1.11

Following Energy Movement in Ecosystems

You can begin to understand energy flows by categorizing living things by their **trophic level** in their ecosystem, according to how they gain their energy. The term "trophic" comes from a Greek word meaning "feeder."

Organisms that can make their own food from basic nutrients and sunlight or some other non-living energy source are placed in the first trophic level (**Figure 1**). Not surprisingly, these organisms are also referred to as producers or **autotrophs** (from Greek words meaning "self-feeders"). Plants, algae, and some types of bacteria are in the first trophic level.

The second trophic level contains organisms that feed on the producers. These organisms are referred to as **primary consumers**. Primary consumers rely on autotrophs directly for their source of energy.

Secondary consumers are animals in the third trophic level. They rely on primary consumers for their source of energy, but they are still dependent on the autotrophs in the first trophic level. Although a wolf eats other animals, it still relies indirectly on the photosynthesis of plants for energy. The deer the wolf eats has eaten the buds of a spruce tree or grass.

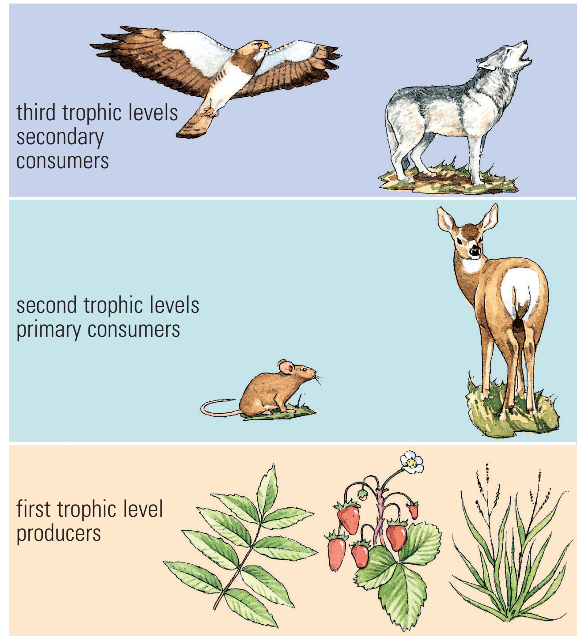

Figure 1
Trophic levels, showing producers and consumers. An ecosystem may contain more than three trophic levels.

Consumers, at whatever trophic level, are sometimes called **heterotrophs**. Heterotrophs cannot make their own food, and so must obtain their food and energy from autotrophs or other heterotrophs. Human beings are heterotrophs.

Energy and Food Chains

Every organism within an ecosystem provides energy for other organisms. Food chains are a way of showing a step-by-step sequence of who eats whom in an ecosystem. The sequence in **Figure 2** shows a one-way flow of energy in a simple food chain from producer to secondary consumer. The deer does not make its own energy; instead it relies on the spruce tree. The deer is a heterotroph. Since the deer receives its energy two steps away from the original source (sunlight) it is in the second trophic level. Using the same reasoning, the wolf, also a heterotroph, is a member of the third trophic level.

Consumers are placed in categories based on their trophic level in a food chain. A carnivore directly feeding on a primary consumer is a secondary consumer. However, if the carnivore eats a secondary consumer (another carnivore), it is now a tertiary consumer — it is at the fourth trophic level. The final carnivore in any food chain is called a top carnivore. Top carnivores are not eaten by other animals (at least, while they are alive). In the example above, the wolf is both a secondary consumer and a top carnivore, since it obtains its energy from the deer and no other animal eats the wolf.

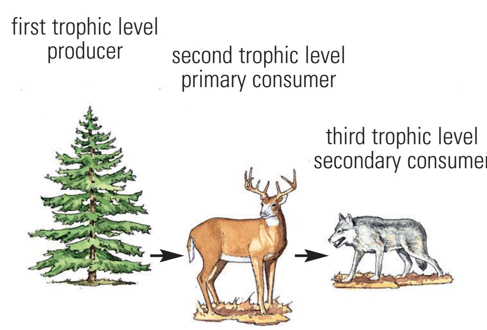

Figure 2
In this food chain, energy flows from a producer (the spruce tree) to a primary consumer (the deer), to a secondary consumer (the wolf).

Food Webs

Consider what would happen if the deer in **Figure 2** depended exclusively on the buds of spruce trees for food. Now imagine what would happen if a new animal were introduced. Spruce budworms also eat the buds of spruce trees. What would happen to the deer if spruce budworms ate most of the spruce buds in a forest? And how would the wolves, in turn, be affected? You might expect that the deer, deprived of food, would die, and so would the wolves. But such dramatic cause-and-effect relationship are rare in natural ecosystems.

Deer also eat buds, stems, and bark of a variety of trees and shrubs, as well as certain grasses. The wolf includes in its diet many different animals, such as rabbits, ground-nesting birds and their eggs, beavers, and muskrats. In reality, each individual organism in an ecosystem is involved in many food chains. They all interlock with each other to form a feeding relationship called a **food web** (**Figure 3**).

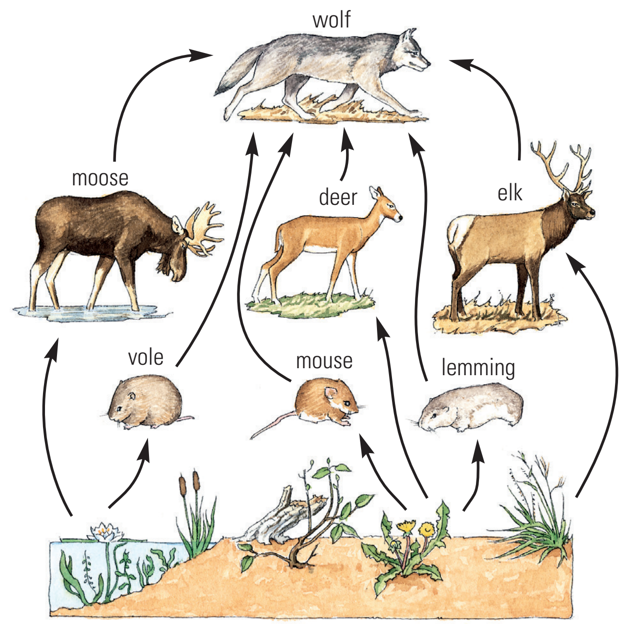

Figure 3
A simplified food web shows the wolf as the top carnivore and plants as producers. Notice that both the vole and the deer belong in the second trophic level of this web. Of course, in a real ecosystem that contained these organisms, there would also be many more other organisms, and the food web would be much more complicated.

The most stable ecosystems, those with the greatest biodiversity, have such complex and well-developed food webs that the reduction in numbers or even the complete removal of one type of organism may have only a small effect on the overall web. If spruce budworms eat most of the spruce buds, deer will switch to another tree or grass, and wolves will not be much affected. However, where abiotic factors limit the number of organisms, the webs begin to look more like food chains.

This is particularly true in the Arctic, where the number of producers is small. Because there is less energy available from the Sun and temperatures are often low, producers in the Arctic can't photosynthesize as rapidly as they do in the south. Less energy is available, so fewer organisms can live in that ecosystem. The limited number of organisms means that their relationships with each other are more direct. In these situations, the loss of any one member will have a profound effect on all the remaining organisms. The lower the biodiversity of an ecosystem, the simpler the food web, and the more vulnerable each organism is.

Limits on Energy Transfer

Producers use energy from sunlight and basic nutrients to make molecules of sugar. Sugar molecules contain the chemical energy that drives ecosystems. Photosynthesis provides the energy required by the entire ecosystem. Without photosynthesis, energy would not move from the abiotic environment to living things. Solar energy must be converted into chemical energy before it can be used by living things.

Every time energy is transferred within an ecosystem, some of the energy changes form. For example, some of the energy from the Sun is converted into chemical energy by plants as they photosynthesize. Animals, in turn, rely on the chemical energy (food) produced by plants to sustain their lives. However, not all of the chemical energy that a plant creates can reach the animal that eats it. The plant uses most of that energy to stay alive and to manufacture the chemicals it needs to grow. Once an animal takes chemical energy from a plant, it doesn't store it all.

Most of that energy is used to move its limbs, pump blood, keep its body warm, and manufacture the chemicals it needs to carry out its own life processes.

For example, a mouse that has eaten grass seeds cannot store all the energy from the seeds. It must use some to stay warm, to keep its cells and organs functioning, to move around, to feed its young, and so on. Once the energy has been used, it is not available to be transferred. When an animal such as a fox eats the mouse, only a small fraction of the energy that was stored by the grass reaches the fox. It is true of all food chains that the farther up the chain you travel, the less energy is available. In every ecosystem, there is less energy available to secondary consumers than there is to primary consumers.

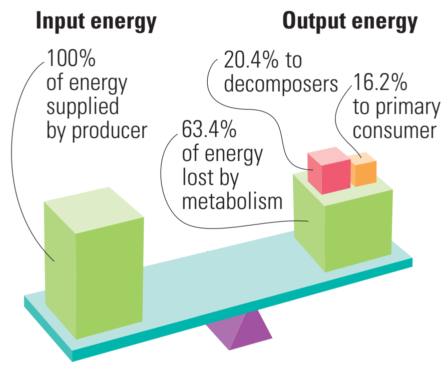

Figure 4
In any system, the energy input must equal the energy output. Most of the energy transformed from light to chemical energy by a plant is used to maintain the plant and to grow. Every time the plant uses some of its energy store, it also loses energy as heat. As a result, when the plant is eaten, only a small amount of energy is available for the primary consumer and decomposers. (Bacteria and fungi acquire 20.4% of the energy found in the producers during decomposition after the plant dies.)

Thermodynamics

There is another limitation. The energy flowing from the Sun through ecosystems must obey basic scientific principles known as the laws of thermodynamics. **Thermodynamics** is the study of energy transformations.

- The **first law of thermodynamics** states that although energy can be transformed (changed) from one form to another, it cannot be created or destroyed (**Figure 4**).
- The **second law of thermodynamics** states that during any energy transformation, some of the energy is converted into an unusable form, mostly thermal energy (heat) that cannot be passed on. Each time energy is transformed, some energy is lost from the system. As a result, the amount of energy available in each step of a chain of transformations is always less than the amount of energy available at the previous step. This applies to all systems, including food chains (**Figure 5**).

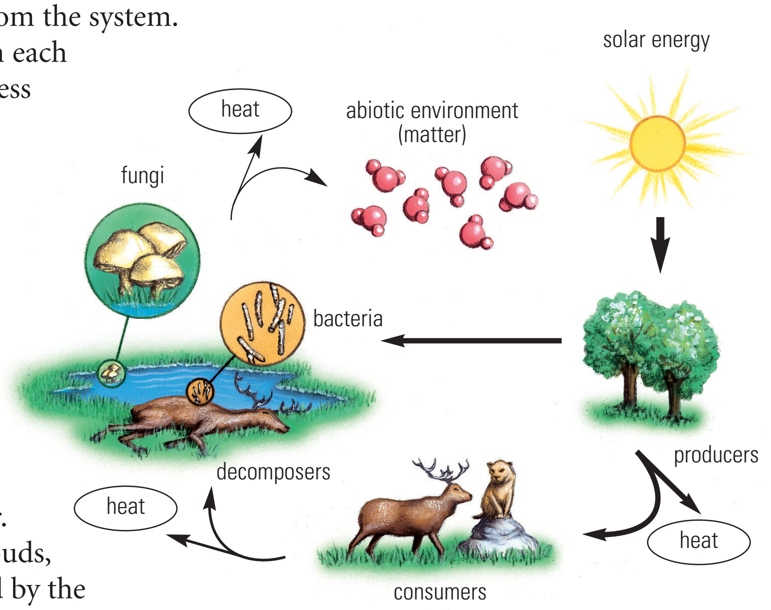

Figure 5
Because of the second law of thermodynamics, energy is lost each time energy is transferred from one organism to another, and inside each organism as it uses the energy to survive.

Limits on Energy Transfers and the Number of Trophic Levels

Let's return to the simple spruce —> deer —> wolf food chain. If you follow the energy flow, you can see that there are several factors that reduce the available energy at each transfer.

A deer grazing on spruce may eat only the buds, not the whole tree. Not all of the bud is digested by the deer. Some is eliminated in the deer's wastes (feces). Energy is lost to waste heat during the chemical transformation of digestion. Some of the remainder is used to fuel the deer's cells, resulting in loss of energy as waste heat is generated in the process. Some of this heat is used to maintain the deer's body temperature, but it is all lost eventually to the surrounding air. As a result, only about 10% of the energy of the plant that was transferred to the deer becomes available to the wolf.

By not consuming parts of the deer, such as its bones, hooves, skin, and fur, the wolf uses only a portion of the energy stored in the total deer tissue. And like the deer, it loses energy in digestion and body maintenance.

In general, the overall loss of energy at each step sets a limit on the number of trophic levels in a food chain at about five. In most ecosystems, there wouldn't be enough energy to support a higher-level consumer.

Graphing Energy in Ecosystems: Ecological Pyramids

Graphs called pyramids can be used to represent energy flow in food chains and food webs or the populations of organisms in a food chain. These graphs help the ecologist visualize more clearly the relationships in an ecosystem and to compare ecosystems.

Pyramid of Energy

It is possible to measure the amount of energy available at each trophic level.

Creating a pyramid graph allows us to understand the relationships and energy flow better (**Figure 6**). The comparatively larger mass of the individual tertiary consumers and the vast amount of energy that they expend while hunting limits the number of individuals that can be supported at the top position of the pyramid.

Pyramid of Numbers

A pyramid of numbers can be drawn by counting the number of organisms at each trophic level in an ecosystem. When these numbers are then represented on a vertical graph, with the volume of each level representing the number of organisms at that level, the graph sometimes takes on the general shape of a pyramid (**Figure 7**). Ecologists have found that there are many exceptions because of the physical size of the members of a food chain. For example, many tiny aphids (an insect that feeds by sucking sap from plants) may be found feeding off a single plant (**Figure 8**).

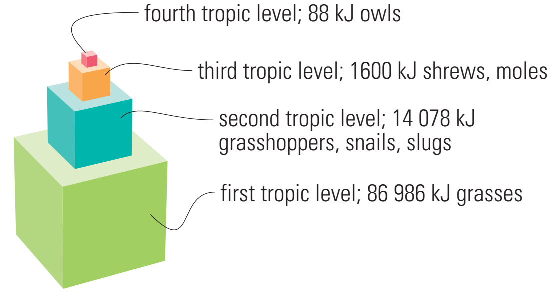

Figure 6

A pyramid of energy for a grassland ecosystem. At each level, the energy found in the bodies of the organisms is graphed. The larger the volume of the level, the greater the energy at that level. As you can see, only about one-thousandth of the chemical energy from photosynthesis stored in the producers in this food web actually reaches the top predator (the owl) at the fourth trophic level. Energy is measured using joules (1000 joules (J) = 1 kilojoule (kJ)).

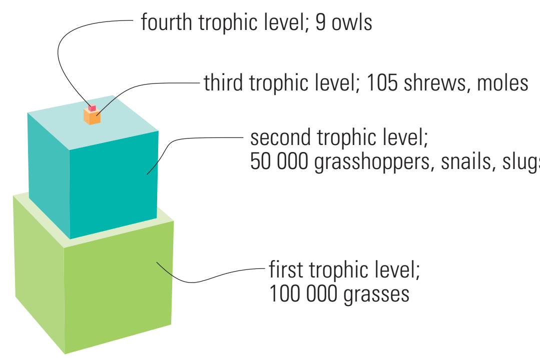

Figure 7

A pyramid of numbers for a grassland ecosystem. In this ecosystem, the number of producers is greater than the number of primary consumers.

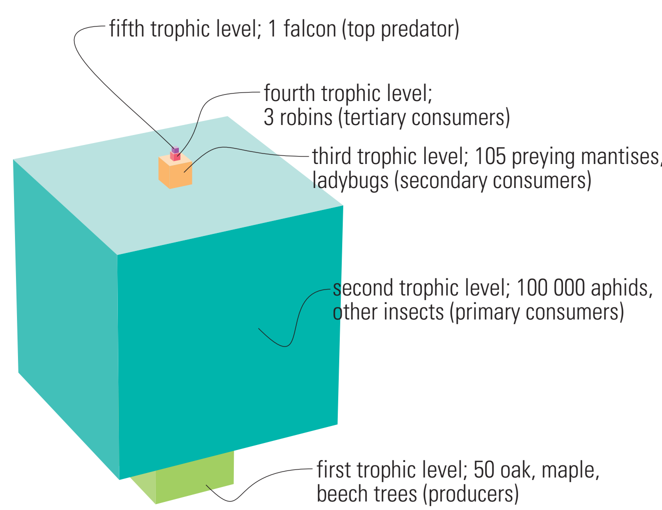

Figure 8

A pyramid of numbers for a deciduous forest ecosystem. Because an aphid is much smaller than a tree, a single plant may provide food for thousands of aphids.

Pyramid of Biomass

Another useful way to represent an ecosystem is through a pyramid of **biomass**. To make such a pyramid, the dry mass (after water has been removed) of the dry tissue in the plants or animals is measured and graphed (**Figure 9**). Occasionally, a graph of biomass is not a regular pyramid. Such ecosystems, however, are rare.

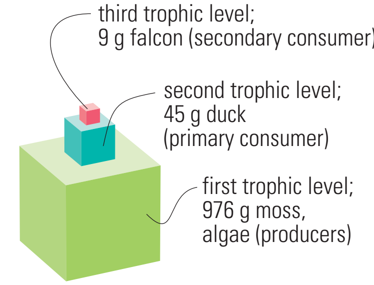

Figure 9
A pyramid of biomass for a Newfoundland peat bog. The numbers represent the dry mass (g) for all organisms at that trophic level found in 1 m^2. As you can see, there is less biomass at each trophic level.

The Energy Budget

Regardless of the pyramid used to illustrate a food chain or web, each shows that the end result is the same. The energy available to maintain a food chain inevitably runs out unless the original energy, sunlight, is continuously fed into the system. Also, in every ecosystem there is a limit to how much energy is available. It is obvious that primary consumers have access to the most energy. This finding has very real implications for humans as the world population continues its dramatic rise.

Cultural Change: The Human Use of Energy in Ecosystems

Although the planet is an estimated 4.6 billion years old, the impact of humans is relatively recent. Researchers believe that modern humans have been part of worldwide ecosystems for somewhere between 60 000 and 90 000 years. Until about 12 000 years ago, however, the influence of humans on ecosystems was very small. Since that time there have been two major shifts: the agricultural revolution and the industrial revolution. Each of these cultural changes has placed increasing demands on ecosystems for energy and reduced the amount of energy available to other organisms.

By increasing the food supply, improving health, and increasing the lifespan for humans, each of these cultural changes was followed by an increase in the human population. Recently, the increase has accelerated, threatening the ability of ecosystems to sustain themselves. The increasing rate of extinction and the loss of entire ecosystems provides evidence of the strain caused by the growing human population.

Hunting and Gathering

Humans were hunters and gatherers for most of our history. Our ancestors survived by collecting edible plants and eating animals that they caught or dead animals that they found or stole from predators. They lived in small groups that moved to a new area if local resources became depleted.

The energy demands made on the ecosystem were limited to two sources: wood for fuel and food (chemical energy) obtained from plants and animals. Because of limited food resources, human populations grew very slowly or were stable.

Agriculture

Somewhere between 10 000 and 12 000 years ago, a cultural shift known as the agricultural revolution began. The gradual movement from a nomadic existence to the farm was made possible by a change in climate. The planting of crops and domestication of animals allowed people to remain in one place. Trees were cut and the lumber was used to make permanent housing.

Wetlands were drained and forests were cut so the land could be cultivated.

Farms produced more food energy for humans, and allowed the population to grow, but they also made greater demands on local ecosystems. The additional energy needed to sustain a farming community must be supplied by the ecosystem. In effect, humans began to take a larger share of the energy budget for the ecosystems they inhabited.

Industry

With the invention of technological devices to perform work, the demand on the energy of ecosystems grew. Energy from ecosystems was used to power machines. The products helped to increase food production and improve the health of humans. Although each industrial improvement allowed the local ecosystem to support a greater population of humans, an increasing population places greater demands on the ecosystem (**Figure 10**).

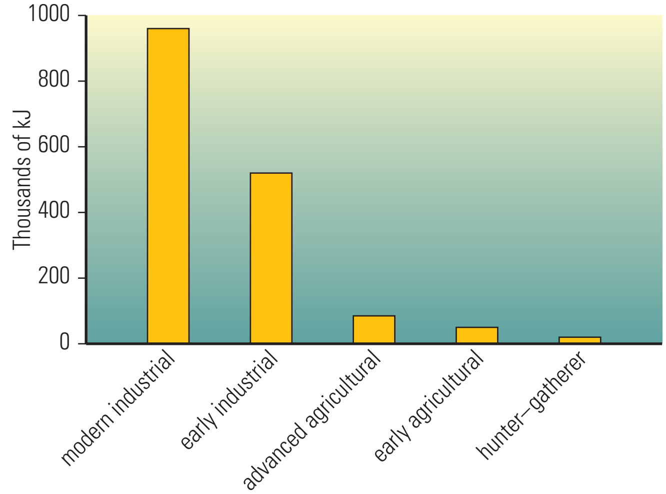

Figure 10

The amount of energy people use each day depends on the type of society they live in.

Challenge

1,2,3 One way of understanding an ecosystem is through the study of energy transfers. What energy transfers would need to be considered in your Challenge?

Understanding Concepts

1. In your own words, explain what is meant by the term "trophic level."
2. Why are producer organisms called autotrophs?
3. How does a heterotroph differ from an autotroph?
4. What type of food would be consumed by a secondary consumer? Explain your answer.
5. In your own words, explain what is meant by the term "top carnivore." Give three examples of a top carnivore, including the ecosystem in which you would find each one.
6. Distinguish between a food chain and a food web using examples for each.
7. Explain why an Arctic ecosystem would be more fragile than a southern forest ecosystem.
8. In your own words, explain the first and second laws of thermodynamics.
9. Explain why only about 20% of the energy available in a plant is transferred to the primary consumer.
10. Using the example of a cat and a mouse, explain the factors that account for the loss of energy in the transfer from mouse to cat.
11. What data would you need to collect to create an ecological pyramid of numbers?
12. What problem might you encounter if you tried to show energy flow through an ecosystem using a pyramid of numbers?
13. How might a pyramid of energy for a grassland community differ from summer to winter? Speculate about the effects of the differing abiotic conditions by drawing an ecological pyramid of energy for each season. Include an explanation for any differences.
14. **Figure 11** shows pyramids of biomass and numbers for a deciduous forest. Explain why the two are different.

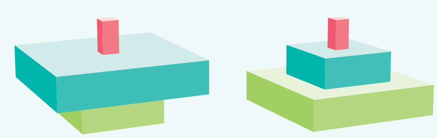

Figure 11

Reflecting

15. Despite warnings about future shortages and the pollutants released, we continue to burn oil and coal for energy. What evidence, if any, suggests attitudes toward conservation are changing? Are they changing quickly enough?