Teacher Preparation Notes for
Food Webs, Energy Flow, Carbon Cycle, and Trophic Pyramids[1]

To begin this hands-on, minds-on activity, students view a video about ecosystem changes that resulted when wolves were eliminated from Yellowstone National Park and later returned to Yellowstone. Then, students learn about food chains and food webs, and they construct and analyze a food web for Yellowstone. Students use what they have learned to understand a trophic cascade caused by the elimination of wolves from Yellowstone. Next, students learn that the biosphere requires a continuous inflow of energy, but does not need an inflow of carbon atoms. To understand why, students apply fundamental principles of physics to photosynthesis, biosynthesis, and cellular respiration, the processes which result in carbon cycles and energy flow through ecosystems. In the final section, students use the concepts they have learned to understand trophic pyramids and phenomena such as the relative population sizes for wolves vs. elk in Yellowstone. Thus, students learn how ecological phenomena result from processes at the molecular, cellular, and organismal levels.

For virtual instruction, you can use Food Webs – What effects did the elimination and return of wolves have on other populations in Yellowstone?, Carbon Cycles and Energy Flow through Ecosystems and the Biosphere, and Trophic Pyramids.

As background for this activity, students should have a basic understanding of cellular respiration and photosynthesis. For this purpose, we recommend the analysis and discussion activities, “How do organisms use energy?” (https://serendipstudio.org/exchange/bioactivities/energy) and “Using Models to Understand Photosynthesis” (https://serendipstudio.org/exchange/bioactivities/modelphoto).[2]

This multipart activity will probably require 3-4 50-minute classes. Depending on your students, you may want to use:

- part or all of one 50-minute period to complete pages 1-3 of the Student Handout (through question 10);
- one 50-minute period to make the food web and answer the questions on page 4 of the Student Handout;
- 1-2 50-minute periods for pages 5-10 of the Student Handout.

Table of Contents

Learning Goals – pages 2-4
Supplies – page 4
Instructional Suggestions and Background Information
    General – pages 4-5
    Wolves in Yellowstone National Park – pages 5-6
    Food Chains and Food Webs – pages 6-7
    Trophic Relationships in Yellowstone – pages 7-10
    Carbon Cycles and Energy Flow through Ecosystems and the Biosphere – pages 10-12
    Trophic Pyramids – pages 12-14
Additional Resources (including images for food web cards) – pages 15-19

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[1] By Drs. Ingrid Waldron and Lori Spindler, Dept Biology, Univ Pennsylvania. © 2024. The Student Handout and these Teacher Preparation Notes are available at https://serendipstudio.org/sci_edu/waldron/#ecolfoodweb.

[2] You may also want to have your students complete "Using Models to Understand Cellular Respiration" (https://serendipstudio.org/exchange/bioactivities/modelCR) and/or “Photosynthesis and Cellular Respiration – Understanding the Basics of Bioenergetics and Biosynthesis” (https://serendipstudio.org/exchange/bioactivities/photocellrespir).

Learning Goals

Learning Goals related to Next Generation Science Standards[3]

Students will gain understanding of Disciplinary Core Idea LS2.B, Cycles 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."
>
> "Plants or algae form the lowest level of the food web. At each link upward in a food web, only a small fraction of the matter consumed at the lower level is transferred upward, to produce growth and release energy in cellular respiration at the higher level. Given this inefficiency, there are generally fewer organisms at higher levels of a food web.[4] Some matter reacts to release energy for life functions, some matter is stored in newly made structures, and much is discarded. The chemical elements that make up the molecules of organisms pass through food webs and into and out of the atmosphere and soil, and they are combined and recombined in different ways. At each link in an ecosystem, matter and energy are conserved."
>
> "Photosynthesis and cellular respiration are important components of the carbon cycle, in which carbon is exchanged among the biosphere, atmosphere, oceans and geosphere through chemical, physical, geological, and biological processes."

Students engage in Scientific Practices:

- "Constructing Explanations – Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena…"
- "Developing and Using Models – Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of the system."

The Crosscutting Concept, "Energy and Matter: Flows, Cycles and Conservation" is a central theme of this activity. Specifically, this activity helps students to understand that:

- "Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of and within that system."
- "Energy cannot be created or destroyed – only moves between one place and another place, between objects and/or fields, or between systems."
- "Energy drives the cycling of matter within and between systems."

This activity helps to prepare students for the Performance Expectations:

- HS-LS2-4. "Use a mathematical representation to support claims for the cycling of matter and flow of energy among organisms in an ecosystem."
- HS-LS2-5. "Develop a model to illustrate the role of photosynthesis and cellular respiration in the cycling of carbon among the biosphere, atmosphere, hydrosphere and geosphere."[5]

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[3] Quotations are from https://www.nextgenscience.org/ and http://www.nextgenscience.org/sites/default/files/HS%20LS%20topics%20combined%206.13.13.pdf

[4] As discussed on pages 13-14 of these Teacher Notes, total biomass at each trophic level or numbers of organisms at each trophic level often do not show a pyramid shape, but the net rate of biomass production at each trophic level does consistently show a pyramid shape.

[5] This activity can be used to prepare middle school students for 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." For middle school students, you may want to use one of the following as a complementary or alternative activity.

Additional Content Learning Goals

- A **producer** is an organism that produces all of its organic molecules from small inorganic molecules. A **consumer** is an organism that consumes organic molecules produced by other organisms. Consumers can be categorized as (1) **primary consumers** which eat producers, (2) **decomposers** which consume dead organic matter, (3) **secondary consumers** which eat primary consumers and/or decomposers, or (4) **trophic omnivores** which eat organisms at more than one trophic level.
- In a **trophic relationship** one organism consumes organic molecules from another organism (or a decomposer consumes organic molecules from dead organic matter). A **food chain** shows a simple sequence of trophic relationships (e.g. producer → primary consumer → secondary consumer). A **food web** shows the multiple, complex trophic relationships among organisms in an ecosystem.
- Decomposers are crucial to prevent excessive accumulation of dead organic matter.
- Understanding a food web can help us to understand how changes in the population size of one organism can influence the population size of another organism in an ecosystem. For example, a **trophic cascade** can occur when a decrease in a predator population results in an increase in an herbivore population which in turn results in decreased plant growth.
- The **carbon cycle** results from the processes of:
  - **photosynthesis**, which moves carbon atoms from CO_2 to small organic molecules, and **biosynthesis**,[6] which produces larger, more complex organic molecules;
  - eating by animals, which moves carbon in organic molecules from one organism to another;
  - **cellular respiration**, which moves carbon atoms from organic molecules to CO_2.
- The following **general principles** apply to all biological processes, including photosynthesis, biosynthesis and cellular respiration.
  - The atoms in molecules can be rearranged into other molecules, but atoms cannot be created or destroyed by biological processes.
  - Energy is neither created nor destroyed by biological processes.
  - Energy can be transformed from one type to another (e.g. the energy in sunlight can be transformed to chemical energy in glucose).
  - During energy transfers and transformations, some of the input energy is transformed to heat.[7]
- **Energy flows through ecosystems**. Photosynthesis transforms sunlight to chemical energy in sugars (e.g., glucose). In cellular respiration, glucose is one input for reactions that provide the energy to make ATP from ADP + P. Hydrolysis of ATP provides the energy for many biological processes. Each of these biological processes produces heat. Heat cannot be used

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Carbon TIME (http://carbontime.bscs.org/) provides a sequence of activities about carbon cycles and energy flows. "Eco-Inquiry" (http://www.caryinstitute.org/educators/teaching-materials/eco-inquiry/who-eats-what) includes "Who Eats What?" which is an introduction to food webs.

[6] We use biosynthesis to refer to the processes that use the products of photosynthesis to make other types of organic molecules. Some sources use the term biosynthesis to include photosynthesis.

[7] Throughout this activity we have used heat as a more familiar, although somewhat inaccurate, term for thermal energy. "*Thermal energy* refers to the energy contained within a system that is responsible for its temperature. Heat is the flow of thermal energy." (https://www.khanacademy.org/science/physics/work-and-energy/work-and-energy-tutorial/a/what-is-thermal-energy) Heat is "energy that is transferred from one body to another as the result of a difference in temperature" (https://www.britannica.com/science/heat). Thus, throughout the Student Handout and these Teacher Preparation Notes, it would be more accurate to substitute "thermal energy" for the term "heat". We have used somewhat simplified language to discuss energy, and you may prefer to follow the more sophisticated recommendations for helping students understand energy in the NSTA Press book, "Teaching Energy Across the Sciences K-12".

as the input energy for photosynthesis or for other biological processes. Instead, heat is ultimately radiated out to space. Therefore, the biosphere, with all of the Earth's living organisms, depends on constant input of light energy from the sun. In contrast, the earth does not receive a significant inflow of carbon atoms, and this is not a problem because the carbon cycle constantly recycles carbon atoms.

- The **biomass** of an organism is the mass of the organic molecules in the organism.
- The **net rate of biomass production** is highest for the producers in an ecosystem and smaller for each higher trophic level in the ecosystem. One major reason why is that many of the organic molecules that an animal eats are used for cellular respiration and thus are not available for biomass production.
- The reduction in the net rate of biomass production at higher trophic levels results in a **trophic pyramid**. One practical implication is that the amount of land needed to produce meat is about ten times greater than the amount of land needed to produce an equivalent biomass of plant food.

Supplies for "Trophic Relationships in Yellowstone"

For each group of 2-4 students:

- a deck of 24 cards for a partial Yellowstone food web (to be reused in each class, so you will need a deck of cards for each student group in your largest class)
    - Pages 16-19 of these Teacher Preparation Notes have the images for these cards. We recommend that you print the cards on card stock and/or laminate these cards for durability. Before you laminate the cards, we recommend that you use markers to mark the edges of each deck with a different color stripe to help you keep track of which cards belong in which deck. A PDF file suitable for professional printing and cutting of cards is available at https://serendipstudio.org/exchange/bioactivities/foodweb.[8]
    - There are 42 trophic relationships between the 23 organisms and dead organic matter represented on the 24 cards of the full deck. If you have limited time for your students to make the food web, you can use an alternative deck with 18 cards and 28 trophic relationships. This alternative smaller deck is available at https://serendipstudio.org/exchange/bioactivities/foodweb.[9]
- a lab table or other surface ~2 ft. x ~2 ft. (~60 cm x ~60 cm) which students can write on with chalk or dry erase marker as they create their food web or a large piece of paper (e.g. from an easel pad) or poster board. [10]
- If students are writing on lab tables, chalk or a dry erase marker to draw rectangles and arrows

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[8] Please note that the following corrections for the cards that will be used to make the food web have been made in the cards at the end of these Teacher Preparation Notes, but not in the PDF for printing (due to my technical limitations). These corrections are: willows have been added to the food that bison eat, bison have been added to the eaters of willow, and the measurements for beetles have been corrected. We are grateful to Craig Douglas (http://www.douglasanimation.com/) for his help with preparing the cards and the PDF.

[9] If you use this alternative smaller deck you will need to modify the chart near the bottom of page 3 of the Student Handout (see page 3 in the Student Handout for "Food Webs – What effects did the elimination and return of wolves have on other populations in Yellowstone?" (https://serendipstudio.org/sci_edu/waldron/#foodweb)).

[10] If it is not feasible for you to provide such a large surface for students to write on, you can provide each student group with a reusable card stock or poster board set of the rectangles described in the chart on the bottom of page 3 of the Student Handout; if you are using this approach, we recommend that you provide masking tape or 42 thin strips of paper of varying length that students can use to draw arrows (one set for each student group in your largest class, plus a few extras in case some are damaged).

Instructional Suggestions and Background Information

In the Student Handout, numbers in bold indicate questions for the students to answer, and capital letters in bold indicates steps for students to do as they model the Yellowstone food web.

To maximize student learning, we recommend that you have your students work in pairs or small groups to complete groups of related questions. Student learning is increased when students discuss scientific concepts to develop answers to challenging questions; students who actively contribute to the development of conceptual understanding and question answers gain the most. After students have worked together to answer a group of related questions, we recommend having a class discussion that probes student thinking and helps students to develop a sound understanding of the concepts and information covered.

You can use the Word document for the Student Handout to prepare a revised version that may be more suitable for your students. If you use the Word document, please check the format by viewing the PDF.

A key for this activity is available upon request to Ingrid Waldron (iwaldron@upenn.edu). The following paragraphs provide additional instructional suggestions and background biology information – some for inclusion in your class discussions and some to provide you with relevant background that may be useful for your understanding and/or for responding to student questions.

Wolves in Yellowstone National Park

The recommended part of the "Ecosystems Video" (https://www.learner.org/series/the-habitable-planet-a-systems-approach-to-environmental-science/ecosystems/ecosystems-video/) should engage student interest and introduce your students to the Yellowstone ecosystem.[11] The part on Yellowstone begins at 13 minutes and 40 seconds. We recommend that you end at 22 minutes because the rest of the video includes statements that have been contradicted by recent research. The speculation that the mere presence of wolves might discourage willow consumption has not been supported by empirical evidence (https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/08-2017.1). The reintroduction of wolves to Yellowstone has only resulted in increased willow growth in scattered spots, but not generally. One reason is that, as elk have become less numerous, bison have become more numerous, and bison also eat willows. Another reason appears to be that the earlier decrease in beaver colonies has lowered the water table in many places, and a lower water table is less favorable for willow growth. It appears that there are two alternative stable states, one dominated by elk and grassland and the other with more beavers and willow, and the reintroduction of wolves has not been sufficient to cause the elk-grassland state to switch to the beaver-willow state. (https://esajournals.onlinelibrary.wiley.com/doi/epdf/10.1002/ecm.1598)

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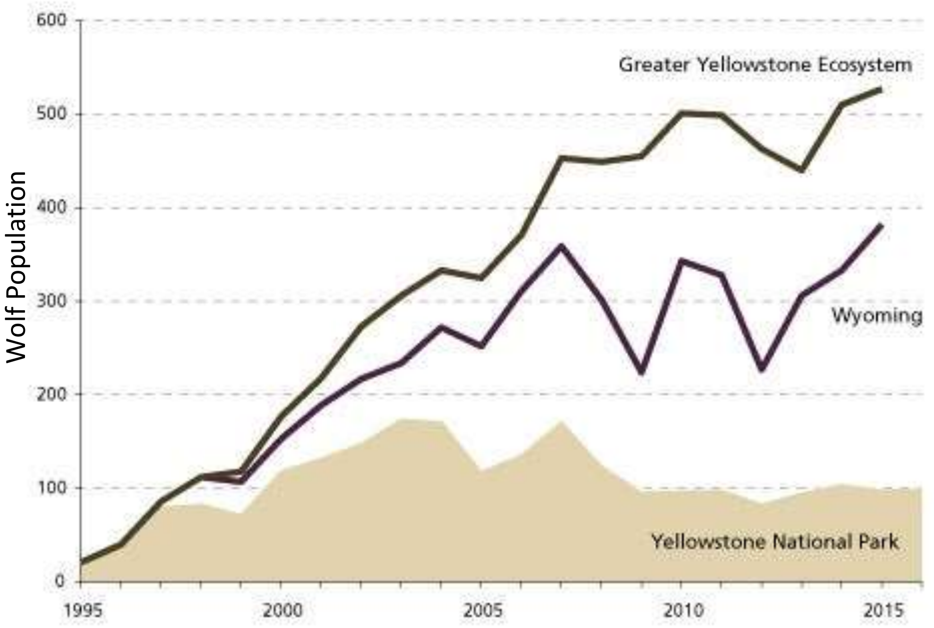
[11] You may be attracted to the video "Wolves of Yellowstone", but we recommend that you not use this video because many of the statements that are presented as fact in this video are actually quite speculative.

Yellowstone National Park includes ~3500 square miles, mainly in Wyoming. The park includes a variety of habitats, including forests, grasslands, and aquatic habitats.

Questions 1-4 are intended to start students thinking about phenomena that will be revisited in the rest of the activity. As your students discuss their answers to these questions, you can guide them to ask questions and formulate hypotheses that will set the stage for what follows.

The graph on page 1 of the Student Handout shows trends in wolf and elk populations in the Northern Range in Yellowstone National Park where many elk and wolves spend the winter. This graph shows trends in number of wolves for Yellowstone National Park and for larger areas.



(https://www.nps.gov/yell/learn/nature/wolves.htm)

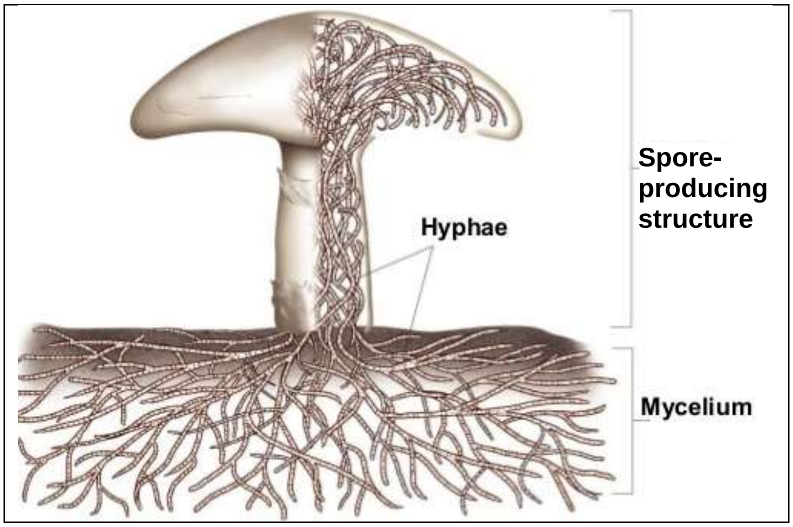
Food Chains and Food Webs

Your students should understand that, in food chains and food webs, the arrows point from the organism that is consumed to the organism that consumes. In other words, the arrows show the direction of flow of nutrition.

We use the term producer for organisms that use energy from sunlight to make their organic molecules. Producers include plants and algae.[12] We use the term consumer for organisms that eat other organisms.

Scavengers such as coyotes, bears, ravens, and eagles feed on carrion such as the remains of an elk killed by a wolf pack. Detritivores such as earthworms and termites ingest dead organic matter, extract nutrition, and excrete smaller particles which decomposers can more readily digest. Decomposers such as bacteria and fungi release enzymes into dead organic matter; these enzymes digest complex organic molecules into smaller soluble molecules that are absorbed by the decomposers. Dead stuff doesn't accumulate on the forest floor because scavengers, detritivores, and decomposers consume the dead organic matter and ultimately the digested molecules return to the soil or air (see next section of this activity). An entertaining and informative 4-minute video, "Dead Stuff: The Secret Ingredient in Our Food Chain" (https://www.youtube.com/watch?v=KI7u_pcfAQE), summarizes some of this information and introduces food chains and food webs. You may want to show this video during your discussion of student answers to question 6.

If your students are not familiar with fungi, you may want to introduce them to the basic structure of the mycelium (a network of hyphae in the soil, rotting log, or other organic matter) and an above-ground structure that produces spores (e.g. a mushroom). The hyphae in the mycelium secrete digestive enzymes and absorb nutrients.



(http://image.slidesharecdn.com/funginotes-131009165742-phpapp02/95/fungi-notes-4-638.jpg?cb=1381337957)

The trophic omnivore category includes the more familiar category of omnivores (animals that eat both plants and animals).[13] The trophic omnivore category is broader and includes any organism that consumes organisms at more than one trophic level (e.g. a carnivore that consumes both primary and secondary consumers). An animal that eats a trophic omnivore is also a trophic omnivore. To understand why, consider a trophic omnivore that eats producers and primary consumers; this trophic omnivore can be considered to be both a primary consumer and a secondary consumer; therefore, an animal that consumes this trophic omnivore is consuming from two different trophic levels, so it is also considered to be a trophic omnivore. To stimulate your students to think about this issue, you can include the following question in the Student Handout.

10a. Why is an animal that eats trophic omnivores also categorized as a trophic omnivore?

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[12] In addition to producers that use sunlight as their energy source, there are producers in deep-sea hydrothermal vents and iron-rich rocks deep below the earth's surface that use chemical energy contained in compounds such as ammonia or hydrogen sulfide.
Producers are autotrophs. Consumers are heterotrophs. If you want, you can easily include the terms, autotroph and heterotroph, in the Student Handout.

[13] You are no doubt aware that, despite the name, an omnivore doesn't eat everything.

Trophic Relationships in Yellowstone

The Latin names for the animals and plants included in the Yellowstone National Park food web are as follows:

American Robin – *Turdus migratorius*
Aspen – *Populus tremuloides*
Beaver – *Castor canadensis*
Bison – *Bison bison*
Coyote – *Canis latrans*
Cutthroat trout – *Oncorhynchus clarkii*
Deer mice – *Peromyscus maniculatus*
Earthworm – *Lumbricina* spp.
Elk – *Cervus elaphus*
Gray Wolf – *Canis lupus*
Grizzly bear – *Ursus arctos*
Springtails – *Collembola* spp.
Uinta ground squirrel – *Spermophilus armatus*
Yellow-bellied marmot – *Marmota flaviventris*
Willow – *Salix* spp.

As your students begin to construct their Yellowstone food webs, you may want to point out that the cards include not only the trophic relationships for the organism, but also a general estimate of the size range (length) of the organism. We have used the more familiar term "eat" for most of the cards, but for bacteria and fungi we have used the term "consume" since these organisms do not ingest dead organic matter, but rather secrete enzymes into the environment and then absorb digested nutrient molecules.

To make an accurate food web in a reasonable amount of time, it is important for your students to complete each step in the procedure and check it off before proceeding to the next step. The chart on the bottom of page 3 of the Student Handout provides both a helpful organization and hints for making the food web. You may need to remind students that a primary consumer eats only producers and a secondary consumer eats only primary consumers and/or decomposers. Consumers which consume food from more than one trophic level are trophic omnivores. For example, wolves are trophic omnivores, since they eat coyotes as well as primary consumers.

The Yellowstone food web includes both a green food web that begins with producers and a brown food web that begins with dead organic matter.[14] This is an example of the general principle that the Yellowstone food web is made up of many interrelated sub-webs. For example, sub-webs can be identified in different habitats, e.g., in the soil; above-ground in grassland or forest; in rivers, streams or ponds; or in the adjacent riparian ecosystems.

After your students have made their initial attempt to create the Yellowstone food web, if there are discrepancies between their food web and the food web shown in the key (available upon request to iwaldron@upenn.edu), you may want to ask questions that call your students' attention to information on the cards that they can use to make a more accurate food web.

To make a manageable food web for the students to construct, we have made multiple simplifications. As discussed on page 4 of the Student Handout, we have omitted most of the types of organisms found in Yellowstone National Park; we have omitted many of the trophic

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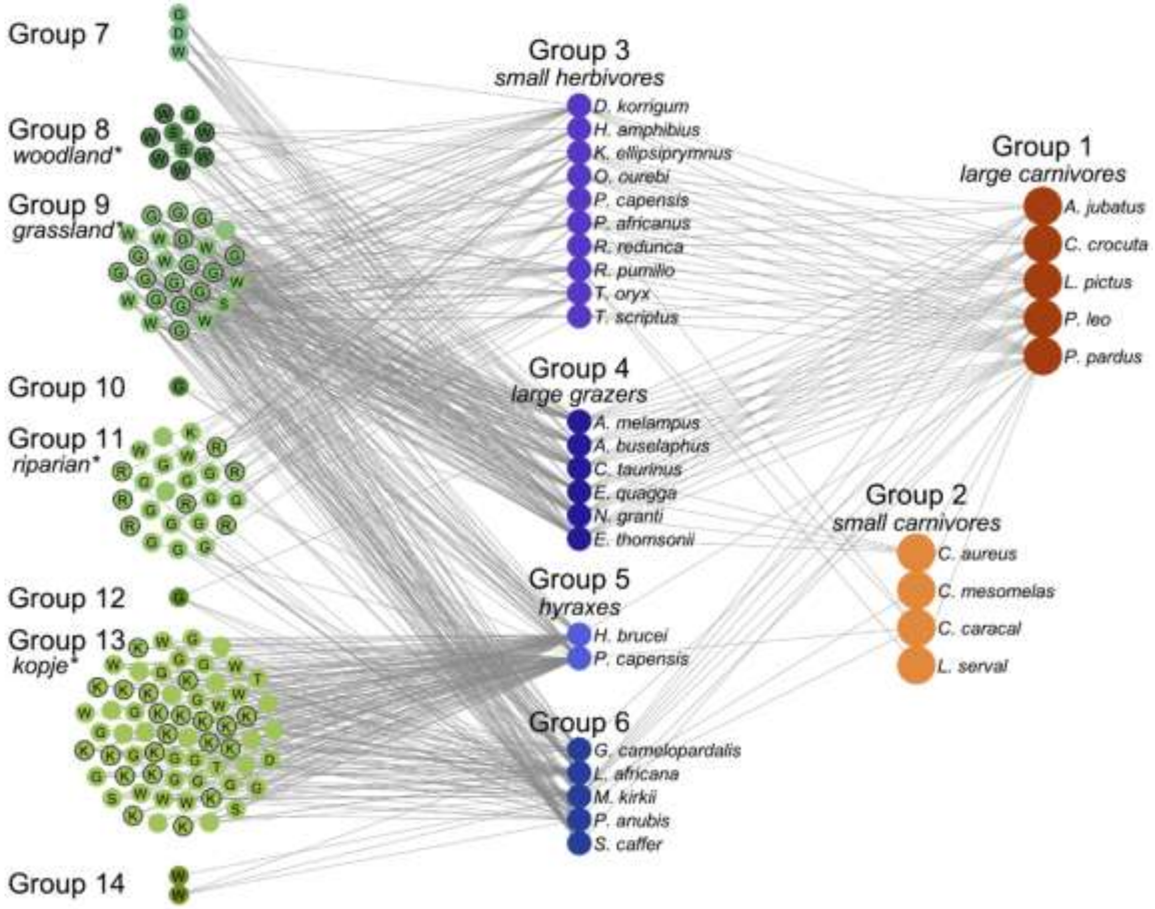
[14] American robins and Uinta ground squirrels belong to both the green and brown food webs. Your students should notice the tiny size of most of the organisms in the brown food web.

relationships for the organisms included in this activity; and we have not distinguished between more important and less important trophic relationships. Additional complexities include the following.

- We have not distinguished between the many different types of fungi, Protista, nematodes, mites, grasses, or “other flowering plants” in Yellowstone. Consequently, we have omitted mention of the different trophic relationships for different species within each of these groups.
- Many types of animals consume different types of food at different times of year and/or at different life stages.
- None of the many parasites present in any biological community have been included.
- Humans are an important part of the Yellowstone food web. Although hunting is not permitted in Yellowstone National Park, many Yellowstone elk are killed by human hunters when they migrate out of the park during the winter. Human hunters killed roughly 25,000 elk per year in Wyoming, compared to roughly 10,000 elk per year killed by the ~500 wolves living in the greater Yellowstone ecosystem (https://www.wyofile.com/many-elk-yellowstone-wolves-eat/).

All or almost all published food webs are incomplete, since it is virtually impossible to research and describe all the many species and trophic relationships in real biological food webs. For example, one analysis of a plant-mammal food web for the Serengeti ecosystem included 129 species of plants and 32 species of mammals, but excluded many other mammals, reptiles, amphibians, birds, invertebrates and decomposers. The Serengeti food web in the figure below illustrates one way to organize complex food web data by grouping species according to similarities in spatial location and trophic relationships.



(http://journals.plos.org/ploscompbiol/article/figure/image?size=large&id=info:doi/10.1371/journal.pcbi.1002321.g003)

Top-down control occurs when population size at a higher trophic level influences population size at a lower trophic level. An example of top-down control of population size is the trophic cascade from wolves to elk to willows (see pages 1 and 4 of the Student Handout). Bottom-up control occurs when the population size at a trophic level is influenced by the rate of production of its food source (or the producers' population size is influenced by the availability of resources needed for growth). An example of bottom-up control is the effect of willow availability on beaver population size.[15]

For question 14, the changing availability of taller willows is believed to be one important reason for the mid-twentieth century decrease and recent increase in number of beaver colonies (http://www.bioone.org/doi/abs/10.3955/046.086.0404). The presence of a beaver colony often fosters greater willow growth by raising the water table. Thus, beavers and willows have a mutually beneficial relationship, known as mutualism. The recovery of willows in some parts of Yellowstone, but not in others, appears to be due in part to insufficient soil moisture in many places in the absence of beaver dams. Thus, in order to recover, willows need beavers and beavers need willows; this creates a "catch 22" that appears to have slowed recovery of both willows and beavers after wolves were reintroduced to Yellowstone. If you want your students to learn more about trophic cascades and keystone predators, we recommend the video “Some Animals Are More Equal Than Others: Keystone Species and Trophic Cascades” (http://www.hhmi.org/biointeractive/some-animals-are-more-equal-others-keystone-species-and-trophic-cascades).

Carbon Cycles and Energy Flow through Ecosystems and the Biosphere

In this section, students develop an understanding of the carbon cycle and energy flow through ecosystems by reviewing and applying their knowledge of the processes of photosynthesis, cellular respiration, biosynthesis and fundamental principles of physics.

Question 15 is intended to stimulate students to think about questions and hypotheses that will be explored in the rest of this section. By the time students reach question 22 at the end of this section, they should be prepared to provide an accurate explanation of why the biosphere requires a constant input of energy from the sun, but does not need an inflow of carbon atoms. You may want to clarify that, although we speak of energy flow, energy is always a property of a physical system and not a disembodied separate substance. For example, increased heat energy corresponds to increased random motion of molecules.

The general principle in question 16b is the familiar Conservation of Matter. The general principles in question 16c will be familiar as the first Law of Thermodynamics and an implication of the second Law of Thermodynamics. Additional information about energy and the processes of photosynthesis and cellular respiration is provided in “Cellular Respiration and Photosynthesis – Important Concepts, Common Misconceptions, and Learning Activities” (https://serendipstudio.org/exchange/bioactivities/cellrespiration; this includes an explanation of the estimate that cellular respiration of one molecule of glucose results in the production of ~29 ATP).

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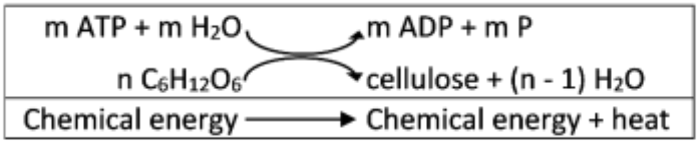
[15] Another example of bottom-up control occurred when the very severe winter of 1996-97 (when ice over snow prevented access to grass and other forage for elk) resulted in high elk mortality.

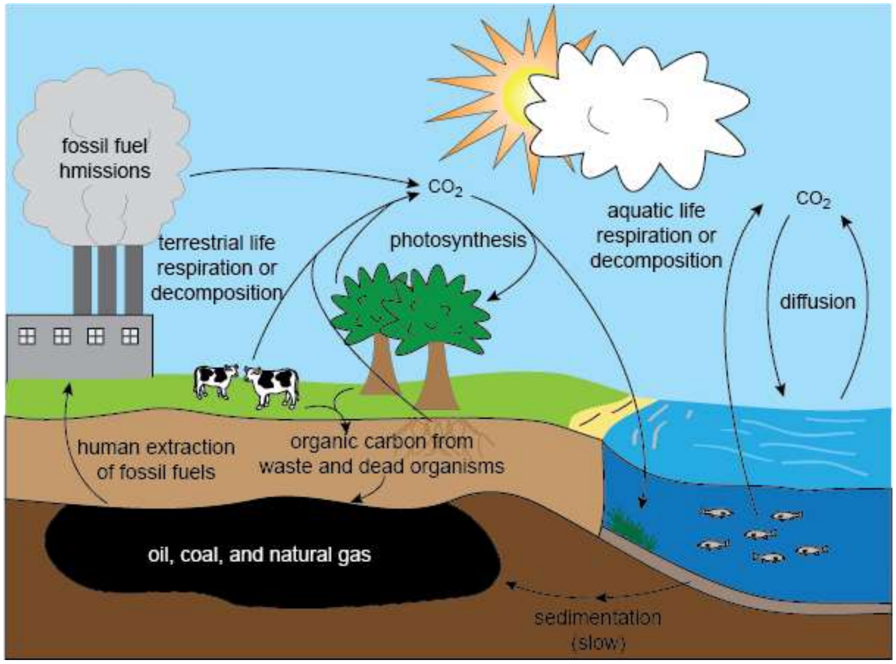


If you want to show your students an example of biosynthesis, you can use this figure which shows the synthesis of the polymer cellulose (the major component of plant cell walls). As is typical of biosynthesis, this reaction is powered by the hydrolysis of ATP.

Students may be puzzled by the idea that photosynthesis, biosynthesis and cellular respiration produce heat, since leaves generally do not feel warm. This can be explained by considering that only a small amount of heat is produced by the biological processes in a single leaf and other processes such as transpiration tend to cool leaves. If your students are familiar with compost piles, you may want to discuss how compost piles heat up due to the metabolic activity of decomposers.

One goal for this activity is to help your students understand the relationships between phenomena observed at different organizational levels, including the relationships between the molecular/cellular processes of cellular respiration, photosynthesis and biosynthesis and ecological phenomena such as carbon cycles and energy flow through ecosystems. Students often find it challenging to link their understanding of phenomena observed at different organizational levels, so you may want to reinforce this understanding in your class discussions of the questions in this section of the activity. Questions 18-19 focus on how photosynthesis, biosynthesis, cellular respiration and trophic relationships contribute to carbon cycles. Questions 20-21 focus on how the same processes result in the through-flow of energy.

The carbon cycle shown in the Student Handout is simplified to help students clearly understand the basic processes. However, this may leave students puzzled about how CO_2 concentration in the atmosphere has been increasing. To help them understand this, you may want to show them the more complete overview of the carbon cycle shown in the figure below. Resources for teaching about the carbon cycle and global warming are available at https://serendipstudio.org/exchange/bioactivities/global-warming and https://serendipstudio.org/exchange/bioactivities/ClimateChange .



(http://media1.shmoop.com/images/biology/biobook_eco_11.png)

Useful background for this section is provided in Sections 3 and 4 of Unit 4 of the online textbook available at https://www.learner.org/series/the-habitable-planet-a-systems-approach-to-environmental-science/ecosystems/online-textbook/.

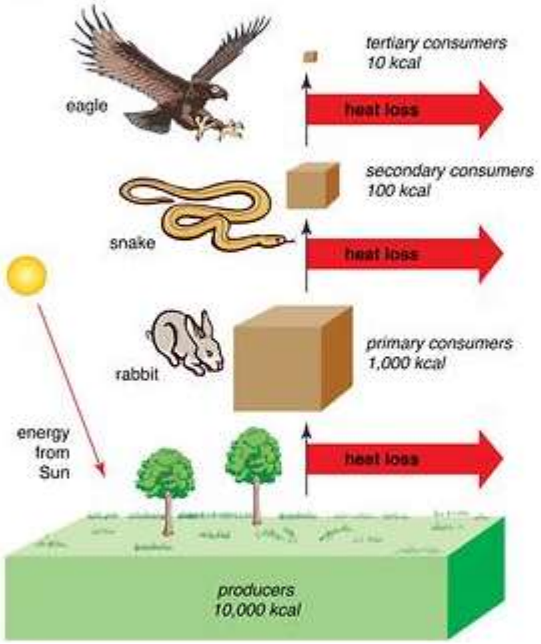
Trophic Pyramids

This section begins with a common observation – that producers are more abundant in nature then primary consumers, which are in turn more abundant than secondary consumers. This section will help students understand why that is true.

Biomass is the mass of the organic molecules in an organism. Organic molecules and water are the main types of matter in most organisms, so biomass is often estimated by weighing a dried specimen.[16]

Trophic pyramids are also known as ecological pyramids. A trophic pyramid can be converted to an energy pyramid (see figure). Less energy is available at each higher trophic level, because each energy transformation or transfer results in heat, which is lost from the ecosystem and ultimately from the biosphere.

The flowcharts on page 8 of the Student Handout show how cellular respiration reduces the net rate of biomass production for producers and consumers. For consumers, the loss of indigestible food molecules in feces also reduces the net rate of biomass production.



The units of energy should be kilocalories per area per time. (https://www.britannica.com/science/trophic-pyramid)

Page 9 of the Student Handout discusses the net rate of biomass production at different trophic levels in a forest in New Hampshire (see table below).[17] (Each trophic omnivore is classified in the consumer level of the main type of food they eat.)

Trophic Level	Net Rate of Biomass Production
Producers	1000 g/m^2/year
Primary Consumers and Decomposers	200 g/m^2/year
Secondary Consumers	30 g/m^2/year
Tertiary Consumers	3 g/m^2/year

Student answers to question 26 should include the loss of CO_2 and H_2O produced by cellular respiration for primary consumers and decomposers, plus the loss of indigestible food molecules

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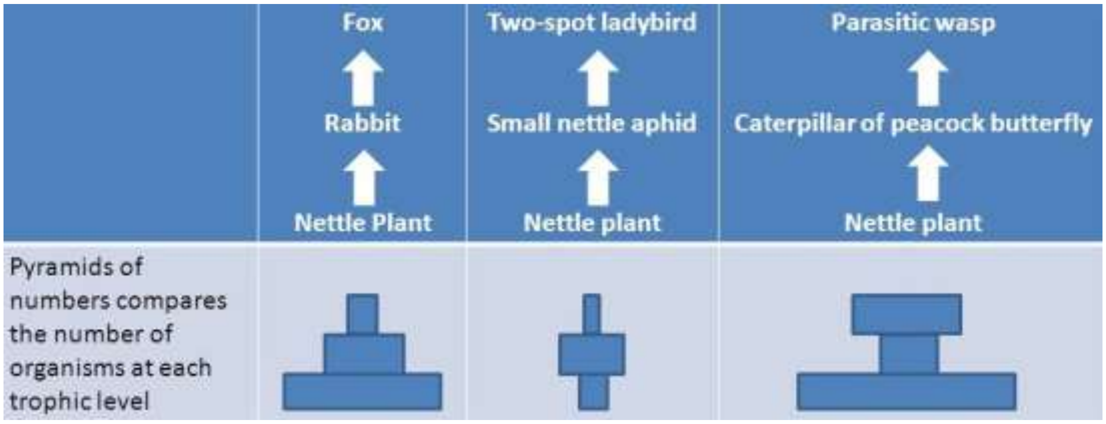
[16] A proxy measure of biomass is the mass of carbon in an organism; the mass of carbon is approximately half of the dry weight. Unfortunately, biomass is sometimes used to refer to the total weight of an organism; this definition is *not* used in this learning activity.

[17] Information about the ecology of the Hubbard Brook Experimental Forest in New Hampshire is available in pages 1151-2 in Freeman et al., Biological Science, 2014; Scientific American, March 1978, pages 93-102; and https://hubbardbrook.org/online-book/online-book.

in feces for primary consumers. The relative importance of these different processes varies for different types of organisms. For example, one study found that the proportion of consumed biomass that is used for cellular respiration is ~80% for chipmunks vs. 33% for herbivorous insects. (This difference reflects the fact that chipmunks are homeotherms, whereas herbivorous insects are poikilotherms; homeothermy is metabolically expensive.) The proportion of the biomass consumed that is lost as feces is ~18% for chipmunks vs. ~50% for herbivorous insects that eat leaves. (Leaves have more cellulose and other relatively indigestible molecules than the nuts, seeds and fruits eaten by chipmunks). As a result of these differences, biomass production for chipmunks is ~2% of the biomass consumed, whereas biomass production for herbivorous insects is ~17% of the biomass consumed.

The quantitative results in student answers to question 28a should help students understand why food chains are generally limited to 4 or 5 trophic levels. Question 28b helps students to understand that generalizations such as the "10% rule" often do not apply in specific cases. For example, the forest primary consumers plus decomposers had a net rate of biomass production that was 20% of the rate for producers. One reason for this relatively high percent may be that the researchers included decomposers, which are often ignored in simplified trophic pyramids.

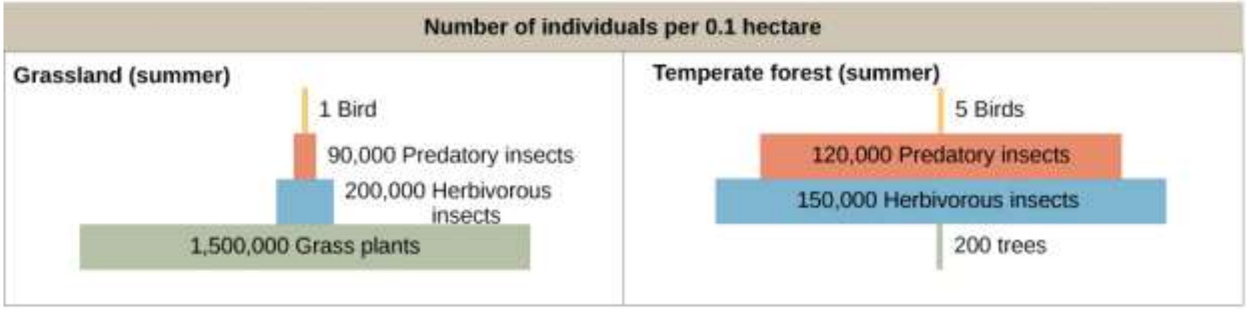
You should be aware that the shape of trophic pyramids is highly dependent on the specific methodology used. Trophic pyramids for the net rate of biomass production always show the classic pyramid shape with each trophic level smaller than the previous trophic level. However, this is not true for trophic pyramids for number of organisms or for total biomass of organisms at each trophic level. For example, a trophic pyramid for the number of individuals may show more individuals at a higher trophic level, e.g. if the organisms at the higher trophic level are smaller, such as insects feeding on trees or other plants (see figure below and figure on the next page). Similarly, the amount of biomass may be greater at a higher trophic level, e.g. if the organisms at the higher trophic level are more long-lived, such as fish or whales feeding on plankton. This explains why, the biomass of marine consumers is roughly 5 times the biomass of marine producers (https://www.pnas.org/content/pnas/115/25/6506.full.pdf, pages 6508-6509). In conclusion, trophic pyramids for number of individuals or amount of biomass tend to show the classic pyramid shape only if organisms at different trophic levels have similar size and longevity (http://www.esa.org/history/Awards/papers/Brown_JH_MA.pdf, page 1785).



(https://slideplayer.com/slide/3461369/12/images/20/Caterpillar+of+peacock+butterfly.jpg)

If you want to discuss these issues with your students, you could add the following to the Student Handout.[18]

So far, we have discussed trophic pyramids that show the net rate of biomass production at different trophic levels. Another type of trophic pyramid shows the number of organisms at different trophic levels. As you can see in the figure below, comparisons of the number of organisms at different trophic levels do not always show a pyramid shape.



29a. Label the appropriate trophic levels in the figure as producers, primary consumers, or secondary consumers.

29b. Explain why the grassland data show a trophic pyramid with more producers than primary consumers, but the forest data show many more primary consumers than producers.

In question 29 in the Student Handout, students apply the trophic pyramid concepts to the relative number of elk and wolves in Yellowstone (following up on question 2c). It should be noted that several factors influence the relative population size of predators and prey, including the following.

- As noted above, the relative size and longevity of the animals will influence their relative numbers.
- For individual species of predator and prey, the relative numbers will depend on how many of the prey species are eaten by other predators and how much the predator species consumes other prey species. Elk are the primary prey for Yellowstone wolves. However, other animals such as grizzly bears, coyotes and ravens feed on elk that have been killed by wolves. In addition, humans kill ~2-3 times as many elk as Yellowstone wolves (see page 9).

In discussing student answers to question 30, you may want to mention that, as compared to eating plant foods, eating meat from primary consumers not only requires ~10 times as much land, but also requires ~10 times as much water and other resources. The first follow-up activity recommended below explains why eating meat also contributes much more to global warming than eating plant foods.

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[18] The figure in this possible addition to the Student Handout is from https://www.khanacademy.org/science/high-school-biology/hs-ecology/trophic-levels/a/energy-flow-and-primary-productivity.

Possible Follow-Up Activities

Food and Climate Change – How can we feed a growing world population without increasing global warming?
(https://serendipstudio.org/exchange/bioactivities/global-warming)
In the first section of this activity, students analyze information about climate change, global warming and greenhouse gases. Students learn that correlation does not necessarily imply causation, and they analyze the types of evidence that establish causal relationships. In the next two sections, students analyze carbon cycles, how food production results in the release of greenhouse gases, and the reasons why the production of different types of food results in the release of very different amounts of greenhouse gases. In the last section, students propose and research strategies to feed the world's growing population without increasing global warming. (This activity will help students meet the Next Generation Science Standards.)

You may want to encourage your students to research related topics such as:

- aquatic food webs
- eutrophication as an example of bottom-up regulation
- nutrient cycles for nitrogen, phosphorus and water
- biomagnification of concentrations of persistent organic pollutants, mercury, etc. at higher trophic levels
- other topics that students may ask about during the activity.

Sources for Figures in Student Handout

- Trends in wolf and elk populations on page 1 – modified from "Riparian vegetation recovery in Yellowstone: The first two decades after wolf reintroduction" Biological Conservation 198: 93-103, 2016
- Food web on page 3 – http://www.biorewind.com/ecology/
- Giraffe carbon cycle – modified from http://www.bbc.co.uk/schools/gcsebitesize/science/images/bi01002.gif
- Trophic pyramid – modified from https://www2.nau.edu/lrm22/lessons/food_chain/energy_pyramid.jpg
- Other figures constructed by the first author

58-99 cm (length, excluding tail)

Beavers

Eat: Willows

Eaten by: Gray wolves

2.1-2.4 m

Elk

Eat: Grasses, willows, other flowering plants

Eaten by: Gray wolves, grizzly bears

2.1-3.5 m

Bison

Eat: Grasses, willows

Eaten by: Gray wolves

47-70 cm

Yellow-bellied Marmots

Eat: Grasses; other flowering plants

Eaten by: Coyotes

8-10 cm (length, excluding tail)

Deer Mice

Eat: Grasses; other flowering plants

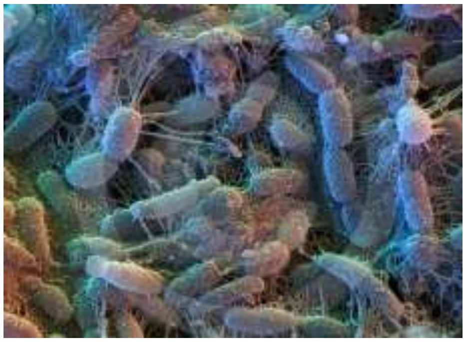
Eaten by: Coyotes

28-30 cm

Uinta Ground Squirrels

Eat: Grasses, other flowering plants, mushrooms,

Eaten by: Coyotes, grizzly bears

 *7-35 cm* **Earthworms** Eat: Dead organic matter, fungi, bacteria Eaten by: American robins	 *0.5-1 mm* **Mites** Eat: Nematodes, fungi Eaten by: Beetles	 *5-20 mm* **Beetles** Eat: Springtails, mites Eaten by: American robins
 *0.25-5 mm* **Springtails** Eat: Fungi Eaten by: Beetles	 *2-6 µm* **Bacteria** Consume: Dead organic matter Eaten by: Protista, nematodes, earthworms	 *0.1-2.5 mm* **Nematodes** Eat: Protista, fungi, bacteria Eaten by: Mites

<80-400 cm

Willows

Eaten by: Beavers, elk, bison

Grasses (including seeds)

Eaten by: Bison, elk, deer mice, Uinta ground squirrels, yellow-bellied marmots

Dead Organic Matter

Consumed by: Bacteria, fungi, earthworms

Other flowering plants (including berries)

Eaten by: American robins, deer mice, elk, grizzly bears, Uinta ground squirrels, yellow-bellied marmots

Fungi

Consume: Dead organic matter

Eaten by: Springtails, mites, nematodes, earthworms, Uinta ground squirrels

Algae

Eaten by: Cutthroat trout

23-28 cm

American Robins

Eat: Earthworms, beetles, other flowering plants

Eaten by: Snakes and birds of prey (not included in this food web)

15-50 cm

Cutthroat Trout

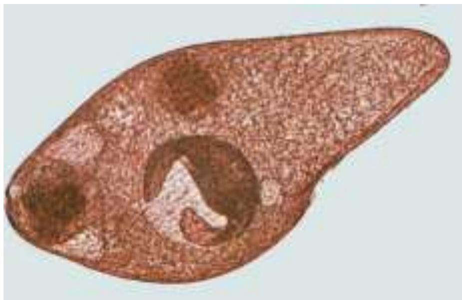
Eat: Algae

Eaten by: Grizzly bears

1.8-3.3 m

Grizzly Bears

Eat: Other flowering plants, cutthroat trout, Uinta ground squirrels, elk



<1 mm

Protista

Eat: Bacteria

Eaten by: Nematodes

1-1.4 m

Coyotes

Eat: deer mice, Uinta ground squirrels, yellow-bellied marmots

Eaten by: Gray wolves

1.4-2 m

Gray Wolves

Eat: Elk, beavers, bison, coyotes