify the five different organisms: amoeba, paramecium, diatom, cyanobacteria and algae.
4. Describe each organism, its look, shape, movement, etc…
5. Create one data table for all tallies.
6. Record how many of each organism is found.
7. Do the same for each sample.
8. Using the data table write a summary of research findings.

Activity 2: Photosynthesis

In this experiment students will be able to detect the presence of photosynthesis and respiration as represented by a change in pH. (Adapted from Flinn Scientific, BioFax, Respiration versus Photosynthesis [2] [1])

Time Needed

30 minutes for the initial setup

10 minutes a day for the next four days

Additional time for conclusion

Objectives

Determine the presence or lack of photosynthesis.

Determine the presence or lack of respiration.

Analyze results.

Discuss findings in writing.

Materials (per group of two to four)

Two small jars (baby food jars are the perfect size)

Elodea

Snail

Spring or filtered water (let sit a few days prior to experiment)

Bromthymol blue (BTB) indicator solution, 0.04% aqueous

Pipette (1 mL)

Pre Lab

Demonstrate for students how the BTB indicates pH by using two jars with BTB solution that mimic the experiment, and add a dilute acid to one and dilute base to the other.

Procedure

1. Each group of students will obtain and label two 4 ounce jars and label them #1 and #2. Using a graduated cylinder, students will measure 95 mL of water and pour into each jar.
2. Add 3 mL of BTB to each jar. The color of the water should be greenish.
3. Add 1 sprig of elodea to jar #1.
4. Add 1 snail to jar #2.
5. Create a data table.
6. Record the initial color of each jar.
7. Set both jars in indirect light for one day.
8. On the second day record the color.
9. Then place both jars in a dark area for one day.
10. On the third day record the color.
11. Then place a snail in jar #1 with the elodea and elodea in jar #2 with the snail. Leave both jars in indirect light for one day.
12. On the forth day record the color.
13. Then place jar #1 in a dark place while leaving jar #2 in indirect light, for one day.
14. On the fifth day record the color.
15. Analyze results and discuss findings in writing.

Discussion

Bromthymol Blue is a pH indicator. When the pH is high the BTB turns blue. When the pH is low the BTB turns yellow. The more dissolved CO_2 in the water the more acidic the water hence a yellow color. The less CO_2 in the water the more basic the water hence a blue color. Photosynthesis, ($6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$), takes CO_2 out of the water, whereas respiration ($C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 38ATP$), puts CO_2 into the water. Students should be able to infer based on pH levels which metabolic activity is occurring and/or dominant. The following table gives the intended results.

Presence of Light	Sample	BTB Color
Light	Elodea	Blue
	Snail	Yellow
	Both	Bluish-green
Dark	Elodea	Yellow
	Snail	Yellow
	Both	Yellow

Disposal

The organisms in this experiment cannot be released into the local environment. Please follow the MSDS for proper disposal of the BTB.

Activity 3: Nitrogen Fixing Bacteria

The purpose of this activity is to demonstrate the symbiotic relationship between bacteria and legumes. (Adapted from Bacteria Symbiosis and Nitrogen Fixation, The College of Agriculture and Environmental Sciences, University of Georgia. [22])

Time Needed

30 minutes for the initial setup

10 minutes a day for seven days

Additional time for conclusion

Objectives

Evaluate the role of microorganisms in agriculture.

Determine whether commercial nitrogen or bacterial nitrogen works better.

Analyze results and communicate in writing.

Materials (per group of 2-4)

4 three inch pots (or larger)

Plastic wrap

Soil (pre-moistened)

Alfalfa seeds (not inoculated)

Nitrogen rich fertilizer

Rhizobium leguminosarum

Water

Ruler

Gloves

Procedure

1. Label containers, #1, #2, #3, and #4.
2. Fill each container three quarters of the way with soil.
3. Place four alfalfa seeds into each container.
4. Container #1 is the control, cover seeds with soil only.
5. Container #2, place seeds, cover with soil and add commercial fertilizer.
6. Container #3, place seeds, bacteria over seeds, cover with soil.
7. Container #4, place seed, bacteria over seeds, cover with soil, and add commercial fertilizer.
8. Put a little water in all containers and cover with plastic wrap.
9. When the plants become visible, remove the plastic wrap.
10. Thin out the plants by leaving the strongest two and pulling out the others.
11. The plant height should be measured everyday for 7 seven days and recorded.
12. One plant should be removed and the presence of nodules should be identified and viewed under the microscope. Record all observations.
13. Graph the data, analyze, and summarize findings in writing.

Discussion

Pay careful attention not to transfer the bacteria into the other two trial systems. Separate trials by keeping all like systems together.

The purpose of trial #4 is to test the response of the bacteria to the presence of nitrogen. Will the bacteria flourish in the presence of nitrogen? Or will they abstain from forming a relationship with the plant roots because nitrogen already exists in the soil?

Activity 4: Phosphate as a limiting factor

The purpose of this lab is to determine the effect of phosphorus containing detergent on algal growth.

Time Needed

30 minutes for the initial setup

10 minutes a day for several days

Time for conclusion

Objectives

Determine if phosphorus is a limiting factor on algal growth.

Demonstrate eutrophication from household wastewater.

Analyze results and summarize in writing.

Materials (per groups of 2-4)

3 wide mouth jars or beakers

Spring water

Dilute dishwasher solution (with phosphate)

Dilute dishwasher solution (without phosphate)

Pond water with algae

Procedure

1. Label containers #1, #2, and #3.
2. Fill each container halfway with algae containing pond water.
3. Using a pipette, sample each container and make a slide.
4. View each slide under the microscope and diagram organism count.
5. Container #1 is the control; add spring water to this container.
6. In container #2 add same amount of dishwasher solution with phosphate.
7. In container #3 add same amount of dishwasher solution without phosphate.
8. Place all containers in a bright location.
9. To measure algae growth, make a slide from each sample and diagram organism count. Do this for several days.
10. Analyze the results and summarize findings in writing.

Discussion

There should be a notable increase in algae in container #2.

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Classroom Materials and Resources

All living specimens can be purchased through Carolina Biological Supply Company. http://www.carolina.com/home.do

Appendix

Implementing District Standards

This unit was designed to be used in a high school level environmental class. The unit meets many of the New Haven Public School inquiry standards as well as some grade specific content standards.

Inquiry Standards

DINQ1 Identify questions that can be answered through scientific investigation.

DINQ3 Formulate a testable hypothesis and demonstrate logical connections between the scientific concepts guiding the hypothesis and the design of the experiment.

DINQ4 Design and conduct appropriate types of scientific investigations to answer different questions.

DINQ5 Identify independent and dependent variables, including those that are kept constant and those used as controls.

DINQ6 Use appropriate tools and techniques to make observations and gather data.

DINQ8 Use mathematical operations to analyze and interpret data, and present relationships between variables in appropriate forms.

DINQ9 Articulate conclusions and explanations based on research data, and assess results based on the design of the investigation.

DINQ10 Communicate about science in different formats, using relevant science vocabulary, supporting evidence and clear logic.

Content Standards

Grade 9

D19 -- Explain how chemical and physical processes cause carbon to cycle through the major earth reservoirs.

D20 -- Explain how solar energy causes water to cycle through the major earth reservoirs.

Grade 10

D.27 Describe significant similarities and differences in the basic structure of plant and animal cells.