UNIT 1

Energy and Matter Exchange in the Biosphere

General Outcomes

In this unit, you will

- explain the constant transfer of energy through the biosphere and its ecosystems
- explain the cycling of matter through the biosphere
- describe energy and matter exchange in the biosphere as an open system and explain how this maintains equilibrium

Unit Contents

Focussing Questions

1. Why can matter be recycled in the biosphere, while energy must be supplied constantly?
2. What roles do photosynthesis and cellular respiration play in the transfer of energy and the availability of matter in the biosphere?
3. How do human activities and technologies affect the quality and availability of energy and matter in the biosphere?

Unit PreQuiz ?

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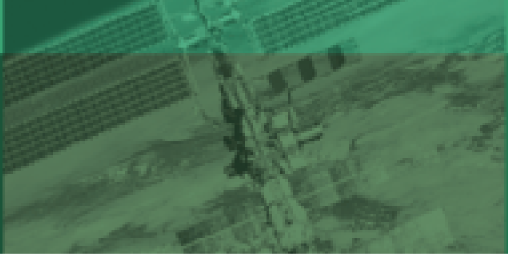
As 2004 drew to a close, two astronauts onboard the International Space Station (ISS) waited—perhaps a little nervously—for the arrival of a vital care package. In early December, they had been placed on a restricted diet to conserve their dwindling food supply. On December 24, the Russian Space Agency launched an emergency shuttle, which reached the station two days later. The shuttle's precious cargo included fuel, oxygen, water, and the welcome addition of fresh food. Had the mission failed, the astronauts would have been faced with only two options: abandon the station or starve.

In the future, astronauts will not face food shortages. They will benefit from technologies that reuse and recycle all solid, liquid, and gaseous materials—including wastes. Such systems are now being developed and tested. The ISS is already outfitted with solar arrays to capture and store the Sun's energy for use in lighting, heating, and powering machinery.

To be fully self-sufficient, the ISS must be able to maintain all life onboard, as well as provide all of the matter and energy needed to support its mechanical systems. This is the most ambitious project ever attempted—a self-sustaining, life-supporting system beyond the boundaries and influence of Earth. What lessons might the ISS offer, in return, to the citizens of the planet that conceived it?



UNIT 1 Preparation

Prerequisite Concepts

This unit builds on your knowledge of the hydrologic cycle.

The Study of Ecology

In 1866, a German biologist and philosopher named Ernst Haeckel invented the term ecology. The word ecology comes from a Greek word that means house or home. At the time, the term was used to describe the observations made and the work done by scientists who studied the nature and history of plants and animals. As more scientists began to ask questions about and explore the interactions of plants and animals, the definition of ecology became broader.

Ecology is the study of the relationships between living things (organisms) and their non-living surroundings, the environment. Ecologists may be found studying events as varied as the cellular processes of microscopic bacteria and the flow of carbon atoms from air, to land, to water throughout the entire planet. Their work may be performed on a mountainside, in a canoe, on a park lawn, in a laboratory, and on computers.

Ecology involves observations, insights, and innovations from many areas of study, within science as well as outside it. Figure P1.1 outlines the connections between these areas of study.

The Biosphere—Earth's Life System

A system is an object or a group of objects that a scientist chooses to study. Everything other than the system is referred to as the surroundings. Systems are separated from their surroundings by a boundary, which may be real or arbitrary. For example, a pond has a distinct boundary that separates the pond from its surroundings. A grassland, on the other hand, may gradually merge with a neighbouring forested region.

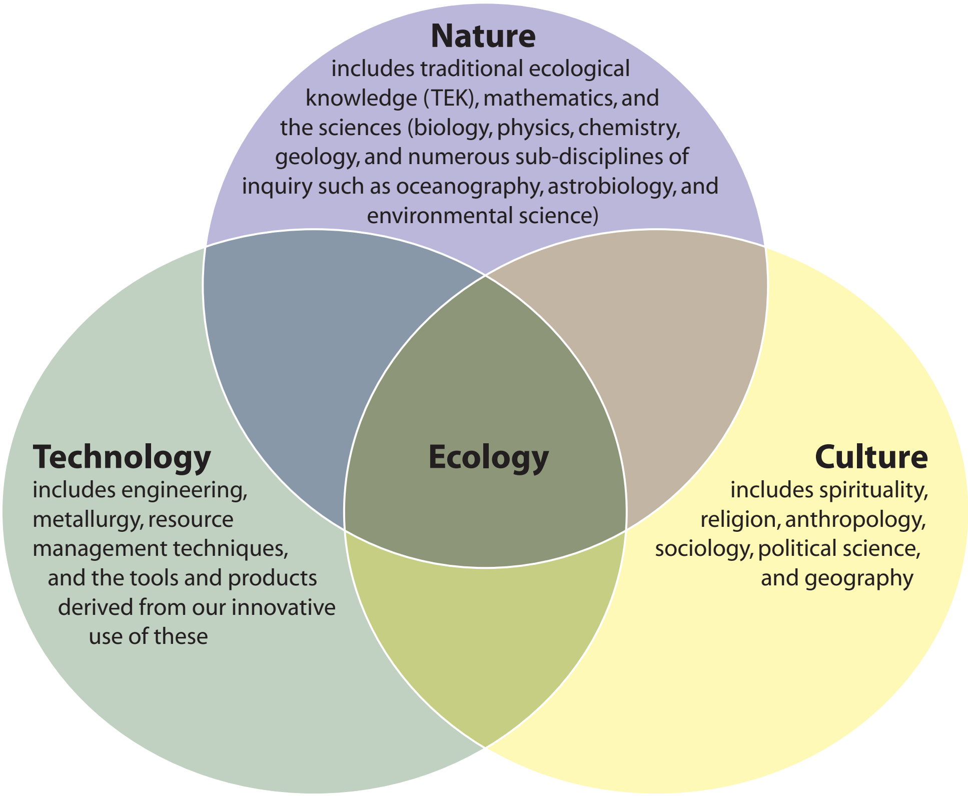


Figure P1.1 Ecology links natural, cultural, and technological dimensions of inquiry. Many areas within and outside of science contribute to our understanding, use, and management of the environment.

Figure P1.2 Organisms may be found on land, in water, several kilometres into the atmosphere, and several metres into the soil. All organisms and their non-living environment make up the biosphere.

In such a case, the boundary of the grassland would be identified by an observer whose boundary might differ from that of another observer.

Systems may be classified into two types according to their interactions with their surroundings.

- An open system is one that allows energy and matter to cross the system's boundary—to enter and leave it.
- A closed system is one that allows only energy (but not matter) to cross the boundary.

In terms of matter, Earth is essentially a closed system. All the matter that is already here remains here. In terms of energy, Earth is an open system. The Sun's energy enters the atmosphere, where some of it is reflected back into space and some is absorbed by the atmosphere. The remaining energy passes on to Earth's liquid and solid surfaces, where some is reflected and some is absorbed. Eventually and ultimately, all of the energy absorbed by the atmosphere and the surface is radiated back into space as heat.

In Unit 1, you will investigate the interactions of matter and energy with the components of the biosphere—the thin layer of air, land, and water on and in which all life on Earth is found.

CHAPTER 1

Energy Transfer in the Biosphere

Chapter Concepts

1.1 How Energy Enters the Biosphere

- Producers (autotrophs) capture energy and store it by photosynthesis or chemosynthesis.
- Consumers (heterotrophs) and decomposers consume autotrophs and other heterotrophs.
- Matter is cycled in the biosphere, but energy follows a one-way path.

1.2 How Energy Is Transferred in the Biosphere

- Food chains and food webs are models that describe feeding relationships and energy transfer between organisms in trophic levels.
- Ecological pyramids are models that describe relationships between trophic levels quantitatively.
- Because all organisms are connected, changes that affect one trophic level affect other trophic levels.

When the United Nations named Sheila Watt-Cloutier one of 2004's seven Champions of the Earth, the Canadian Inuit leader used the occasion to stress her message. "Our elders and hunters have intimate knowledge of the land, sea ice, and have observed disturbing changes to the Arctic climate and environment," she has said. "Our observations are confirmed by western science in the Arctic Climate Impact Assessment." This report—the work of both scientists and indigenous people—highlights the impacts of global warming, which most scientists agree is linked to increased carbon dioxide concentrations in the atmosphere. This increase is due mainly to the burning of carbon-based energy resources.

All organisms need energy to grow and maintain their lives. In this chapter, you will explore how energy is transferred to organisms and to the environment that supports them.

On Earth Day 2005, hundreds of people joined to form this shape of an Inuit drum dancer to send a message to the world.

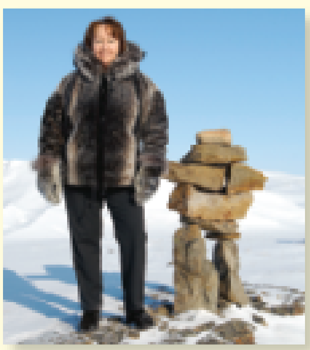
Launch Lab

Considering Connections

In September 2004, Sheila Watt-Cloutier was invited to speak to a committee of United States senators. Her aim was to encourage the United States to reverse its position on the Kyoto Protocol, which came into effect in February 2005. The Kyoto Protocol is an agreement to reduce contributions of gaseous emissions that cause global warming. It was signed by 141 countries.

Procedure

Near the end of her testimony, Watt-Cloutier asked the Senate committee members to consider how the Arctic region, its peoples, and its wildlife are connected to the rest of the world. Read her statement below, and then answer the Analysis questions that follow.



"Use what is happening in the Arctic—the Inuit Story—as a vehicle to re-connect us all, so that we may understand that the planet and its people are one. The Inuit hunter who falls through the depleting and unpredictable sea ice is connected to the cars we drive, the industries we rely upon, and the disposable world we have become." *(Testimony of Sheila Watt-Cloutier, Chair, Inuit Circumpolar Conference to the Senate Committee on Commerce, Science and Transportation, Washington DC, September 15, 2004.)*

Analysis

1. In what ways could an Inuit hunter falling through the sea ice be connected to the activities of people who live south of the Arctic?
2. Aboriginal peoples often talk about how all living things are connected to, and depend on, one another. What does "being connected" mean to you?
3. Do you think you are connected to everyone and everything in the world? Can you prove that you are *not*? Explain your ideas to a partner, and share them with the class.

SECTION 1.1

How Energy Enters the Biosphere

Section Outcomes

In this section, you will
- **explain** how energy enters the biosphere through the processes of photosynthesis and chemosynthesis
- **describe** how energy is transferred in the biosphere through the activity of producers (autotrophs) and consumers (heterotrophs)
- **perform** an investigation to demonstrate the storage of light energy in the form of the chemical energy of starch in green plants

Key Terms

cellular respiration
photosynthesis
producers
consumers
albedo
chemosynthesis
primary consumers
secondary consumers
tertiary consumers
decomposers

Figure 1.1 The fast-moving ruby-throated hummingbird is a common site in much of Canada, from Alberta to Nova Scotia. Each summer, the tiny birds begin a migration trek that takes them as far south as Mexico.

The ruby-throated hummingbird (*Archilochus colubris*) is one of Canada's smallest birds. Ranging in size from 7.5 cm to 9 cm, the hummingbird flaps its wings between 55 and 75 times each second. In flight it can reach speeds of nearly 100 km/h. The "hummer" is barely a blur as it darts from flower to flower in search of sweet nectar. Not surprisingly, the ruby-throated hummingbird expends, and therefore needs, a great deal of energy to stay alive. It gets this energy by eating insects caught in flight, as well as from the nectar sipped from the flowers of plants.

The Need for Energy

All organisms need energy to stay alive. They use this energy to grow, maintain body processes, and reproduce. Many kinds of organisms require energy to move, as well. Energy to support these activities is released in the bodies of organisms from carbohydrates and other energy-rich organic molecules. In animals, plants, and most other species (kinds) of organisms, the process that releases this energy is **cellular respiration**. (For a small number of species that live in environments without oxygen, the energy-releasing process is fermentation.) The word equation and chemical equation below summarize the process of cellular respiration.

How is energy stored in energy-rich molecules in the first place? It is stored through the process of photosynthesis. Through **photosynthesis**, plants, algae, and some kinds of bacteria use the Sun's light energy to chemically convert carbon into carbohydrates such as sugars and starches. The word equation and chemical equation below summarize the process of photosynthesis.

cellular respiration	$C_6H_{12}O_6(s) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(\ell) + \text{energy}$ carbohydrates (sugars and starches) + oxygen → carbon dioxide + water + energy
photosynthesis	$6CO_2(g) + 6H_2O(\ell) + \text{light energy} \rightarrow C_6H_{12}O_6(s) + 6O_2(g)$ carbon dioxide + water + light energy → carbohydrates (sugars and starches) + oxygen

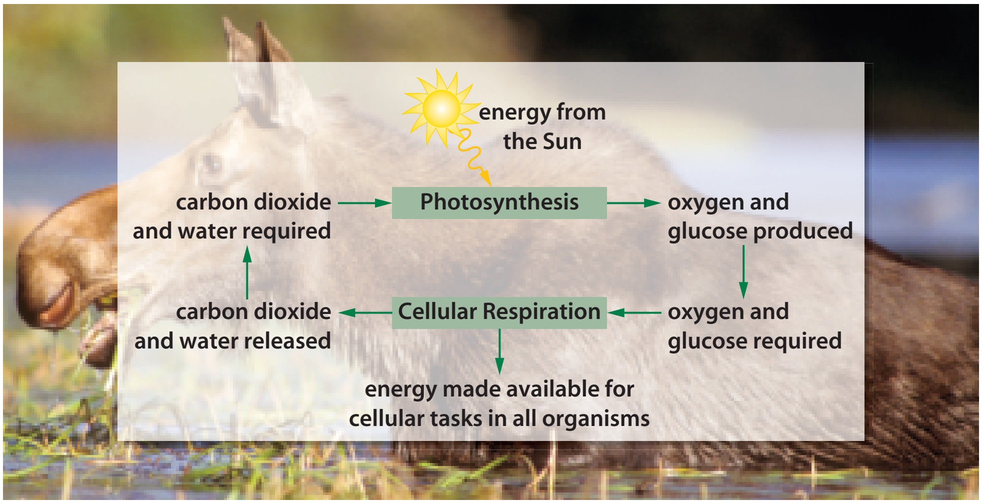


Figure 1.2 Energy from the Sun is captured by photosynthetic organisms (producers). These organisms convert this energy to glucose and other energy-rich compounds such as starches, proteins, and fats. These compounds provide energy and matter for the producers themselves, as well as for consumers of the producers. Notice that photosynthesis and cellular respiration are almost the reverse of each other. Both processes use the same matter, but the form of energy used and released is different.

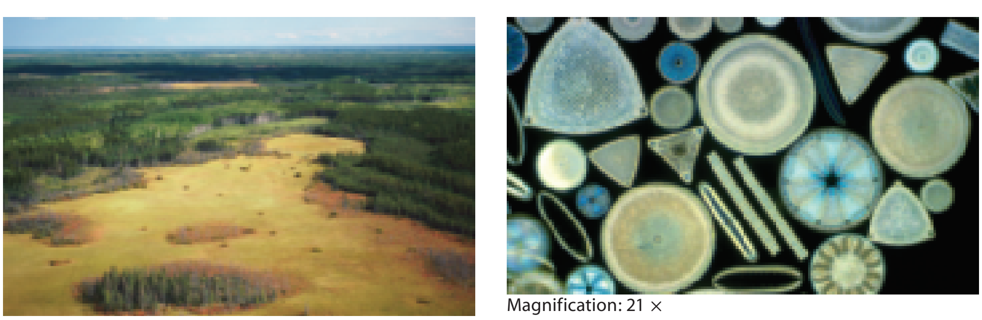
Organisms that are able to use the Sun's energy to produce food for themselves in this way are called **producers**. Producers are also known as autotrophs, which means "self-feeders."

The ruby-throated hummingbird and other animals are not able to make the energy-rich molecules they need to fuel their life processes. Instead, they must obtain these molecules by consuming other organisms (or absorbing nutrients from them). Thus, animals and some other kinds of organisms are *heterotrophs*, which means "other-feeders." Heterotrophs that consume other heterotrophs or autotrophs are called **consumers**. (You will look at consumers and producers in greater detail later in this section as well as in Section 1.2.) Figure 1.2 outlines how producers and consumers are linked through the processes of photosynthesis and cellular respiration.

1. What is cellular respiration?
2. What is photosynthesis?
3. In what way does the energy involved with photosynthesis differ from the energy involved with cellular respiration?
4. What is the connection between organisms that are producers and organisms that are consumers?

A Closer Look at Producers

The Sun is the source of energy for all producers that grow on Earth's surface or that float on or near the surface of the ocean and other bodies of water (see Figure 1.3). About 10^{22} J (joules) of the Sun's radiant energy reaches Earth each day.



Magnification: 21 ×

A Boreal forests occur in most of Canada, in Russia, and Scandinavia. Dominated by coniferous trees, boreal forests make up about one-third of all the forest area on Earth.

B A single millilitre of ocean water may contain thousands of microscopic producers (phytoplankton) called diatoms.

Figure 1.3 From low-growing mosses to towering trees, much of Earth's land surface supports the growth of green plants, which help nourish land-dwelling consumers. In the open ocean, producers float freely near or on the water surface, where the Sun's energy is able to reach them.

INVESTIGATION 1.A

Storing Solar Energy in Plants

Target Skills

Performing an experiment to investigate variables related to the storage of solar energy in plants

Ensuring the safe and responsible handling of equipment and materials, both personally and with regard to the welfare of others in the class

As photosynthesis takes place in the leaves of a plant, carbohydrates are produced. Some of the first carbohydrates that are synthesized are simple sugars such as glucose. Some of this glucose is converted to starch. Starch is a higher-energy molecule than glucose, and it is stored for later use by the plant. Starch turns a brownish-purple colour when it is stained with iodine solution. In this investigation, you will test the hypothesis that plants need light energy to carry out photosynthesis and, thus, convert and store this energy in the form of starch.

Question

Do plants need sunlight to make food for themselves through photosynthesis?

Hypothesis

If plants need sunlight to perform photosynthesis and make starch, then the leaves of plants that are exposed to sunlight should show the presence of starch and the leaves of plants that have been denied sunlight should not.

Prediction

Re-read the introduction to this investigation, as well as the whole procedure. In your notebook, record a prediction about the results you would expect to see if the hypothesis is correct.

Materials

- small test tube
- stopper or stirring rod
- water
- 5 g of cornstarch
- hot plate
- tweezers (or forceps)
- 4 Petri dishes
- tongs or oven mitts
- 400 mL beaker of boiling water
- 150 mL beaker with 50 mL of hot ethanol in a hot water bath
- Lugol's iodine solution (in a dropper or spray bottle)
- plants with solid green leaves such as geranium (*Pelargonium*) or ivy (*Hedera*)—one plant grown for 4 days exposed to sunlight or under grow lights, and one plant placed in the dark for 4 days
- plants with variegated leaves such as *Coleus*, variegated geranium (*Pelargonium*), or spider plant (*Chlorophytum*)—one plant grown for 4 days exposed to sunlight or under grow lights, and one plant placed in the dark for 4 days

Safety Precautions

Ethanol ignites easily and iodine stains skin and clothing. Handle all chemicals with great care.

Procedure

1. Confirm the colour change that occurs when iodine solution is applied to starch. Place 10 mL of warm water in a test tube. Add cornstarch to the water until it no longer dissolves. Mix with a stirring rod or stopper and shake the test tube. Now add one drop of iodine solution to the mixture, then mix once again.
2. You will test for starch in the leaves of four plants. Two of the plants have variegated leaves, and the other two have solid green leaves. (A variegated leaf has streaks or patches of white.) One of the variegated plants and one of the solid green plants were grown in the light for four days. The other two plants, one of each type, were placed in darkness for four days.
3. Take a leaf from each plant. Mark the leaves from plants grown in the light with a notch so you can identify them later. Using tweezers, place each leaf in boiling water for about 10 min. This will soften the cell membranes and remove some of the water-soluble pigments (colouring) in the leaf.
4. Use the tweezers to place each leaf in hot ethanol for about 10 min to remove all the pigment colourings.
5. Use the tweezers to place each leaf in a dry Petri dish. Add a few drops of iodine solution to each leaf (or spray the leaves carefully with the solution). Cover the Petri dishes to prevent ethanol and iodine vapours from escaping.
6. When the investigation is finished, clean up your work area and dispose of all materials as directed by your teacher.

Analysis

1. Which of the leaves you tested showed the presence of starch? Explain how you know.
2. Draw an outline of each leaf. Use shading or a different coloured pen or pencil to indicate where starch was detected.
3. What is the relationship between the pattern in the variegated leaves and the presence of starch?
4. How accurate were your predictions?
5. How valid was the hypothesis?

Conclusions

6. Write a conclusion about the effect of light on the formation of starch in green leaves.
7. What, if any, other factors could have affected the results of this investigation? Explain how you could minimize these factors or their effects.

Extension

8. State a hypothesis and prediction based on the following scenario: Your teacher covers some of the leaves of a solid green plant with aluminium foil. The rest of the leaves are left uncovered. The plant is grown in sunlight for several days. You are then asked to test one covered leaf and one uncovered leaf for the presence of starch. With your teacher's permission, test your hypothesis and prediction.
9. Predict what would happen if you covered the leaf of a solid green plant with a picture-film negative, exposed the plant to sunlight for several days, and then performed the starch test. With your teacher's permission, test your prediction.

As summarized by Figure 1.4, there are three outcomes for this radiant energy.

1. About 30 percent of the energy is reflected from clouds, particles in the atmosphere, or from land or the surface of the ocean back into space. **Albedo** is a term used to describe the amount of reflected energy. Earth's albedo varies from place to place, but the average is about 30 percent. Light-coloured, reflective surfaces and thick cloud cover have high albedos of 80 percent to 90 percent. Dark surfaces such as forest canopies (treetops) and water have lower albedos of 25 percent or less.
2. About 19 percent of the energy is absorbed by gases such as water vapour and carbon dioxide in the atmosphere. Some of this energy will heat the atmosphere, and some will radiate back into space.
3. About 51 percent of the energy reaches Earth's surface. Energy absorbed by the land and oceans warms the planet's surface. Some of the heat from the warmed surface radiates upward into the atmosphere and out into space.

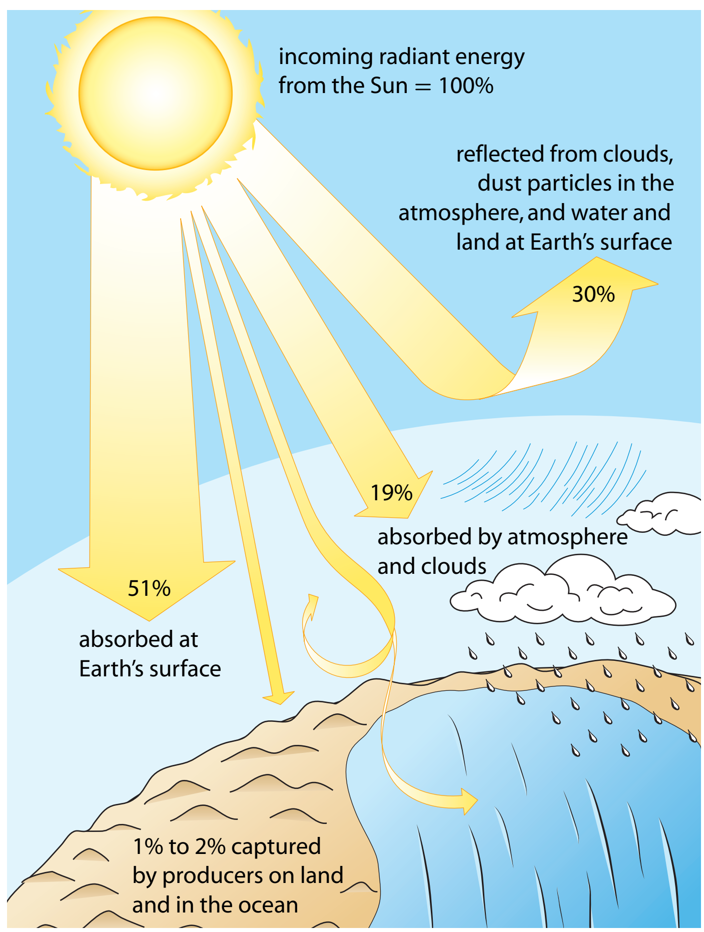


Figure 1.4 Scientists estimate that one to two percent of all the energy that reaches Earth from the Sun is captured by producers and converted to chemical energy through photosynthesis. About half of the incoming energy is absorbed by the atmosphere or reflected back into space without ever reaching Earth's surface.

Of the energy that reaches the ground, only a small fraction reaches producers. Of this, only a portion is used for photosynthesis. The result is that only one to two percent of the total radiant energy that reaches Earth is converted into chemical energy through photosynthesis. (The amount varies from place to place, depending on factors such as the type of organisms present and the intensity of the light.)

Even though the fraction of the Sun's energy that reaches producers is very small, the role of these organisms is significant. Producers generate about 150 billion tonnes to 200 billion tonnes of organic (carbon-containing) matter each year. This amount of life-sustaining matter supports most life on Earth.

Q5 What percentage of the Sun's energy is absorbed by Earth's land and ocean surfaces?

Q6 How does the amount of energy from the Sun that reaches producers compare with the amount of energy from the Sun that first reaches Earth's atmosphere?

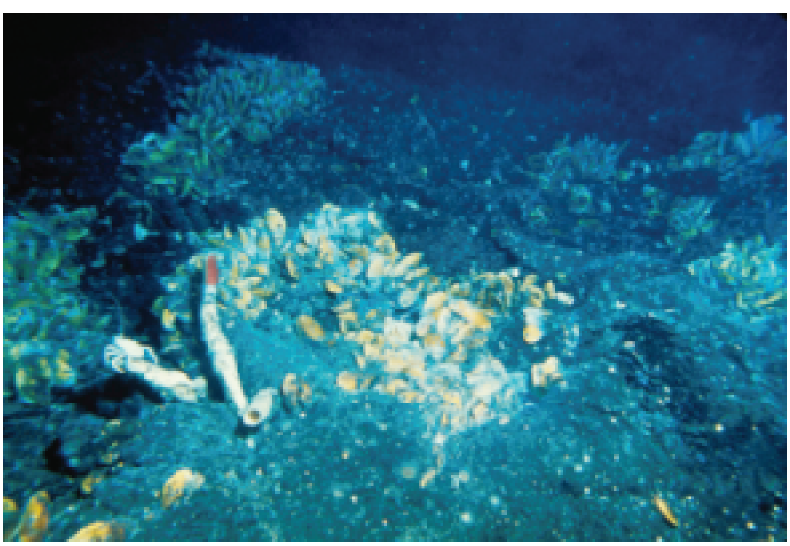


Figure 1.5 This deep-sea vent community, clustered near a black smoker, was discovered on the ocean floor off the Galápagos Islands. Here, giant tubeworms (*Riftia pachyptila*) several metres in height sway in the steam-heated water. Blind shrimp, clams, mussels, crabs, fishes, and even octopuses are other common members of the vent communities.

Energy for Life in the Deep Ocean

In 1977, a group of geologists were exploring volcanic deep-sea vents near the Galápagos Islands off the west coast of South America. Housed in a small submarine, the geologists had descended to a depth of about 2500 m to study the vents. Sometimes referred to as "black smokers", many deep-sea vents spew out hydrogen sulfide-containing water that looks like clouds of dark smoke. Drawing closer to these vents, the scientists encountered the last thing they were expecting: life. Here in this otherwise barren, Moon-like environment, far below the deepest penetration of the Sun's rays, they found a wealth of species, most of which were new to science (Figure 1.5).

Chemosynthetic Producers

The unusual deep-sea vent organisms live near what is often scalding-hot, acidic water. (Heated by geothermal activity, the water surrounding deep-sea vents can reach 350 °C.) Because light does not penetrate to the depths of the ocean floor, these heat-resistant vent organisms cannot rely on photosynthesis to support producers. Instead, bacteria dwell within the tissues of tube worms that live on and near the black smokers. These micro-organisms are able to split the hydrogen sulfide molecules spewing from the deep-sea vents. The bacteria then capture the energy stored in the chemical bonds of the molecules. Unlike photosynthesis, which produces oxygen, sulfuric acid is produced as a byproduct of this process, which is called **chemosynthesis**.

The discovery of chemosynthetic bacterial producers living in the extreme conditions of deep-sea vents inspired scientists to investigate other extreme environments. A variety of species have since been discovered in colder regions of the ocean floor (called cold-water seeps), in hot springs, in intensely salty lakes, and in deep caves. Chemosynthetic producers are also found in places far less extreme than these. For example, beneath the soil you walk on live types of chemosynthetic bacteria. They convert ammonia in the soil to other nitrogen compounds that are used by different kinds of plants and micro-organisms. These nitrifying bacteria, as they are called, play an important role in the nitrogen cycle, which you will explore in Chapter 2.

Q 7 How is chemosynthesis similar to and different from photosynthesis?

A Closer Look at Consumers

Only producers are able to capture energy from the Sun (or inorganic molecules). Thus, all other organisms directly or indirectly depend on producers to meet their needs for energy. As noted earlier, these dependent organisms must consume organic matter (other organisms) as a source of energy, so they are called consumers. Consumers can be classified into groups based on how they obtain their food.

Herbivores are organisms that eat plants. Herbivores are termed **primary consumers**, because they are the first (primary) eaters of plants and other producers. On land, insects, snails, grazing mammals, and birds and mammals that eat seeds and fruits are the most common primary consumers. In water, some species of fish, small invertebrate animals such as clams, and some aquatic insects are common primary consumers. In the deep-ocean vents, tubeworms and mussels are common primary consumers.

Carnivores are animals that eat other animals. Carnivores that eat mainly herbivores are **secondary consumers**. Spiders, frogs, and insect-eating birds are examples of secondary consumers. Often, secondary consumers are themselves consumed by other carnivores, which are called **tertiary consumers** (the third set of eaters). In the deep-ocean vents, giant crabs and blind fish are secondary and tertiary consumers. There may also be higher levels of consumers above these.

The members of another consumer group, **decomposers**, obtain their energy-rich molecules by eating or absorbing leftover or waste matter (Figure 1.6). This waste matter includes the feces of living organisms, dead bodies, or body parts of other organisms. Decomposers include certain kinds of fungi, bacteria, earthworms, and insects. Decomposers are important to the biosphere because they return organic and inorganic matter to the soil, air, and water. These materials can then be used again by producers to make new energy-rich organic molecules. Decomposers are the matter recyclers of the biosphere. They ensure that the matter needed by all organisms is always available.

Q 8 Why are herbivores classified as primary consumers?

Q 9 What are secondary and tertiary consumers?

Q 10 Why are decomposers heterotrophic organisms and not producer organisms?

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Web Link

Canada is at the forefront of deep-sea research and technology. In fact, the first black-smoker-releasing chimneys from the ocean floor were brought to the surface with the aid of a remotely operated submersible vehicle, called ROPOS, and a Canadian Coast Guard research vessel. What is Canadian deep-sea research centred on, what is being investigated, and how does Canada contribute to our understanding of deep-sea biology and geology?

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Figure 1.6 In most cases, decomposers can be classified as more than one type of consumer, depending on their food source. For instance, the beetle *Tenebrio molitor* larvae ("mealworms") shown here eat decaying plant material as well as dead insects and feces.

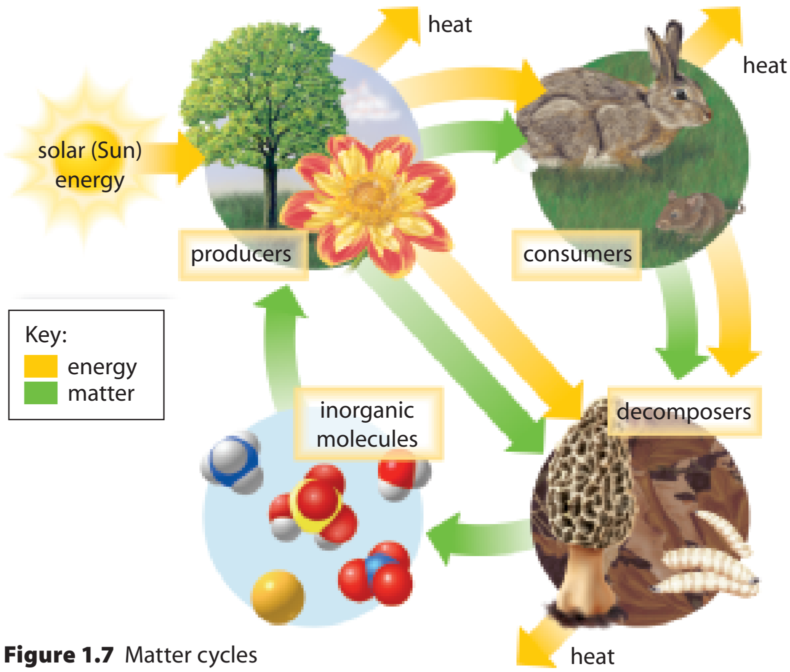

Figure 1.7 Matter cycles within the biosphere, but energy passes through it. As chemical energy is transferred from producers to consumers to decomposers, all the energy eventually dissipates into the environment as heat.

The Fate of Energy in the Biosphere

Earth is a closed system to matter. With the exception of meteorites that reach the surface and satellites and space probes that we launch into space, no matter enters or leaves the biosphere. In other words, Earth has the same supply of matter today that it has had for the billions of years of its history. Atoms and molecules are cycled—used and reused endlessly—in the biosphere.

Energy does not and cannot cycle as matter does. Energy follows a one-way path through the biosphere (Figure 1.7). Why should this be? Recall from previous studies that energy cannot be created or destroyed. It can only be converted from one form to another or transferred from one object to another. This idea is known as the *first law of thermodynamics*. For example, radiant energy from the Sun may be converted into the chemical energy stored in the bonds of carbohydrate molecules. That chemical energy may be converted into motion (kinetic energy) and heat. The total amount of energy in all these conversions does not change.

No process of energy conversion is 100 percent efficient, however. With each conversion of energy, there is less energy available to do useful work. This idea is known as the *second law of thermodynamics*. For example, when you ride in a car, the chemical energy of the fuel is transformed into kinetic energy, sound energy, and (ultimately) heat that randomly disperses into the environment. The same is true of energy released by cells during cellular respiration. This dispersed energy is "lost" for any use by living systems. It cannot be recaptured to support life.

The second law of thermodynamics has important consequences for living systems. Each time a cell uses energy to perform a function, some of that energy is dispersed ("lost") as unusable heat. If additional energy is not supplied to the cell, it will eventually cease to function—it will die. A constant supply of energy, therefore, is necessary to sustain life. This is why producers are essential to life on Earth. Producers are the means by which all organisms are connected to each other through the transfer of energy. You will examine this interrelationship in greater detail in the next section.

Q 11 In what ways do the laws of thermodynamics apply to the processes that take place in and between organisms?

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FYI

All organisms transfer energy to the environment as heat as they carry out cellular respiration and other energy-related activities. While sleeping, a person produces about as much heat as a 100 W light bulb!

Section 1.1 Summary

- For most organisms, energy enters the biosphere through the process of photosynthesis. For organisms that live in the deep ocean and (mainly) in other extreme environments, energy enters their part of the biosphere through the process of chemosynthesis.
- The energy-releasing process of cellular respiration and the energy-storing processes of photosynthesis (and chemosynthesis) are related to each other, providing organisms with the energy and matter they need to survive. Photosynthetic producers capture the

Sun's energy and convert it to chemical energy in the form of high-energy carbohydrate molecules. Chemosynthetic producers capture the chemical energy stored in chemical bonds and convert it to chemical energy in the form of high-energy carbohydrate molecules.

- Consumers (heterotrophs) must eat other organisms for the energy they need. Primary consumers eat autotrophs. Secondary and tertiary consumers eat other heterotrophs. Decomposers consume dead organic material.
- According to the laws of thermodynamics, energy cannot be created or destroyed, only transformed from one form to another. No energy transformation is completely efficient. Therefore, as energy is transferred from one organism to another, much of it is lost as unusable heat to the environment.

Section 1.1 Review

1. Compare the general chemical reaction for photosynthesis to the general chemical reaction for cellular respiration.
2. Describe, using specific examples, the main similarities and differences between photosynthesis and chemosynthesis.
3. Herbivores eat plants and carry out cellular respiration to access the energy stored in carbohydrates, such as glucose. Explain how plants access the energy stored in glucose.
4. Explain why only a fraction of the energy from the Sun that reaches the biosphere is available for use by photosynthetic organisms.
5. Distinguish among producers, primary consumers, secondary consumers, and tertiary consumers in terms of energy.
6. Summarize the two laws of thermodynamics introduced in this section.

Use the following information to answer the next question.

Albedo

The table below lists the albedos of several of Earth's natural features.

Albedo of Natural Features

Features	Albedo
thick clouds	90 percent
thin clouds	40 percent
fresh snow	80–90 percent
sand	30–35 percent
forest	7–18 percent
grass	18–25 percent

7. If global warming is occurring, as most scientists accept it is, and if the Arctic is experiencing losses of snow and ice cover, as satellite evidence and resident Inuit observers report it is, describe how incoming radiant energy from the Sun could be affected as a result of changes in albedo.
8. Skunk cabbage (*Symplocarpus foetidus*), shown in the photograph, is a woodlands and wetlands plant that grows in eastern North America as well as in northeastern Asia. It is one of the first wetland plants to bloom in the spring. Inside the spike-like structure that pushes out of the ground is a cluster of tiny flowers that produce enough heat to raise the temperature within this structure to between 16 °C and 24 °C. In the photograph, the snow has melted in a ring surrounding the emerging plant. Explain what has happened to produce this result.

Eastern skunk cabbage (*Symplocarpus foetidus*)

SECTION 1.2

How Energy Is Transferred in the Biosphere

Section Outcomes

In this section, you will
- **explain** the structure of trophic levels in ecosystems
- **explain** what happens to energy as it is transferred from one trophic level to another through the biosphere
- **describe** and **illustrate** the transfer of energy using models such as food chains and food webs
- **gather** and **analyze** data and information to assess the effect of organism diversity on an endangered ecosystem

Key Terms

trophic level
food chain
food web
pyramid of numbers
biomass
pyramid of biomass
pyramid of energy

In the biosphere, an ecological system, or *ecosystem*, is made up of all the organisms that live in an area and the physical environment of that area. The physical environment includes water, inorganic substances (minerals), and sunlight—that is, non-living things. Organisms, their products (wastes and remains), and the effects they have on their environment are living components of an ecosystem. Together, the interacting living and non-living components form a self-regulating system through which energy and matter are transferred. Describing and understanding how these transfers occur is a major theme of ecology. (You will examine ecosystems in greater detail in Unit 2.)

Trophic Levels Describe Feeding Relationships in Ecosystems

The modified flowchart in Figure 1.8 summarizes three ways to represent feeding relationships in ecosystems. Organisms in an ecosystem can be identified by how they obtain their food and the kind of food they eat. For example, organisms can be classified as producers, herbivores, carnivores, and decomposers. Organisms also can be identified by the type of food-maker or food-consumer they are. For example, organisms could be classified as producers, primary consumers, secondary consumers, and tertiary consumers.

Another, related way to think about feeding relationships among organisms uses the concept of a trophic level. The word trophic comes from a Greek word that means "food." So a **trophic level** in an ecosystem is a feeding level through which energy and matter are transferred. The first trophic level in any ecosystem provides all the chemical energy required to fuel the other trophic levels. Thus, the first trophic level consists of producers. All remaining trophic levels in any given ecosystem consist of consumers. Notice in Figure 1.8 that decomposers may feed at any of the trophic levels.

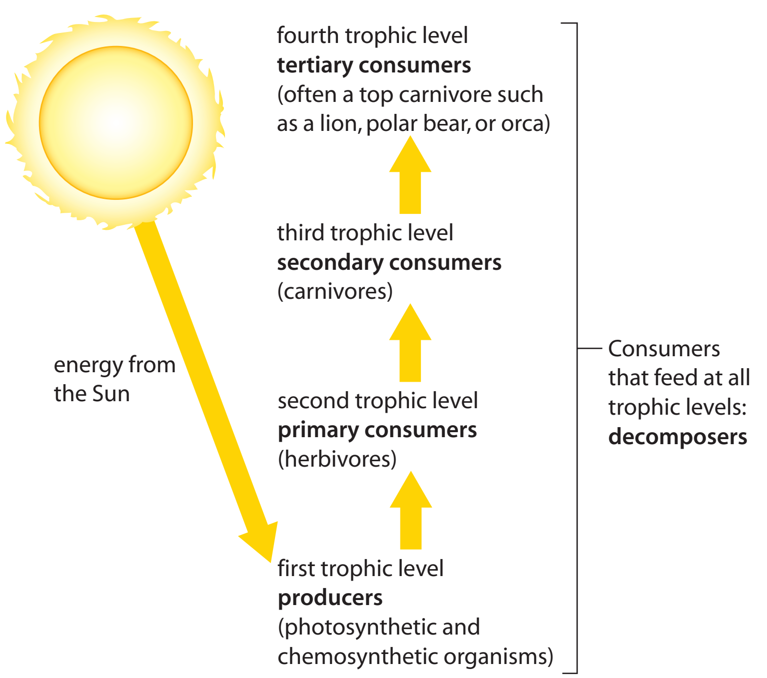

Figure 1.8 Organisms in an ecosystem may be identified by how they obtain their food, or by consumer level, or by trophic level.

12. In terms of feeding relationships, in what ways can organisms in an ecosystem be identified?
13. What is a trophic level?
14. Which trophic level or levels contain producers and which contain consumers?

Food Chains and Food Webs

In the 1920s, a young ecologist named Charles Elton set out from Oxford University in England to study the organisms on a desolate island in the frigid Arctic waters off the northern coast of Norway. Together with another ecologist, Victor Summerhayes, Elton was interested in documenting the feeding relationships in this remote place, called Bear Island. It was here that

Elton first introduced the concept of food chains and the related concept of food webs.

A **food chain** is a model that shows the linear pathways through which food is transferred from producers to primary consumers and to higher trophic levels. Figure 1.9 compares a food chain in a terrestrial (land) ecosystem with one in a marine (ocean) ecosystem.

Elton quickly found that simple food chains could not adequately describe the tangled web of feeding relationships that he observed. Thus, he developed the concept of a food web. A **food web** is a model of food (energy) transfer in an ecosystem that shows the connections among food chains. Figure 1.10 on the next page compares food webs for a woodland-lake ecosystem and an Arctic ecosystem. Use the Try This exercise in the margin to examine these food webs.

Energy Transfer and Trophic Levels

Food chains generally have only a few trophic levels, usually somewhere between three and six. The length of a food chain has limits because the laws of thermodynamics limit the amount of energy that can be transferred from one trophic level to another. As energy is transferred from producers and consumers, only some of that energy is passed along at each step. Consider what it would be like to be in a contest where each team of players had to toss a bucket of water from one person to another until it reaches the last player in the line. There would be only a little water left over for the last player, because some of the water would be spilled each time the bucket was tossed to the next person. Similarly, each time energy is transferred in a food chain, some of the energy is transformed into unusable heat.

How Much Energy Is Transferred from One Trophic Level to Another?

The efficiency with which energy is transferred from one trophic level to the next varies among different kinds

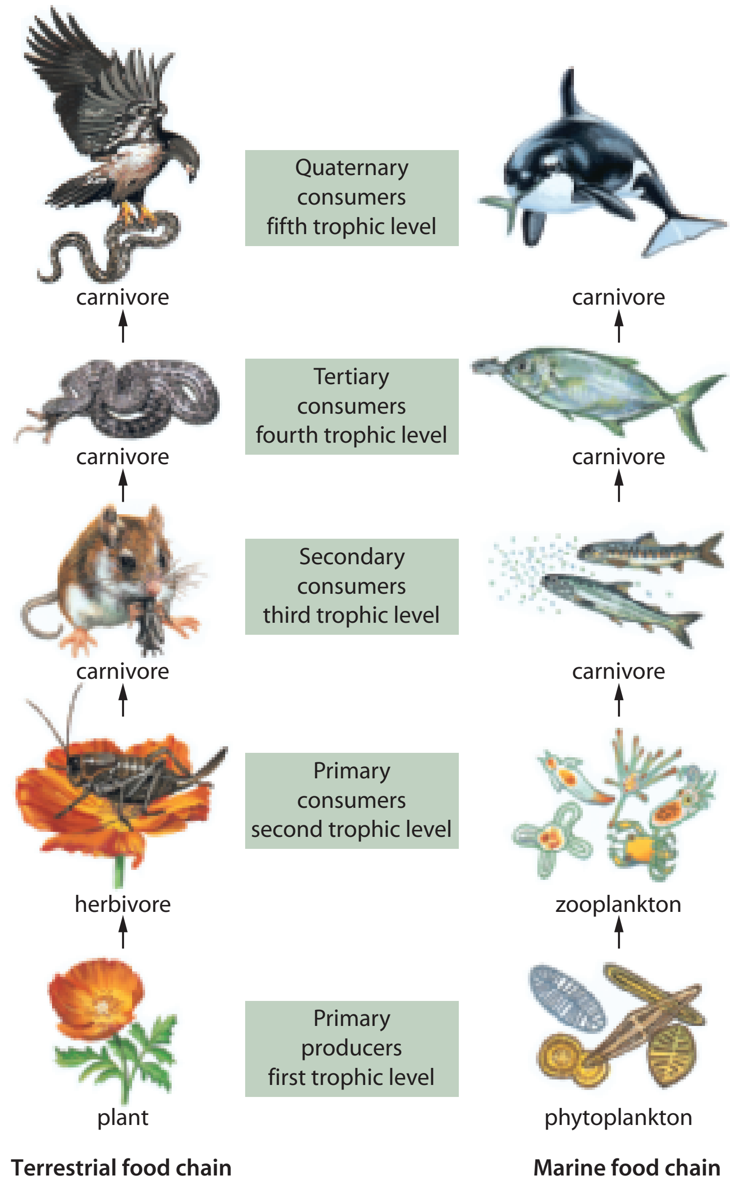

Figure 1.9 Terrestrial and aquatic ecosystems contain different species of organisms but can have the same overall structure of feeding relationships, as shown in these food chains.

of organisms. It usually ranges between 5 percent and 20 percent. In other words, about 80 percent to 95 percent of the chemical energy that is available at one trophic level is *not* transferred to the next one. Figure 1.11 on page 18 shows why.

For convenience, ecologists often assume that 10 percent of the energy at one trophic level is transferred to the next trophic level. For example, assume that 3500 kJ of the energy captured by grain plants such as barley is available to a cow that eats the plants. Following the assumption of 10 percent energy transfer, only 350 kJ of the energy in the cow

Figure 1.10 A woodland-lake food web **(A)** compared with an arctic food web **(B)**.

would be available to a person who eats some beef. This 10 percent assumption is referred to as the "rule of 10." (You may also see it called the 10 percent rule or the 10 percent law, but it is not a scientific law.) The rule of 10 makes energy calculations easier, but it is an oversimplification. Thought Lab 1.1 will give you some practice working with energy values. In Investigation 1.B, you will consider how much energy from the Sun is available to you through your diet.

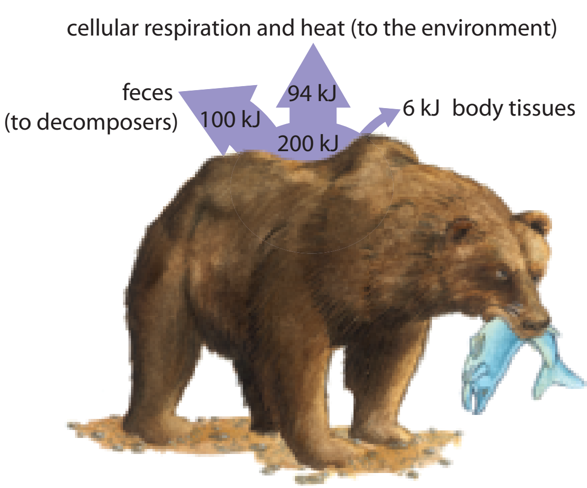

Figure 1.11 A grizzly bear transfers energy to waste products and to the environment, as heat, during cellular respiration. Although the energy values are estimates, very little energy (6 kJ) is transferred to the bear for growth and maintenance. Cellular respiration enables the bear to access the energy content in food so that it can roam, hunt, gather berries, stay warm, reproduce, and survive the winter.

15 Why is less energy transferred from one trophic level to the next in an ecosystem?

16 Explain why there is a limit to the length of food chains.

Modelling Feeding Relationships through Ecological Pyramids

The high visibility of organisms on the barren tundra enabled Charles Elton to observe the number and size of organisms found at each trophic level in the arctic ecosystem that he studied. Through these studies, Elton recognized a pattern in the distribution of the energy and the numbers of organisms among trophic levels. Figure 1.12 shows the pattern that results by sequencing producers and consumers in order of the amount of energy available at each trophic level. Elton was the first to suggest the pyramid-shaped pattern shown in Figure 1.12. Initially called "Eltonian pyramids", these models of feeding relationships are now referred to as *ecological pyramids*. There are three types: pyramids of numbers, pyramids of biomass, and pyramids of energy.

Pyramids of Numbers

In many ecosystems, animals at higher trophic levels are fewer in number than organisms at lower trophic levels. For instance, in Figure 1.12, there are fewer secondary consumers than there are primary consumers. And there are fewer primary consumers than there are producers. The pattern that results is called a **pyramid of numbers**, and it is usually depicted with a shape like that shown in Figure 1.13 on page 20. Each bar of a pyramid of numbers represents a different trophic level and its width represents the relative numbers of organisms at that level.

Counting the numbers of organisms in an ecosystem can be a useful (but time-consuming) way to estimate the amount of energy in each trophic level. However, pyramids of numbers do not always take the upright shape shown in Figure 1.13. Consider a forest ecosystem. Sunlight filters through the forest canopy and is captured through photosynthesis. The trees are producers at the first trophic level, but there are very few trees compared with the number of other forest organisms. There are, for example, thousands and thousands of plant-eating insects at the second trophic level. At the higher trophic levels, large numbers of carnivorous insects and woodland birds consume the plant-eating insects. A pyramid of numbers for this woodland ecosystem has an inverted shape such as the one shown in Figure 1.14 on page 21.

Q17 Explain why a pyramid of numbers can be upright or inverted.

Pyramids of Biomass

One limitation of a pyramid of numbers is that it does not take into account the size of individual organisms. Many

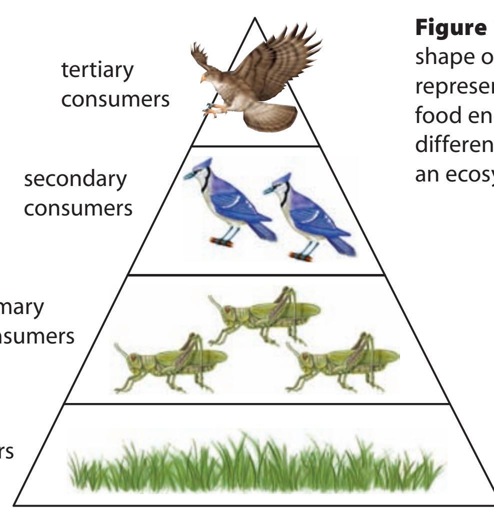

Figure 1.12 The pyramid shape of this diagram represents the amount of food energy available at different trophic levels of an ecosystem.

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Try This
Compare the two food webs in Figure 1.10. How do the lengths (number of trophic levels) of food chains within these food webs compare? How does the overall complexity of these food webs compare? How might the overall complexity of food webs in a tropical rainforest ecosystem compare? Explain your reasoning in all your answers.

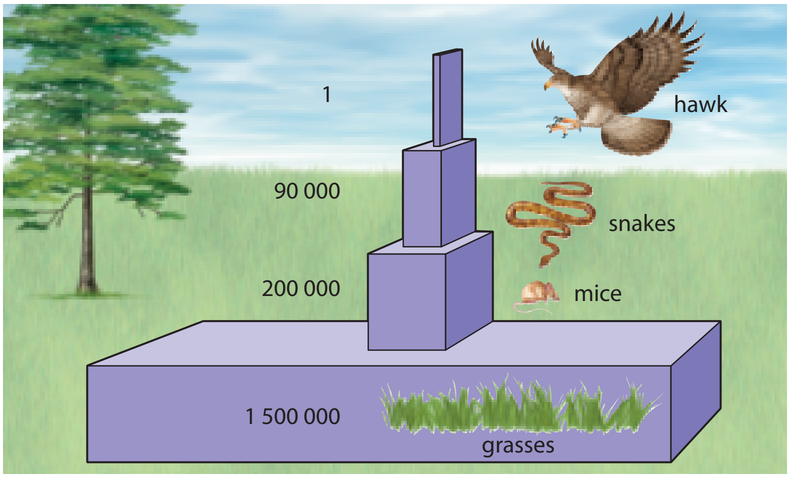


Figure 1.13 This pyramid of numbers for a grassland ecosystem represents the relative numbers of organisms at each link in a food chain (and, thus, at each of several trophic levels).

organisms tend to be larger than the food they eat. Thus, birds tend to be larger than the seeds or insects they consume, and wild cats such as the cougar (*Puma concolor*) tend to be larger than the prey that they catch. There are exceptions, however. A cougar may successfully bring down a moose or an elk. Beetles that dine on a tree are clearly much smaller than their food.

To overcome this limitation, ecologists began to use an alternative measure of energy transfer within an ecosystem: biomass. **Biomass** is the dry mass of living, or once-living, organisms per unit area. Biomass measurements

Thought Lab 1.1 Analyzing Energy Transfers

Target Skills

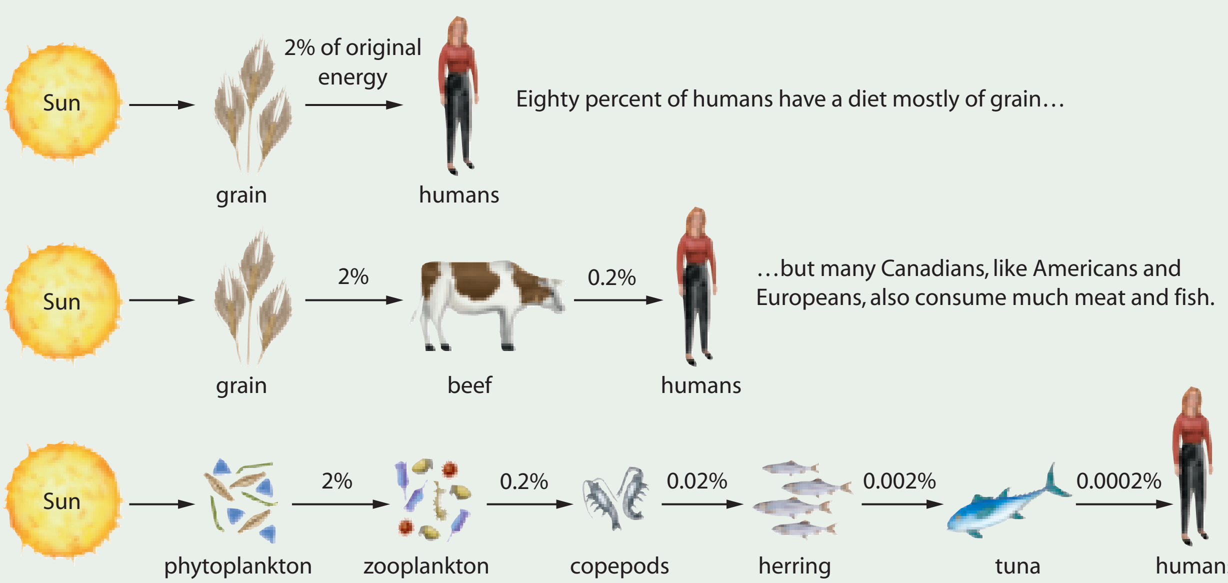
Analyzing data on energy transfer from producers to consumers

Procedure

1. Recall that only a very small fraction of the Sun's radiant energy is absorbed by and incorporated into plant material. For ease of calculation, assume that the amount of energy captured by plants and contained in their tissues is two percent of the total energy available from sunlight. Also assume that 10 percent of the energy at one trophic level is transferred to the next level. (Remember, though, that the 10 percent value is an oversimplification.) Based on this information, answer the Analysis questions.

Analysis

1. The three food chains shown here represent typical food chains for people with different diets. Study the food chains and determine the percentage of the Sun's energy available to humans at the end of each chain.
2. About 80 percent of the world's population eat mostly grain-based foods. Why do you think this is the case?
3. How might diet influence the number of humans that Earth can ultimately support?
4. One square metre of land that is planted with rice produces about 5200 kJ of energy per year. A chicken farm produces about 800 kJ/m^2 of potential food energy per year. Assume that a human must consume 2400 kJ per day to survive. Although it is an oversimplication to imply that a person could survive by eating only one type of food, calculate the total area of land needed to support the student population of your school for year on a diet of (a) rice and (b) chicken.



of a population of organisms are an excellent indicator of the amount of energy present in the living tissue of an ecosystem. From these measurements (usually given in g/m^2), a **pyramid of biomass**, such as the one in Figure 1.15, can be constructed.

Each level of a pyramid of biomass represents a trophic level. The pyramid demonstrates how the amount of biomass changes as energy is transferred from one trophic level to the next. One complication with pyramids of biomass arises because scientists define biomass in different ways. Some scientists include only living materials in their calculation of biomass. Other scientists also include once-living materials, such as dead trees, shrubs, and grasses. There are also exceptions to the upright pyramid shape, as there is with pyramids of numbers. For example, in an ocean ecosystem, at any moment in time, the biomass of the producers (microscopic floating organisms called phytoplankton) may be much less than the biomass of zooplankton, the floating organisms that feed upon them. The result is an inverted pyramid of biomass such as the one shown in Figure 1.16 on page 22.

How can there be fewer producers than consumers in an ocean ecosystem? The phytoplankton producers grow and reproduce at a rate that far exceeds that of the zooplankton. The number of producers doubles in size every few days,

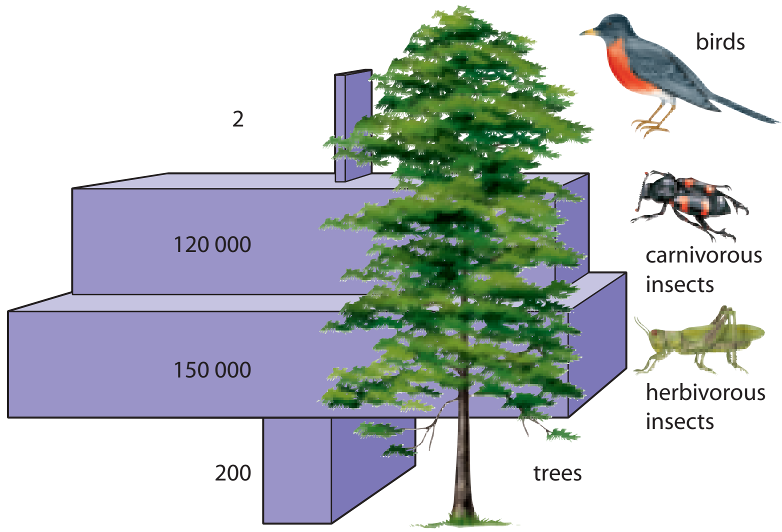


Figure 1.14 In this reversed pyramid of numbers for a woodland ecosystem, a single tree at the first trophic level may feed thousands of plant-eating insects at higher trophic levels.

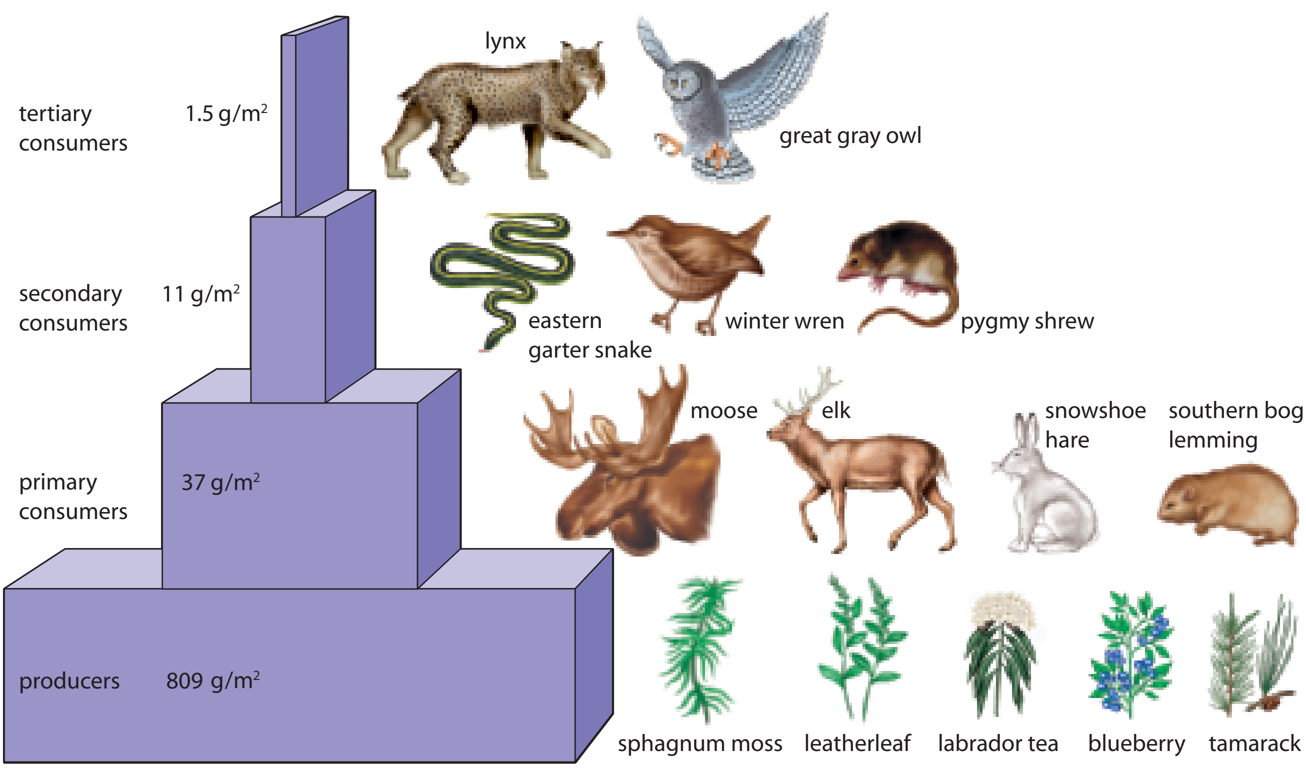


Figure 1.15 This pyramid of biomass shows the relative dry mass, in grams per square metre, of organisms in a bog ecosystem. Some examples of organisms at each trophic level are included. (Diagrams are not to scale.)

INVESTIGATION 1.B

Target Skills

Relating personal energy consumption to feeding relationships and energy transfer through an ecosystem

Creating and **analyzing** a food web based on a human diet

Calculating the percentage of solar energy assimilated by a human diet

Weave Your Own Food Web

Like all organisms on the planet, humans are part of food webs. In this investigation, you will draw a food web based on a record of your food consumption over three days, illustrating the specific feeding relationships and patterns of energy transfer in your ecosystem. You will follow the path of solar energy as it is transferred through various trophic levels to you at the top of each food chain. Using the rule of 10, you will calculate the percentage of the Sun's energy that is available to you through your diet, based on the food choices you make.

Procedure

1. For three days, keep a full record of the food and beverages you eat. Design a chart to record your food and beverage intake. Be sure to include both the type and amount of food or drink consumed, other than water. Be as accurate as you can. For instance, if you eat a slice of pizza, you should record all the items and approximate amounts of each (i.e. the dough, as well as all the toppings) separately. You may have to rely on your own judgment at times, as not all food will fall into a neat category.

2. Using the nutritional information from food labels, the Internet, and/or the library, look up the amount of energy in each food or beverage item you consumed and record the values in kilojoules (kJ). Since the food energy recorded on most food labels show kilocalories (kcal), rather than kilojoules, you will need to convert all kilocalorie values to kilojoules. One kilocalorie is equal to 4.2 kilojoules (1 kcal = 4.2 kJ). (Note that the "calories" shown on food labels are actually kilocalories. Sometimes they are capitalized to indicate this. Thus, 1000 calories = 1 Calorie = 1 kilocalorie.) Try to be as accurate as you can. ICT

3. Calculate the total number of kilojoules of food energy you ate over the entire three days. Then calculate your average daily consumption by dividing this total by three.

4. Organize the food and beverages you consumed over the three days into the following categories:

   Producers (First Trophic Level): Includes all plant-based food such as grains, vegetables, fruit, and all sweeteners.

   Primary Consumers (Second Trophic Level): Includes plant-eating organisms (herbivores) such as most livestock (cattle, chicken, lamb) and some wild game (deer, moose, bison), plus eggs and dairy. Also includes aquatic herbivores such as tilapia, carp, and catfish, as well as shellfish.

   Secondary Consumers (Third Trophic Level): Includes flesh-eating (carnivorous) fish such as salmon, sardines, and trout. Because pigs eat both plant and animal tissue, include pork in this category as well.

   Tertiary Consumers (Fourth Trophic Level): Includes higher-level carnivores such as tuna and sharks, which feed on many fish and sea animals. Tertiary consumers are higher on the food chain than secondary consumers.

   If you are unsure which category a food or beverage falls into, research it on the Internet or in the library. If that fails to provide an answer, make an educated guess.

5. Using the food record you kept, calculate the number of kilojoules contained in the food you consumed in each category. Once you have calculated these totals, divide each total by three to get the average number of kilojoules you consumed each day from each trophic level.

6. Next, divide each daily average by the average number of kilojoules you consumed daily (calculated in Step 3). This will give you the percentage of your diet that comes from each trophic level. For instance, imagine that you get 5862 kJ from the first trophic level and that your total consumption of food energy per day is 8373 kJ. To calculate the percentage of your diet from the first trophic level:

$$\frac{5862 \text{ kJ}}{8373 \text{ kJ}} \times 100 = 70 \text{ percent}$$

   This means that 70 percent of the energy in your diet comes from producers. Similarly, if you consume 1674 kJ from the second trophic level and 837 kJ from the third trophic level, 20 percent of the energy in your diet comes from primary consumers and 10 percent comes from secondary consumers.

7. Create a food web that illustrates the food you consumed over the three-day period. Place yourself in the highest trophic level and use arrows to show the path that energy follows through the food web.

Analysis

1. What percentage of your food comes from comes from producers? From primary consumers? From secondary consumers? From tertiary consumers?

2. Using the rule of 10 and the assumption that the producers transform about 2% of the Sun's energy through photosynthesis, determine the percentage of the Sun's energy assimilated through your current diet. You may want to draw food chains to help you visualize how much energy is transferred between trophic levels. Refer to the food chains in Thought Lab 1.1 as a guide. For example:

   Step 1: If 70% of the energy in your diet comes from producers, the percentage of the Sun's energy represented by this portion of your diet is calculated as follows:

   $$0.70 \times 0.02 = 0.0014 = 0.14\%$$

   (What do these values mean? 0.70 is equivalent to 70%; it is the percentage of energy from producers in your diet. 0.02 is equivalent to 2%. It is the percentage of the Sun's energy captured by producers during photosynthesis.)

   Step 2: If 20% of the energy in your diet comes from primary consumers, the percentage of the Sun's energy represented by this portion of your diet is:

   $$0.20 \times 0.02 \times 0.10 \times 0.10 = 0.00004 = 0.0040\%$$

   Step 3: If 10% of the energy in your diet comes from secondary consumers, the percentage of the Sun's energy represented by this portion of your diet is:

   $$0.10 \times 0.02 \times 0.10 \times 0.10 \times 0.10 = 0.000002$$
   $$= 0.00020\%$$

   Step 4: Therefore, the total percentage of the Sun's energy assimilated is:

   $$0.14\% + 0.0040\% + 0.00020\% = 0.1460\% = 0.15\%$$

3. Compare your results with those of your classmates. Who assimilated the largest percentage of the Sun's energy through their diet? Who assimilated the least? Determine what percentage of these students' food came from which trophic levels. From what trophic level did the person who assimilated the highest percentage of the Sun's energy consume the most food? What about the person who assimilated the least?

4. How many trophic levels are represented in the longest food chains in your food web? Do you think you would assimilate more of the Sun's energy if your food chains were longer? What if they were shorter?

Extension

5. It requires seven times more land to sustain a meat-based diet than a plant-based diet. In other words, the same amount of land required to feed one meat-eater can grow enough crops to feed seven vegetarians. Similarly, the world's cattle eat the same amount of food that would feed 8.7 billion people if humans consumed it directly. Finally, it is estimated to take about 43 000 L of water to produce about half a kilogram of ground beef (Dr. David Pimentel, professor of ecology and agricultural sciences at Cornell University, 1997). Based on these facts, what would be the benefits of vegetarianism in overcrowded or densely populated nations?

but this is not reflected in their biomass because they are eaten as quickly as they reproduce. Thus, enough energy is being transferred to the zooplankton to keep the ecosystem from collapsing. A similar inverted relationship often exists between the zooplankton and the fish that consume them.

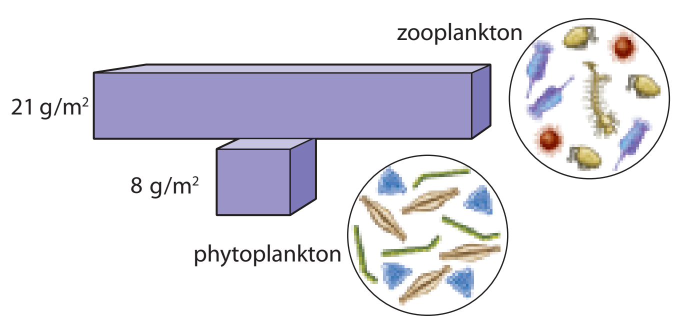


Figure 1.16 In this inverted pyramid of biomass for an ocean ecosystem, the mass of zooplankton (in grams per square metre) in the second trophic level is greater than the mass at the first trophic level of the phytoplankton on which they feed.

BiologyFile

Web Link
The Northern River Basins Study relied on traditional ecological knowledge to help describe the ecology of northern Alberta. What information and perspectives did Aboriginal knowledge bring to this study?

www.albertabiology.ca
WWW

Pyramids of Energy

A third type of ecological pyramid may be used to remove the exceptions of the other two types. A **pyramid of energy** shows the total amount of energy that is transferred through each trophic level (Figure 1.17). A pyramid of energy is always upright, because there can never be less energy in a lower trophic level than in a higher one. Thus, even though phytoplankton have less biomass, more energy flows through the first trophic level than the second trophic level (zooplankton), and the pyramid of energy for the ocean ecosystem remains upright. A pyramid of energy also clearly shows how little energy is left at the highest trophic level. This is why food chains are restricted in size.

> **Q 18** Describe two ways that a pyramid of energy is different from a pyramid of numbers and a pyramid of biomass.

Energy Transfer and Stability in Ecosystems

According to the Inuit in the northern regions of Canada, Alaska, and Eurasia, weather patterns in the Arctic are changing. Inuit elders have observed and described how the sea ice is unusually thin in areas and that the spring melt season is starting earlier in the year. The weather, they say, has become *uggianaqtuq* (pronounced OOG-gi-a-nak-took), an Inuktitut word meaning "to behave in an unusual way."

These observations are increasingly supported by qualitative and quantitative observations from western scientists. Changes that affect climate, numbers and distribution of organisms, and their diversity are being described throughout the world. Ecologists have learned that the stability of feeding relationships in ecosystems decreases with a decrease in the number of species (that is, biodiversity)—especially the number and variety of producers. Understanding food web interactions is important for predicting how biodiversity may increase or decrease in ecosystems, whether in the Arctic, the boreal forest, or the prairie grasslands. In Investigation 1.C, you will explore this idea further as you research the role that certain species play in the food web of an ecosystem that is unstable—an endangered grassland ecosystem.

Section 1.2 Summary

- A food chain is a model that shows the linear pathway through which food is transferred from producers to primary consumers and to progressively higher feeding levels. A food web is a more

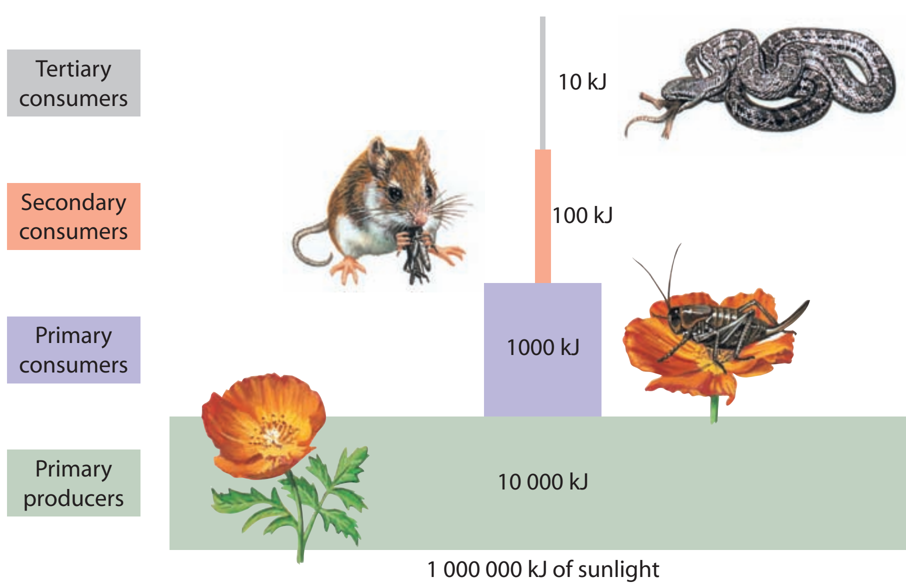


Figure 1.17 This pyramid of energy transfer shows 10 percent efficiency in energy transfer from one trophic level to the next. The rate of efficiency can vary from 5 to 20 percent. This assumes that 1 percent of solar energy is captured by primary producers.

complex model of energy transfer that shows the connections among several food chains. Both are based on the common concept of trophic (feeding) levels.

- Only part of the available energy from one trophic level can be transferred to the next trophic level. As a result, food chains are limited in length. On average, it is assumed that only 10 percent of energy available at a particular trophic level is transferred to the next trophic level.
- Ecological pyramids are used to describe quantitative relationships between trophic levels. A pyramid of numbers is based on the number of organisms in each trophic level. A pyramid of biomass is based on the biomass of organisms in each trophic level. A pyramid of energy is based on the total amount of energy in each trophic level and cannot be inverted.
- Changes within one trophic level may result in changes to a higher or lower trophic level, as well as energy transfer through an ecosystem. These changes may affect ecosystem biodiversity and stability.

Thought Lab 1.2 Energy Fluctuation in an Ecosystem

Target Skills

Analyzing food source data from an aquatic community to understand variables that may be causing a change in population size of a certain species

Due to the numerous links back and forth between trophic levels, and the fact that some organisms can occupy more than one trophic level at a time, species survival tends to be linked to the status of other trophic levels. In this activity, you will consider the effect changes in the numbers of Pacific herring (*Clupea pallas*) have on other species in an Arctic ocean ecosystem: the steller sea lion (*Eumetopias jubatus*).

The numbers of steller sea lions in Alaska and Canada have been shrinking. Between the late 1970s and early 2000s, the body size of the sea lion has also been shrinking, as has the number of pups born each year. The sea lion is a protected species in both the United States and Canada, so scientists have been puzzled as to why its numbers keep decreasing. The decrease in body length and mass might suggest that the sea lions are not getting enough to eat. Coincidently, there has also been a decrease in number of Pacific herring in the region due to over-fishing, food shortages, and possibly changing water temperatures. Pacific herring have been a major food source for the sea lions in the past, but scientists believe that sea lions are now consuming larger amounts of walleye pollock (*Theragra chalcogramma*), which has been increasing in number in the Arctic. Could this change in the feeding patterns of the sea lions be the reason for their decline?

Procedure

Examine the following table and answer the Analysis questions that follow.

Available Energy in Two Types of Fish

Type of fish	Fatty or non-fatty?	Available energy (kJ/g)
Pacific herring (*Clupea pallas*)	fatty	4.4–11.7
walleye pollock (*Theragra chalcogramma*)	non-fatty	3.2–5.9

Analysis

1. How might the change in energy content of the sea lions' prey affect the body size of the sea lions?
2. How might the body size of sea lions relate to their overall population numbers?
3. Suggest two reasons why the number of sea lion pups might be decreasing each year.
4. You are an ecologist who has recently discovered a decrease in the numbers of kelp (a type of seaweed) in the same Arctic ecosystem. You have also found an increase in the numbers of sea urchins that feed off of the kelp and a decrease in the number of sea otters (*Enhydra lutris*) feeding on the sea urchins. You know that there are no longer enough sea lions in the area to support the orcas ("killer whales"), *Orcinus orca*, but the numbers of the whales remains stable. Draw a food web to explain the feeding relationships in this ecosystem. Using your food web, explain how a change in the diet of the sea lions could result in a decline in the numbers of kelp. (**Hint:** What dietary change have the killer whales most likely made?)

INVESTIGATION 1.C

Target Skills

Working co-operatively to research, synthesize, and analyze information about the ecology and trophic levels of a threatened species and an endangered ecosystem

Drawing a food web to depict feeding relationships between the threatened species and other species

Analyzing information to assess how ecological variables may affect the threatened species and its ecosystem

Presenting the result of an investigation to a group

Ecology of an Endangered Prairie Ecosystem

While most people are concerned about endangered species, few realize that these species are often members of an ecosystem that is also endangered. Endangered ecosystems, such as the tropical rainforest, have the highest rate of species loss on the planet. How does the health of an endangered ecosystem affect the livelihood of an endangered species, and vice versa? Loss of an endangered species may change the feeding relationships and energy transfer within its food web. Such changes may be difficult for an endangered ecosystem to recover from. Similarly, environmental changes that affect the ecosystem may also affect the endangered species, which may also be susceptible to these stressors. In this investigation, you will investigate an endangered species living in one of the most threatened ecosystems in the world—the North American prairie.

Procedure

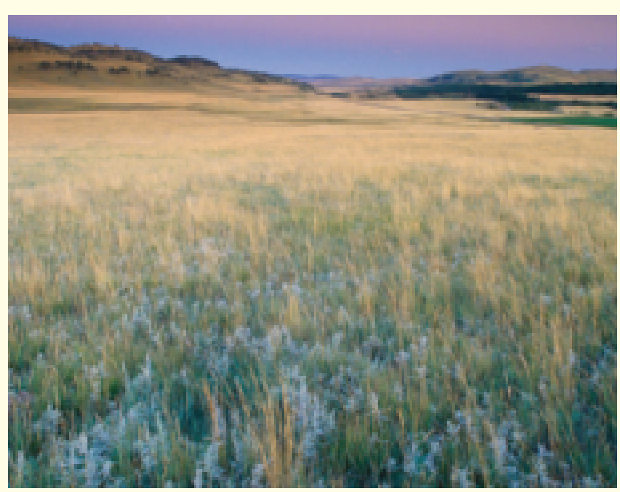
1. With your group, research the ecology of the prairie ecosystem and one of the eight endangered species listed below that are found in this ecosystem. Use Internet or library resources, or contact an ecologist. Find out about your species' role in its food web and possible explanations for its threatened existence, as well as factors that may be endangering the prairie ecosystem. Consider and collect information you may need to answer the Analysis questions. ICT
    - Burrowing owl (*Athene cunicularia*)
    - Swift fox (*Vulpes velox*)
    - Prairie rattlesnake (*Crotalis viridis*)
    - Sage Grouse (*Centrocercus urophasianus*)
    - Sprague's Pipit (*Anthus spraguen*)
    - Long-billed curlew (*Numenius americanus*)
    - Loggerhead shrike (*Lanius ludovicianus*)
    - Ord's kangaroo rat (*Dipodomys odrii*)
2. As a group, list the different trophic levels and links in the food web that your species belongs to.
3. On your own, draw a food web to depict your species' feeding relationships with other species. (Share your food web with your other group members for feedback and possible modification.)
4. Present your research findings in a presentation to your class.

Analysis

1. List the main factors threatening the existence of your species, as well as the existence of the prairie ecosystem. Do any of these factors overlap? If so, which ones?
2. How would the extinction of your species affect the feeding relationships and energy transfer in its food web?
3. Describe the connection between energy transfer and ecosystem stability. How might changes to the food web hypothesized in question 2 affect the stability of the endangered prairie ecosystem?
4. Make a future prediction concerning the survival of your species and the prairie ecosystem based on your research findings.

Extension

5. Create an action plan that could help preserve the species you investigated and/or the prairie ecosystem.



1. Explain why a food web cannot exist without producers.
2. Describe the role(s) of fungi in a food web.
3. Use word processing or graphics software to draw a food chain that includes tuna. Your food chain can include either the names of the organisms or both the names and an illustration of the organisms. ICT
4. Use word processing or graphics software to draw a food web of a deep-sea vent community. Your food chain can include either the names of the organisms or both the names and illustrations of the organisms. ICT
5. A major volcanic eruption ejects millions of tonnes of ash into the atmosphere. Explain how this eruption could indirectly affect the size of a population of herbivorous fish living in a pond thousands of kilometres from the volcano.
6. a) Use graphics or word processing software to draw a pyramid of numbers to represent a hypothetical aquatic community in which 4×10^9 phytoplankton support 11 herbivorous fish which, in turn, can feed one carnivorous fish. ICT
   b) Use graphics or word processing software to draw a pyramid of biomass for the aquatic community described in part (a) of this question. You do not have to use exact values. ICT
7. A pyramid of biomass shows the relative biomass per unit area for each trophic level. Explain why it is important to include the unit area in a biomass comparison.
8. a) Explain how changes to a lower trophic level (for example, a decrease in the number of producers) affect higher trophic levels.
   b) Explain how changes to higher trophic levels (for example, an increase in the number of secondary or tertiary consumers) affect lower trophic levels.
9. Identify situations in which the first trophic level (primary) consumers can have a significant influence on the amount of photosynthetic activity in a community.

Use the following information to answer the next question.

Energy Transfer

Assume that a one square kilometre field produces 300 t/km^2 of grain in one year. The grain that is grown in the field contains 14 190 kJ/kg of energy. One beef cow, with an average mass of 500 kg, needs 7.7 kg of grain every day. Assume that an average person needs 2400 kJ of energy per day to survive and beef contains 13 900 kJ/kg.

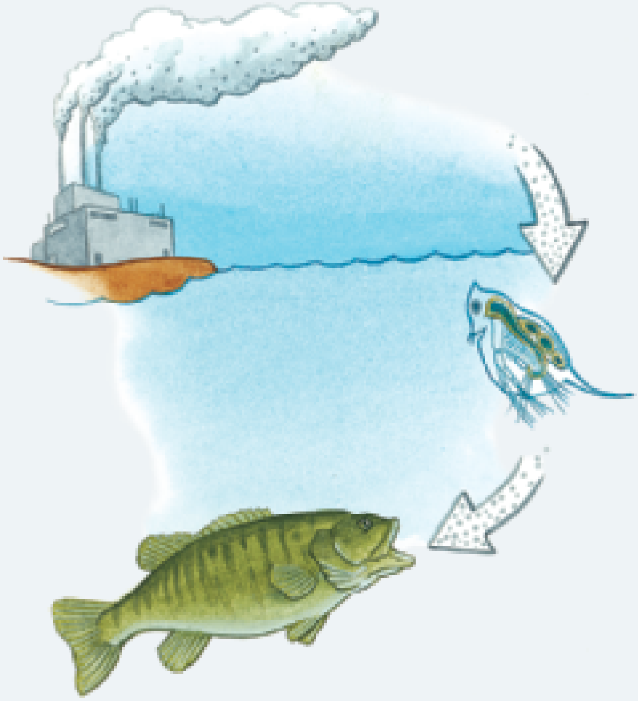
10. a) Calculate how many cattle, in theory, this 1 km^2 field could support for one year.
    b) Calculate the number of people, in theory, that this 1 km^2 field could support for one year if the people ate only the grain. (Keep in mind that this is an over-simplification. A person could not survive by eating only one type of food.)
    c) Calculate the number of people the field could support for a year, if the people ate only beef. (Keep in mind that this is an oversimplification. A person could not survive by eating only one type of food.)
    d) Compare the numbers of people that the field could support in parts (b) and (c). What do the results suggest about the most efficient use of farmland (rangeland for cattle or cropland for growing grain) to feed the most people. Include the disadvantages or limitations of this approach.

Biomagnification: A Fish Story

Fish are an excellent source of energy and nutrients—in fact, they have been called the perfect food. In recent years, however, many scientists have reported finding toxic chemicals in fish. Methylmercury (a toxic form of mercury) is one such chemical. Chronic exposure to methylmercury damages the kidneys, liver, and nervous system. In pregnant women, it interferes with the brain development of the fetus.

Some chemical compounds break down more readily than others—some in a matter of days or weeks, but others not for years. Chemicals such as mercury are persistent—that is, they resist decomposition by micro-organisms and environmental conditions. As a result, these chemicals or their derivatives can remain in the environment for decades.

Mercury occurs naturally in rocks, and natural processes release mercury into the soil and water. The major sources of mercury in the environment, however, result from human activities. Improper disposal of batteries and fluorescent lamps, burning hospital waste, and burning coal for fuel release significant amounts of mercury into the environment. Some micro-organisms in aquatic systems convert elemental mercury to methylmercury, which plants and animals more easily absorb. Over time, the methylmercury accumulates in the tissues of the aquatic organisms. The concentration of methylmercury increases at successively higher trophic levels—a process known as biomagnification.



What's for Dinner?

Health Canada has set an allowable limit of 0.5 ppm (parts per million) of methylmercury in commercial fish, such as salmon and canned tuna. This limit does not apply to large predatory fish, such as shark, however.

Concentration of Methylmercury in Aquatic Organisms

Organism		Concentration (ppm)
Plankton	phytoplankton	0.0109 to 0.176
	zooplankton	0.0110 to 0.376
Crustaceans	shrimp	0.01
	lobster	0.31
Vegetarian fish	tilapia	0.02
	catfish	0.05
Predatory fish	sardines	0.02
	salmon	0.01
	tuna (canned)	0.12
	goldeye (fresh-water)	0.452
	shark	0.99

Note: 1 ppm = 1 mg/Kg (Concentrations vary according to location and species.)
Sources: United States Environmental Protection Agency, Alberta Fish and Wildlife

• • •

1. Sketch a possible food web for five of the saltwater organisms listed in the table above, based on the amount of methylmercury found in their tissues.
2. Calculate how much methylmercury you would ingest if you consumed 0.2 kg of
   a) shrimp **b)** tilapia **c)** goldeye
3. Why does Health Canada recommend that women of child-bearing age not eat shark meat more than once a month?
4. Fish make up about 25 percent of the traditional diet of many Aboriginal peoples in Alberta. How might fish consumption advisories take this into account?
5. What actions could you take to reduce levels of methylmercury in the environment?

Chapter 1 SUMMARY

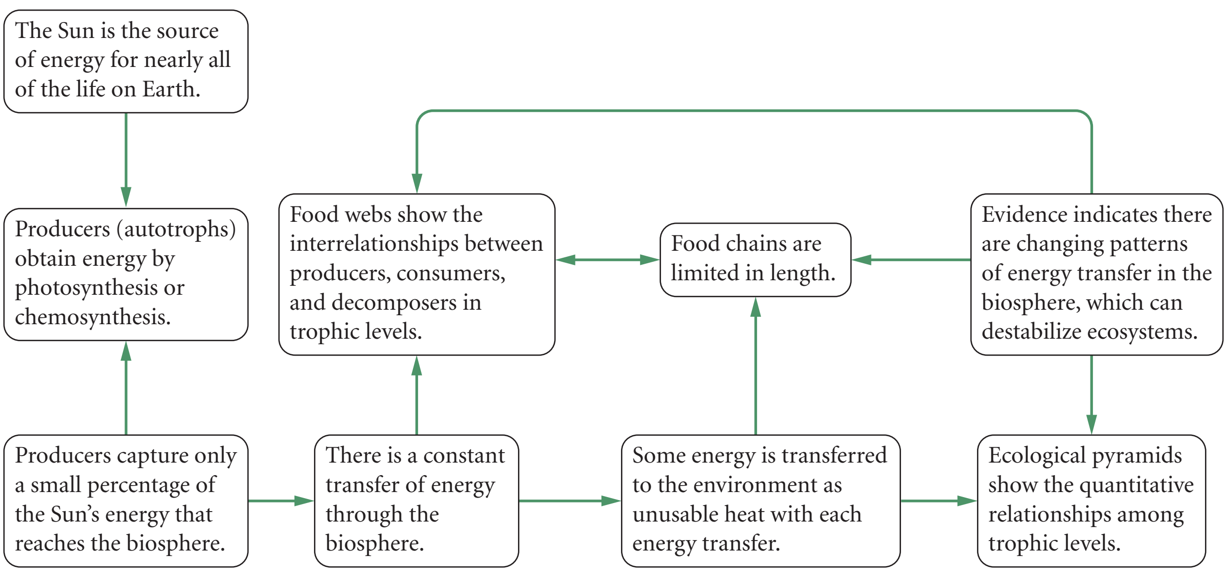
Producers (autotrophic, or self-feeder, organisms) are the basis of all food chains. Producers include photosynthetic organisms (plants, algae, and some kinds of bacteria) and, in select ecosystems, chemosynthetic micro-organisms (certain kinds of bacteria and archaea). Through photosynthesis, producers transform the Sun's radiant energy into energy-rich carbohydrate molecules such as glucose. Through cellular respiration, plants, animals, and most other kinds of organisms use the energy from these molecules to support and sustain their lives.

Consumers (heterotrophic, or other-feeder, organisms) obtain energy by consuming producers and/or other consumers. Primary consumers eat producers, secondary and tertiary consumers eat other consumers, and decomposers consume all kinds of organisms.

Food chains are simple models of energy transfer from one trophic level to another. Food webs are more complex models of energy transfer that show the ways in which organisms in different food chains can interact. Food chains rarely extend beyond four trophic levels because only a small percentage of the energy from one trophic level is transferred to the next level. Ecological pyramids of numbers, biomass, and energy are quantitative models that describe the connections among organisms at different trophic levels.

Because interactions of organisms in ecosystems are so interrelated, changes at any trophic level, or changes to the environment that supports the organisms, can destabilize ecosystems. As a result, the numbers and kinds of organisms can decrease.

Chapter 1 Graphic Organizer



Chapter 1 REVIEW

Understanding Concepts

1. Explain why decomposers, such as mushrooms, are classified as heterotrophs, not as autotrophs.

2. Explain how producer organisms living in deep-sea vent communities are able to survive without using photosynthesis to manufacture food molecules.

3. Describe why there is a limit to the number of organisms in a food chain.

4. **a)** Identify the assumption many ecologists often make about the amount of energy that is transferred from one trophic level to the next trophic level.
   b) How useful is this assumption? Justify your response.

5. List two pieces of evidence, based on traditional knowledge, that energy transfer in the Arctic region is changing.

6. Provide three reasons why solar energy is not completely converted to chemical energy by primary consumers.

7. Select the type of model—a food chain, a food web, pyramid of numbers, or pyramid of biomass—that would be the most informative to show energy transfer between trophic levels in the Arctic Tundra. Justify your selection.

Use the following information to answer the next question.

Ocean Ecosystems

Some transient orcas (*Orcinus orca*), also commonly called killer whales, feed on sea otters (*Enhydra lutris*). (Unlike resident orcas, which live in groups of about 40 individuals and stay in the same area for most of their lives, transient orcas are those that live in very small groups and travel widely in search of food.) Sea otters eat sea urchins, which feed on kelp. Researchers have noted that because killer whales have reduced sea otter population, the size of kelp forests has decreased.

8. Explain how the transient orcas could be having an indirect effect on kelp.

9. **a)** Explain how the same species can occupy more than one trophic level within the same food web.
   b) Explain how this type of interaction can enhance the stability of a food web.

10. Explain why autotrophs (producers) rather than decomposers occupy the lowest level of a food chain.

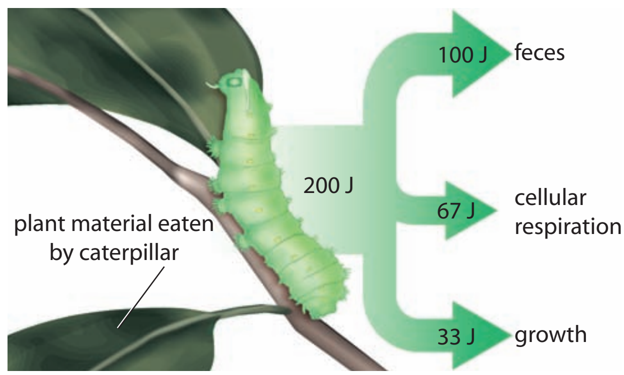
11. **a)** Explain why models showing the relationships among trophic levels in an ecosystem may be shown in the shape of pyramids.
   b) Describe the difference between the information depicted in a pyramid of numbers, a pyramid of energy, and a pyramid of biomass.

Applying Concepts

12. Identify the factors that might cause annual fluctuations in the photosynthetic activity of producer organisms in a grassland ecosystem in southern Alberta.

13. Explain why the energy transfer from a snowshoe hare (*Lepus americanus*) to a carnivorous lynx (*Lynx rufus*) is less efficient than energy transfer from grass to a snowshoe hare.

Use the following information to answer the next question.

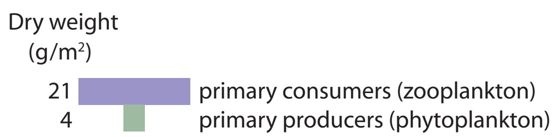


14. Use the diagram above to explain why approximately 80 to 95 percent of the potential energy available at one trophic level is not transferred to the next level.

Use the following information to answer the next question.

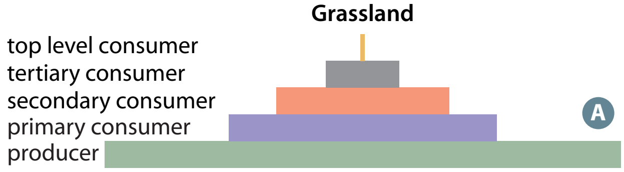
Pyramid of Biomass

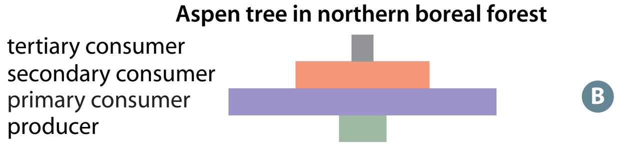
Typically, the shape of a biomass pyramid is similar to that of a pyramid of energy. In some aquatic ecosystems, a relatively low biomass of producers (called phytoplankton) supports a higher biomass of primary consumers (zooplankton). For example, this is a pyramid of biomass based on data obtained through study of the English Channel ecosystem.



15. Explain why the pyramid of biomass in the English Channel is inverted.

Use the following information to answer the next question.





Many ecosystems have a trophic structure that produces a pyramid of numbers with a broad base. In some ecosystems, however, there can be fewer producers than primary consumers.

16. Explain why the trophic structure of a grassland ecosystem results in an upright pyramid of numbers while the trophic structure of an aspen tree in the northern boreal forest is inverted.

Use the following information to answer the next question.

Ecological pyramid data for two ecosystems

Ecosystem A			Ecosystem B	
Trophic level	**Dry weight (g/m^2)**	**Relative number of organisms**	**Trophic level**	**Dry weight (g/m^2)**
primary producers	809	4×10^9	primary producers (phyto-plankton)	4
primary consumers	37	11	primary consumers (zoo-plankton)	21
secondary consumers	11	1		
tertiary consumers	1.5	0		
decomposers	5	millions and millions		

17. a) Use word processing or graphics software to create three separate graphs of the data on this chart. You should end up with two pyramids of biomass and one pyramid of numbers. Clearly label each graph. (**Hint:** see Figure 1.14 on page 21) ICT

b) Describe the advantages and disadvantages of using a pyramid of biomass rather than a pyramid of numbers for Ecosystem A.

18. Suppose that you are investigating possible changes of energy transfer in the taiga (boreal forest) of northern Canada. Explain how traditional knowledge of First Nation, Metis, and Inuit inhabitants of this region could help you with your research.

19. a) You eat a strawberry. Calculate the amount of plant material you would have to eat to gain 1 kg of mass. (Assume the rule of 10 applies.)

b) You eat turkey meat. The turkey ate insects that, in turn, ate plant material. If you could live entirely on turkey meat, calculate the amount of plant material the insects would have to eat to feed enough turkeys so you could gain 1 kg of mass. (Assume the rule of 10 applies.)

Making Connections

Use the following information to answer the next question.

Human Diet

You have seen that there are fewer carnivores than herbivores in ecosystems because of the inefficiency of energy transfer between trophic levels, and that the world could support more people if we ate only plant material. Some people feel this means that humans should switch to a vegetarian diet; others disagree.

20. a) Explain, in terms of energy transfer, why some people believe humans should eat only plant material. Include simple food chains to support your answer.

b) Identify two reasons, in ecological terms, why switching the entire human population to a vegetarian diet might not work.

Use the following information to answer the next question.

Orcas

From 1995 to 2001 the population size of the southern resident population of orcas (*Orcinus orca*) has decreased from a high of 98 individuals to a low of 79 animals, which is a reduction of 20% of the entire population in only 6 years (pers. obs. 2002, Bain 2002). While at this point we do not understand the entire web of causation for this decline, several contributing factors have been reported, such as prey availability and the decrease in salmon stocks, the exposure to toxic chemicals and in particular PCB's (Ross 2001, Dahlheim et al. 2000), as well as the increase in commercial and private vessels mostly for whale watching over the last 10 years (Bain 2002).
[Source: Kriete, *Bioenergetic Changes from 1986 to 2001 in the Southern Resident Killer Whale Population*, Orcinus Orca, 2002.]

21. Explain why this top carnivore is becoming endangered. Focus your argument on the transfer of energy in the marine ecosystem.