Submarine Ring of Fire 2014 – Ironman Expedition

Microbes of Iron

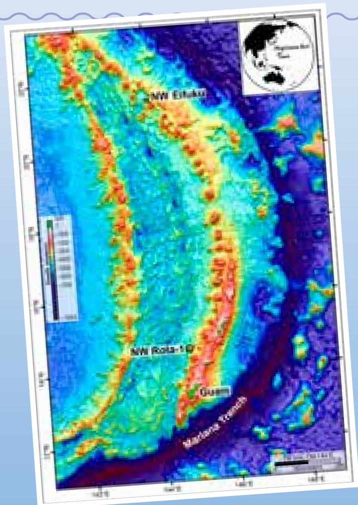


Image captions/credits on Page 2.

lesson plan

Focus

Ecological role of iron-oxidizing bacteria in hydrothermal vent ecosystems

Grade Level

6-8, with adaptations for 9-12 (Life Science)

Focus Question

What is the role of iron-oxidizing bacteria in hydrothermal vent ecosystems?

Learning Objectives

- Students will construct a scientific explanation based on evidence for the roles of photosynthesis and chemosynthesis in the cycling of matter and flow of energy into and out of organisms.
- Students will develop a model to describe the cycling of matter and flow of energy among living and nonliving parts of a chemosynthetic ecosystem.

Materials

For each student group:

- ❑ Directions for setting up Winogradsky columns from http://www.envsci.rutgers.edu/~phelps/lessons/lesson5.pdf
- ❑ 1 - translucent 0.5 liter plastic soda bottle
- ❑ 2 - compressed artist's charcoal sticks
- ❑ 50 ml black mud from a local river, lake, or estuary
- ❑ 1 l of water from each mud/sand location used
- ❑ 1.5 g instant mashed potato or boullion cube
- ❑ 500 ml iron-rich construction sand (see preparation notes in directions)
- ❑ 250 ml graduated cylinder or 1 cup measure
- ❑ 1/4 sheet sandpaper
- ❑ 1 plastic spoon
- ❑ Masking tape and markers for labeling columns

For the entire class:

- ❑ 1 - tube clear silicone caulk
- ❑ craft knife (teacher use only)
- ❑ (Optional) Microscopes and materials for making wet mounts

Audio-Visual Materials

- ❑ (Optional) Interactive whiteboard

Teaching Time

Two 45-minute class periods periods to design and set up columns, approximately 15 minutes at weekly intervals for six weeks to make observations, and one 45-minute class period for presentation and discussion of results

Seating Arrangement

Groups of three or four students

Maximum Number of Students

30

Key Words

Ring of Fire
Microbial mat
Chemosynthesis
Winogradsky column
Marianas Trench Marine National Monument

Background Information

NOTE: Explanations and procedures in this lesson are written at a level appropriate to professional educators. In presenting and discussing this material with students, educators may need to adapt the language and instructional approach to styles that are best suited to specific student groups.

The Ring of Fire is an arc of active volcanoes and earthquake sites that partially encircles the Pacific Ocean Basin. The location of the Ring of Fire coincides with the location of oceanic trenches and volcanic island arcs that result from collisions between large pieces of Earth's crust (tectonic plates) as they move on a hot flowing layer of Earth's mantle (for more about tectonic plate boundaries, please see Appendix A). When two tectonic plates collide more or less head-on, one of the plates usually moves beneath the other in a process called subduction. Subduction produces deep trenches, and earthquakes are common. As the sinking plate moves deeper into the mantle, increasing pressure and heat release fluids from the rock causing the overlying mantle to partially melt. The molten rock (magma) rises and may erupt violently to form volcanoes that in turn may form arcs of islands along the convergent boundary. These island arcs are always landward of the neighboring trenches. The Ring of Fire marks the location of numerous collisions between tectonic plates in the western Pacific Ocean.

The Mariana Arc is part of the Ring of Fire that lies to the north of Guam in the western Pacific. Here, the fast-moving Pacific Plate is subducted beneath the slower-moving Philippine Plate, creating the Marianas Trench (which includes the Challenger Deep, the deepest known area of the Earth's ocean). The Marianas Islands are the result of volcanoes caused by this subduction, which frequently causes earthquakes as

Images from Page 1 top to bottom:
Bathymetric compilation map of the Mariana Arc area showing the location of the 2 focus sites on the expedition, NW Eifuku and NW Rota-1 as well as the Marianas Trench. Multibeam bathymetry (120m grid-cell size) is overlaid on satellite altimetry data. Image credit: NOAA/PMEL Submarine Ring of Fire 2014 Expedition.

Mussel bed at NW Eifuku where pH can be as low as 5.3. Image credit: NOAA/PMEL Submarine Ring of Fire 2006 Expedition.
http://oceanexplorer.noaa.gov/explorations/06fire/logs/may8/media/mussel_water_samp.html

Photograph of iron-oxide-encrusted microbial mat collected using ROV (remotely operated vehicle) at Yellow Top Vent, Northwest Eifuku.
http://oceanexplorer.noaa.gov/explorations/04fire/logs/april12/media/yellow_cone.html

NW Rota-1 seamount has been observed erupting explosively on previous visits. Image credit: Submarine Ring of Fire 2006 Exploration, NOAA/PMEL.
http://oceanexplorer.noaa.gov/explorations/06fire/logs/april29/media/lavabombs.html

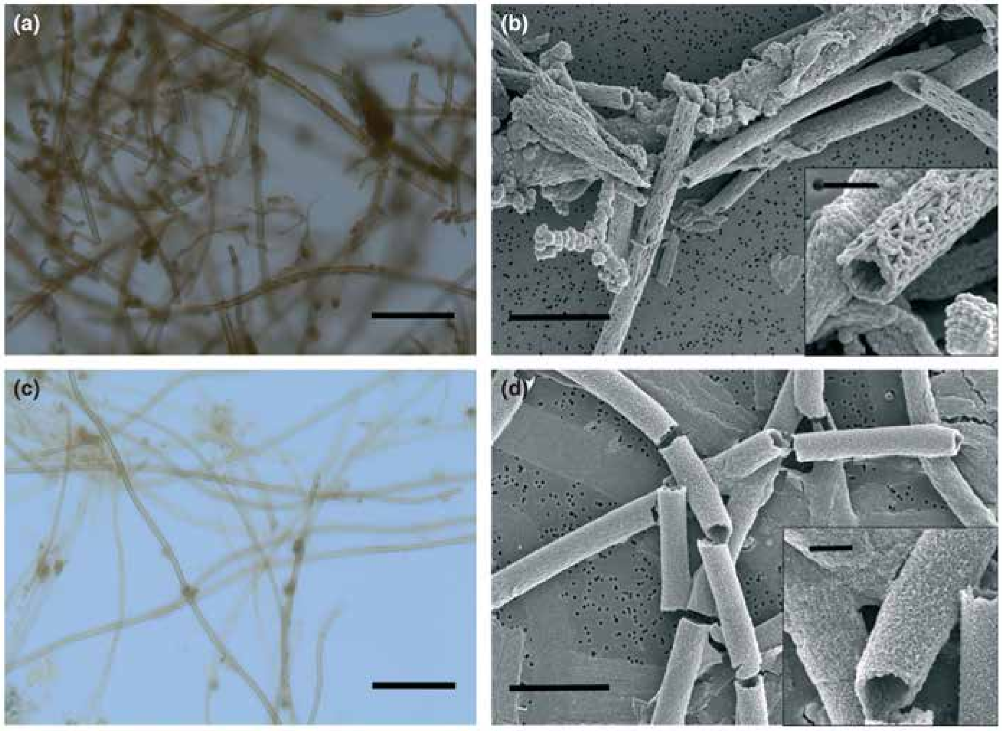
well. In 2003, the Ocean Exploration Ring of Fire Expedition surveyed more than 50 volcanoes along the Mariana Arc, and discovered that ten of these had active hydrothermal systems. The 2004 Submarine Ring of Fire Expedition focused specifically on hydrothermal systems of the Mariana Arc volcanoes, and found that these systems are very different from those found along mid-ocean ridges. In 2006, the third Submarine Ring of Fire Expedition visited multiple volcanoes, including the actively erupting NW Rota-1 and Daikoku, which featured a pond of molten sulfur (visit http://oceanexplorer.noaa.gov/explorations/03fire/welcome.html, http://oceanexplorer.noaa.gov/explorations/04fire/welcome.html , and http://oceanexplorer.noaa.gov/explorations/06fire/logs/summary/summary.html for more information on these discoveries).

Mussel bed at NW Eifuku where pH can be as low as 5.3.
http://oceanexplorer.noaa.gov/explorations/06fire/logs/may8/media/mussel_water_samp.html

Ocean explorers have found dense populations of mussels, crustaceans, and other organisms associated with the hydrothermal vents. Particularly important are microbes that are able to used chemicals in vent fluids as a source of energy, and are the basis for complex food webs. Zetaproteobacteria are a class of microbes that are able to use iron as an energy source, and form dense mats in some areas of the NW Eifuku Seamount. These food webs are based on chemosynthesis, and are fundamentally different from food webs that are based on energy from sunlight captured through photosynthesis. Chemosynthetic organisms may have been the first life forms on Earth, and may give important clues about life on other planets.

Photosynthesis and chemosynthesis are similar in that they are both processes that provide energy needed to form molecules that can serve as energy sources (food) for living organisms. This energy is captured and stored in other molecules, and is moved from one molecule to another molecule when electrons are transferred between the molecules. These transfers take place in a series of reactions called an electron transport chain.

When an atom or molecule loses an electron it is said to be oxidized, and when an atom or molecule gains an electron it is said to be reduced. A reducing substance is a substance that reduces; in other words, it donates electrons. Similarly, an oxidizing substance is a substance that oxidizes; that is, it receives electrons (note that the terms oxidation, reduction, and redox may also be used in slightly different ways for some types of chemistry, but these distinctions are not important for this discussion). Most of the chemicals that are commonly found in hydrothermal vent fluids are highly reduced. In other words, they are electron-rich. This means that these chemicals can provide a source of electrons for chemosynthetic electron transport chains. Most chemoautotrophic bacteria have evolved to use specific chemicals as a source of electrons. For this reason, microbial communities at hydrothermal vents can be characterized by the types of electron donors that are present in the hydrothermal fluids that nourish these communities.



Micrographs showing the overall similarity between representative samples of marine and freshwater sheaths inside microbial mats. The top panels show, (a) a light micrograph of a sample taken from a hydrothermal vent with a syringe sampler (J2-481-BS4), and (b) an SEM image of this sample that shows the fine structure of the sheaths. The lower panels show a sample taken from a local freshwater iron-seep in Maine morphologically dominated by *Leptothrix ochracea*; (c), a light micrograph; (d) an SEM image showing fine structure of the sheaths. Scale bars for a and c are 15 µm, b and d 5 µm with panels insets 1 µm. From Fleming *et al.*, 2013.

Zetaproteobacteria are iron oxidizers. Oxidized iron is insoluble at near-neutral pH, and iron-oxidizing bacteria produce solid iron oxides as a by-product of the oxidation process. These solids may be particles, twisted stalks, hollow sheaths, and irregularly-shaped filaments. Microbial mats formed by Zetaproteobacteria are typically encrusted with iron oxides, and these bacteria are sometimes called "ecosystem engineers" because the iron oxide deposits play a major role in shaping the habitat for these and other microbes. Zetaproteobacteria were first discovered at Loihi Seamount in Hawaii, where they were found to dominate the initial colonization and formation of microbial mats in low-temperature hydrothermal vents (Rassa *et al.*, 2009). The microbial mats and bacteria provide habitats and food sources for other organisms, so complex food webs and diverse communities can develop.

The purpose of the 2014 Submarine Ring of Fire – Ironman Expedition is to investigate the ecology of Zetaproteobacteria mat ecosystems, as well as to explore the NW Eifuku and MW Rota-1 Seamounts in greater detail. The exploration will include the investigation of hydrothermal vent fluids, the effect of vented carbon dioxide on the pH of surrounding waters, the chemical environment of microbial mats in the vicinity of vents, the effects of acidic conditions on mussels and other benthic organisms, and detailed mapping of the summit of NW Eifuku.

In this lesson, students will create a model ecosystem to investigate succession in chemosynthetic bacterial communities.

Learning Procedure

1. To prepare for this lesson:
   a. Review background information about the 2014 Submarine Ring of Fire – Ironman Expedition (http:/oceanexplorer.noaa.gov/explorations/14fire/welcome.html).

   b. Download and review procedures for setting up Winogradsky columns (http://www.envsci.rutgers.edu/~phelps/lessons/lesson5.pdf), which are adapted from "Exploring Biocomplexity in Aquatic Sediments," by Jennifer Lamkie and Craig Phelps (http://www.envsci.rutgers.edu/~phelps/winogradsky.htm) from Rutgers University. This is a series of lessons adapted for middle school students that use a version of the Winogradsky column to show how living things influence the physical environment and vice versa. If you cannot find iron-rich sand, instructions for preparing a suitable substitute are given in instructions for Lesson 5 . Lesson 6 (http://www.envsci.rutgers.edu/~phelps/lessons/lesson6.pdf) shows how to measure the electric current produced by the oxidation and reduction of iron in the column. If you do not want to have your students measure this electric current, you may omit the insertion of carbon electrodes into the plastic bottles.

   You may also want to review other resources linked from http://serc.carleton.edu/microbelife/topics/special_collections/winogradsky.html. In particular, "Investigating Bacteria with the Winogradsky Column," by Brian Rogan (http://www.rrcs.org/Downloads/Investigating%20Bacteria%20with%20the%20Winogradsky%20Column.pdf), provides detailed explanations of procedures and discusses a variety of ways to modify the basic procedure to produce extremophile microbes and to isolate and culture some of the common organisms that grow in Winogradsky systems. While it is not necessary to implement all of these alternatives, it will be helpful for educators to understand them as a basis for assisting students with the design portion of this lesson.

   c. (Optional) Download one or more images of Winogradsky columns (an image search on "Winogradsky column" will produce many examples).

2. Briefly introduce the 2014 Submarine Ring of Fire – Ironman Expedition. If students are not familiar with plate tectonics and time permits, you may wish to use some or all of Multimedia Discovery Missions Lessons 1, 2 and 4, which include interactive multimedia presentations and Learning Activities on Plate Tectonics, Mid-Ocean

Ridges, and Subduction Zones [http://oceanexplorer.noaa.gov/edu/learning/welcome.html?url=http://www.learningdemo.com/noaa/].

3. Lead a discussion of hydrothermal vent ecosystems, emphasizing the role of chemosynthesis. Contrast chemosynthesis with photosynthesis. The "big picture" of chemosynthesis and photosynthesis is that they are both processes that organisms use to obtain energy needed for life functions (such as reproducing, locomotion, synthesizing tissues). One basic way to distinguish chemosynthesis from photosynthesis is the source of this energy. In photosynthesis, the sun is the energy source; in chemosynthesis, energy in chemical compounds is the source.

4. Tell students that their assignment is to investigate the growth of microbial communities in a Winogradsky (pronounced, "vin-oh-GRAD-ski") column, which was invented in the 1880's by Russian scientist Sergei Winogradsky.

   Explain the basic concept of the Winogradsky column, and review set-up procedures. You may want to show one or more images of Winogradsky columns if you downloaded those in Step 1c. Discuss the following details about the purpose of the materials used in their Winogradsky columns:
   - A translucent container is needed to provide light to photosynthetic microbes. Excluding light favors the growth of chemosynthetic bacteria.
   - Mud and water are sources of microbes.
   - Instant mashed potatoes or a bouillon cube provide a source of organic carbon
   - Iron-rich sand provides an energy source (electron donors)

   Tell students that the first part of their assignment is to design a Winogradsky column that will favor the growth of chemosynthetic bacteria. This will require thought about conditions that favor chemosynthetic bacteria, but do not favor photosynthetic organisms. Students should realize that excluding light from a Winogradsky column will produce these conditions. Depending upon curriculum objectives, available time, and student abilities, you may also want to challenge students to consider additional design requirements that might favor the growth of certain types of chemosynthetic bacteria, such as iron-reducing bacteria instead of sulfur-reducing bacteria. The sources cited in Step 1 will provide some ideas if you want to pursue this option.

   Students should submit a written design plan, including a sketch of their proposed design. You may want to allow enough time for students to do some independent research on Winogradsky columns to expand their thinking about the assignment.

5. When you have approved proposed designs, have students proceed with the construction of their designed column, as well as a column that will be exposed to a light source (but not direct sunlight). Students should observe their columns weekly, and record their observations. You may have them make wet mounts for microscopic examination at the end of three and six weeks. Use appropriate safety precautions when making wet mounts, including gloves, antibacterial solution for disposing of slides, and hand washing following completion of the activity.

6. Have each group present and discuss their results. Students should have observed a series of changes in the appearance of the mud in the columns caused by a succession of bacterial species. They should infer that changes caused by one species (for example, the production of waste products) create opportunities for other species. Similarly, changes in the chemical composition of the mud, such as formation of hydrogen sulfide, alter the environment in ways that may favor the growth of other bacterial species.

   Ask students what their observations about Winogradsky columns suggest about the role of microorganisms in underwater volcanic and hydrothermal vent ecosystems in the Mariana Arc region. Be sure students understand that microorganisms, particularly bacteria, are key players in chemosynthetic ecosystems because they are often the first organisms to colonize recently-erupted lava and are able to convert energy from inorganic chemicals into organic molecules that other species can use as a food (energy) source. Be sure students understand that hydrothermal vent and underwater volcanic ecosystems may be suddenly disrupted by new eruptions, and the succession that follows depends upon the severity of the disturbance. If the ecosystem is completely wiped out (for example, covered with molten lava) then the colonization process must begin from scratch with initial establishment of microbial mats. If the destruction is not total, then some of the species that arrived after the microbes (for example, mussels and crustaceans) may still be present so that the entire succession process does not have to be repeated.

   Have students construct an explanation based on evidence for the roles of photosynthesis and chemosynthesis in the cycling of matter and flow of energy into and out of organisms, and a model (diagram or other type of model) that describes the role of living and nonliving parts in a chemosynthetic ecosystem. Explanations may include evidence from direct observations by students, or cited evidence from other sources, or both. Students should realize that matter is cycled and energy flows into and out of organisms even in environments that do not receive sunlight to support photosynthesis.

The BRIDGE Connection

www.vims.edu/bridge/ – In the menu on the left, scroll over "Ocean Science Topics," then "Habitats," then click "Deep Sea," for links to information and activities about hydrothermal vents and deep ocean ecosystems.

The "Me" Connection

Have students write a short essay on why chemosynthetic ecosystems might be directly important to their own lives. You may want to offer a hint that perhaps the energy source used by chemosynthetic bacteria could be useful to other species as well (some estimates suggest that there may be more energy locked up in methane hydrate ices than in all other fossil fuels combined!).

Connections to Other Subjects

English Language Arts

Assessment

Group assignments and class discussions provide opportunities for assessment.

Adaptations to Other Grade Levels

Grades 9-12: Have students construct a variety of Winogradsky columns suggested in "Investigating Bacteria with the Winogradsky Column" (http://www.rrcs.org/Downloads/Investigating%20Bacteria%20with%20the%20Winogradsky%20Column.pdf) to model different types of chemosynthetic communities.

Extensions

1. Visit http://oceanexplorer.noaa.gov/explorations/14fire/welcome.html for daily logs and updates about discoveries being made by the Submarine Ring of Fire 2014 – Ironma Expedition.
2. For additional activities using Winogradsky columns, see the resources cited in Learning Procedure Step 1b.

Multimedia Discovery Missions

http://oceanexplorer.noaa.gov/edu/learning/welcome.html Click on the links to lessons 1, 4, and 5 for interactive multimedia presentations and Learning Activities on Plate Tectonics, Subduction Zones and Chemosynthesis and Hydrothermal Vent Life.

Other Relevant Lessons from NOAA's Ocean Exploration Program

It Looks Like Champagne
(from the New Zealand American Submarine Ring of Fire 2005 Expedition)
http://oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05_champagne.pdf

Focus: Deep ocean carbon dioxide and global climate change (Chemistry/Earth Science)

Students will be able to interpret phase diagrams, explain the meaning of "critical point" and "triple point", define "supercritical fluid," describe two practical uses of supercritical carbon dioxide, and discuss the concept of carbon dioxide sequestration.

The Volcano Factory
(from the Submarine Ring of Fire 2006 Expedition)
http://oceanexplorer.noaa.gov/explorations/06fire/background/edu/media/ROF06.VolFactory.pdf

Focus: Volcanism on the Mariana Arc (Earth Science)

Students explain the tectonic processes that result in the formation of the Mariana Arc and the Mariana Trench; and explain why the Mariana Arc is one of the most volcanically active regions on Earth.

Living With the Heat
(from the Submarine Ring of Fire 2006 Expedition)
http://oceanexplorer.noaa.gov/explorations/06fire/background/edu/media/ROF06.LivingHeat.pdf

Focus: Hydrothermal vent ecology and transfer of energy among organisms that live near vents.

Students describe how hydrothermal vents are formed and characterize the physical conditions at these sites, explain what chemosynthesis is and contrast this process with photosynthesis, identify autotrophic bacteria as the basis for food webs in hydrothermal vent communities, and describe common food pathways between organisms typically found in hydrothermal vent communities.

Other Resources

The Web links below are provided for informational purposes only. Links outside of Ocean Explorer have been checked at the time of this page's publication, but the linking sites may become outdated or non-operational over time.

http://oceanexplorer.noaa.gov - Web site for NOAA's Ocean Exploration program

http://volcano.oregonstate.edu/ - Volcano World Web site from Oregon State University

http://serc.carleton.edu/microbelife/topics/special_collections/winogradsky.html – Web page from Microbial Life - Educational Resources, a collaborative project of the Marine Biology Laboratory, Woods Hole, MA, and Montana State University, Bozeman, MT; with links to resources and information about building Winogradsky columns

http://www.rrcs.org/Downloads/Investigating%20Bacteria%20with%20the%20Winogradsky%20Column.pdf – "Investigating Bacteria with the Winogradsky Column", by Brian Rogan; from the Woodrow Wilson Foundation Leadership Program for Teachers 2000 Summer Biology Institute

http://www.envsci.rutgers.edu/~phelps/winogradsky.htm – "Exploring Biocomplexity in Aquatic Sediments," by Jennifer Lamkie and Craig Phelps from Rutgers University; a series of lessons adapted for middle school students that use a version of the Winogradsky column to help establish the connection between earth and life sciences in students' minds by showing how living things influence the physical environment and vice versa

Rassa, A. C., S. M. McAllister, S. A. Safran, and C. L. Moyer. 2009. Zeta-Proteobacteria Dominate the Colonization and Formation of Microbial Mats in Low-Temperature Hydrothermal Vents at Loihi Seamount, Hawaii. Geomicrobiology Journal, 26:623–638.

Next Generation Science Standards

MS-LS1 From Molecules to Organisms: Structures and Processes

Performance Expectation MS-LS1-6.

Construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms. [Clarification Statement: Emphasis is on tracing movement of matter and flow of energy.] [Assessment Boundary: Assessment does not include the biochemical mechanisms of photosynthesis.]

Science and Engineering Practices

Constructing Explanations and Designing Solutions

Constructing explanations and designing solutions in 6–8 builds on K–5 experiences and progresses to include constructing explanations and designing solutions supported by multiple sources of evidence consistent with scientific knowledge, principles, and theories.

- Construct a scientific explanation based on valid and reliable evidence obtained from sources (including the students' own experiments) and the assumption that theories and laws that describe the natural world operate today as they did in the past and will continue to do so in the future.

Disciplinary Core Ideas

LS1.C: Organization for Matter and Energy Flow in Organisms

- Plants, algae (including phytoplankton), and many microorganisms use the energy from light to make sugars (food) from carbon dioxide from the atmosphere and water through the process of photosynthesis, which also releases oxygen. These sugars can be used immediately or stored for growth or later use.

Crosscutting Concepts

Energy and Matter

- Within a natural system, the transfer of energy drives the motion and/or cycling of matter.

MS-LS2 Ecosystems: Interactions, Energy, and Dynamics

Performance Expectation MS-LS2-3.

Develop a model to describe the cycling of matter and flow of energy among living and nonliving parts of an ecosystem.

[Clarification Statement: Emphasis is on describing the conservation of matter and flow of energy into and out of various ecosystems, and on defining the boundaries of the system.] [Assessment Boundary: Assessment does not include the use of chemical reactions to describe the processes.]

Science and Engineering Practices

Developing and Using Models

Modeling in 6–8 builds on K–5 experiences and progresses to developing, using, and revising models to describe, test, and predict more abstract phenomena and design systems.

- Develop a model to describe phenomena.

Disciplinary Core Ideas

LS2.B: Cycle of Matter and Energy Transfer in Ecosystems

- Food webs are models that demonstrate how matter and energy is transferred between producers, consumers, and decomposers as the three groups interact within an ecosystem. Transfers of matter into and out of the physical environment occur at every level. Decomposers recycle nutrients from dead plant or animal matter back to the soil in terrestrial environments or to the water in aquatic environments. The atoms that make up the organisms in an ecosystem are cycled repeatedly between the living and nonliving parts of the ecosystem.

Crosscutting Concepts

Energy and Matter

- The transfer of energy can be tracked as energy flows through a natural system.

Connections to Nature of Science

Scientific Knowledge Assumes an Order and Consistency in Natural Systems

Science assumes that objects and events in natural systems occur in consistent patterns that are understandable through measurement and observation.

Ocean Literacy Essential Principles and Fundamental Concepts

Essential Principle 1.
The Earth has one big ocean with many features.

Fundamental Concept b. An ocean basin's size, shape and features (such as islands, trenches, mid-ocean ridges, rift valleys) vary due to the movement of Earth's lithospheric plates. Earth's highest peaks, deepest valleys and flattest vast plains are all in the ocean.

Essential Principle 3.
The ocean is a major influence on weather and climate.

Fundamental Concept f. The ocean has had, and will continue to have, a significant influence on climate change by absorbing, storing, and moving heat, carbon and water.

Essential Principle 5.
The ocean supports a great diversity of life and ecosystems.

Fundamental Concept g. There are deep ocean ecosystems that are independent of energy from sunlight and photosynthetic organisms. Hydrothermal vents, submarine hot springs, and methane cold seeps rely only on chemical energy and chemosynthetic organisms to support life.

Essential Principle 6.
The ocean and humans are inextricably interconnected.

Fundamental Concept g. Everyone is responsible for caring for the ocean. The ocean sustains life on Earth and humans must live in ways that sustain the ocean. Individual and collective actions are needed to effectively manage ocean resources for all.

Essential Principle 7.
The ocean is largely unexplored.

Fundamental Concept d. New technologies, sensors and tools are expanding our ability to explore the ocean. Ocean scientists are relying more and more on satellites, drifters, buoys, subsea observatories and unmanned submersibles.

Fundamental Concept e. Use of mathematical models is now an essential part of ocean sciences. Models help us understand the complexity of the ocean and of its interaction with Earth's climate. They process observations and help describe the interactions among systems.

Send Us Your Feedback

In addition to consultation with expedition scientists, the development of lesson plans and other education products is guided by comments and suggestions from educators and others who use these materials. Please send questions and comments about these materials to: oceanexeducation@noaa.gov.

For More Information

Paula Keener, Director, Education Programs
NOAA Office of Ocean Exploration and Research
Hollings Marine Laboratory
331 Fort Johnson Road, Charleston SC 29412
843.762.8818
843.762.8737 (fax)
paula.keener@noaa.gov

Acknowledgements

This lesson was developed and written for NOAA's Office of Ocean Exploration and Research (OER) by Dr. Mel Goodwin, PhD, Marine Biologist and Science Writer, Mt. Pleasant, SC.
Design/layout: Coastal Images Graphic Design, Mt. Pleasant, SC.

Credit

If reproducing this lesson, please cite NOAA as the source, and provide the following URL: http://oceanexplorer.noaa.gov