To do

Carnivores in the tundra ecosystem

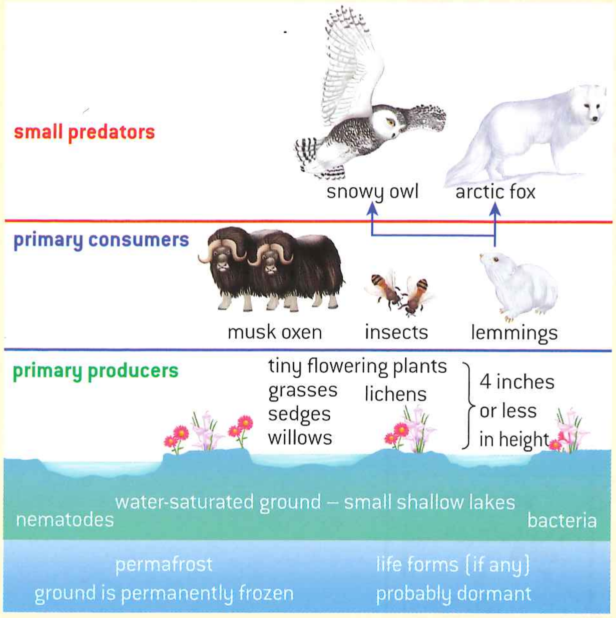


Figure 2.2.5 A food web in the tundra; source Dave Harrison, used with permission

There are several species of bear in the tundra. Polar bears live further north, but are also found in the tundra searching for food. The Kodiak is the largest bear in the Alaskan tundra. It is usually a brown colour. Brown bears are not as fierce as their reputation makes them out to be. They seldom eat meat. Wolves are the top predators of the tundra. They travel in small families (packs) and prey on caribou and other large herbivores that are too slow to stay with their groups. Some wolves change to a bright white colour in the winter. Otters live near rivers and lakes so they can feed on fish. Shrews are the smallest carnivores of the tundra. Even bats are found in the tundra during the summer. They feed on the swarms of insects that fill the air.

The primary production is not sufficient to support animal life if only small areas of tundra are considered. The large herbivores and carnivores are dependent on the productivity of vast areas of tundra and have adopted a migratory way of life. Small herbivores feed and live in the vegetation mat, eating the roots, rhizomes and bulbs. The populations of small herbivores like lemmings show interesting fluctuations that also affect the carnivores dependent on them, such as the arctic fox and snowy owl.

The blue squares represent the appearance and frequency of snowy owls after almost exponential population increases of lemmings. There is then a lag period of about two years before lemming numbers increase again.

1. Draw a food web for the tundra with **only** the animals mentioned.
2. Why do you think the snowy owls only appear when lemming numbers have fallen? (Hint: climate and decomposers.)

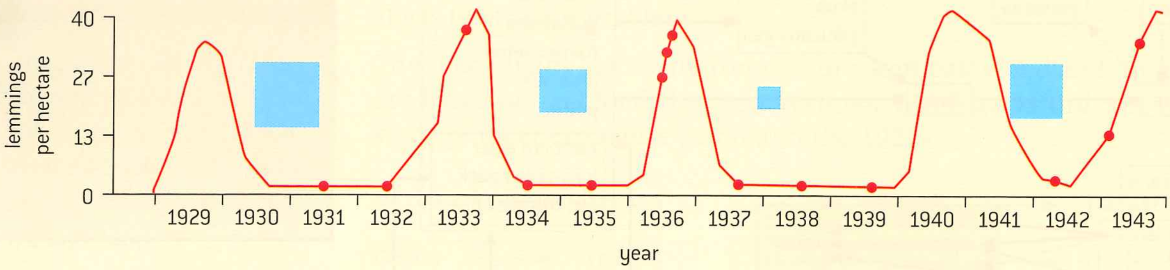


Figure 2.2.6 Snowy owl and lemming numbers in the tundra from 1929 to 1943

To do

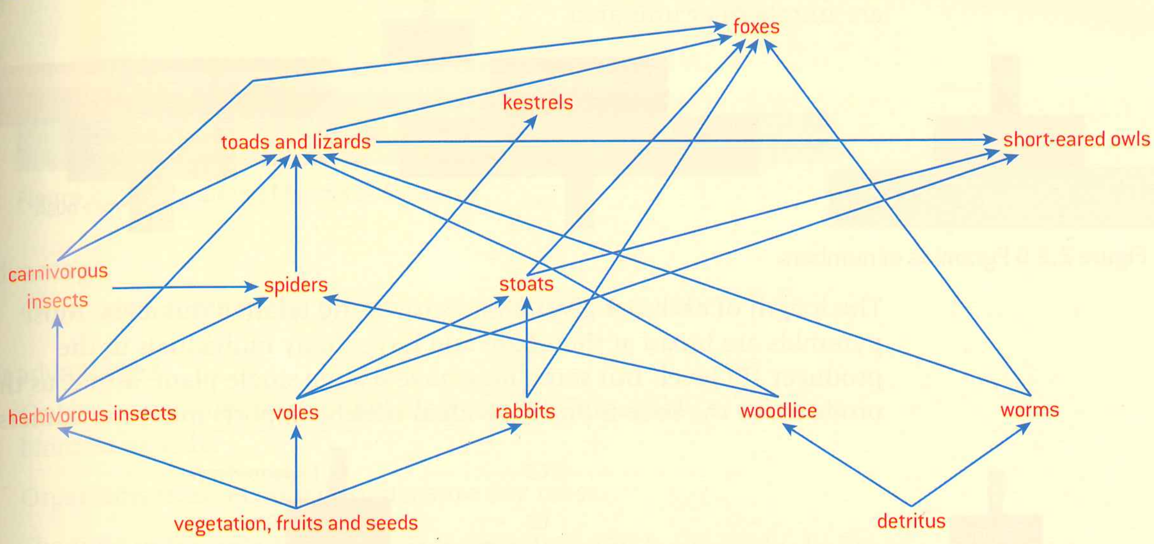


Figure 2.2.7 A simplified food web from the acid heathland at Studland, Dorset, UK

1. What is the longest food chain in this food web?
2. Name two species that are found at two trophic levels.
3. If all kestrels die, what may happen to (a) voles and (b) short-eared owls?
4. If there is a great increase in the rabbit population, what happens to (a) rabbit predators and (b) the vegetation?
5. If a pesticide is added to kill spiders, what may happen to the foxes?

Ecological pyramids

Pyramids are graphical models of the quantitative differences between amounts of living material stored at each trophic level of a food chain.

- They allow easy examination of energy transfers and losses.
- They give an idea of what feeds on what and what organisms exist at the different trophic levels.
- They also help to demonstrate that ecosystems are systems that are in balance.

All pyramids may be represented as in figure 2.2.8.

Key term

Ecological pyramids include pyramids of numbers, biomass and productivity and are quantitative models and are usually measured for a given area and time.

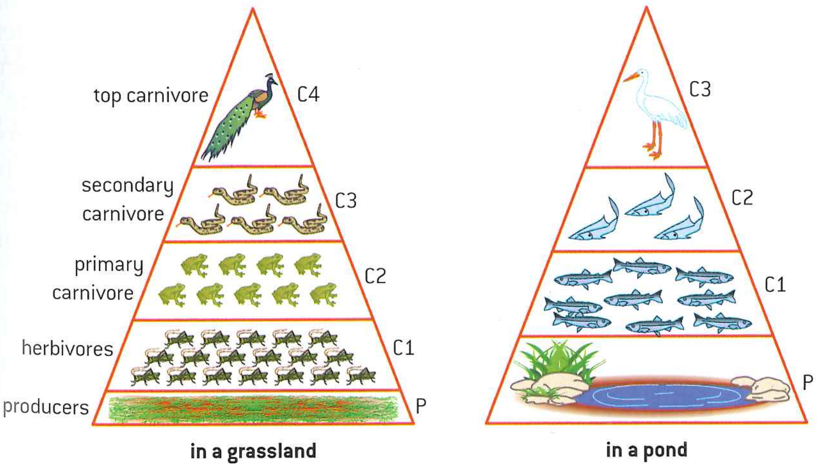
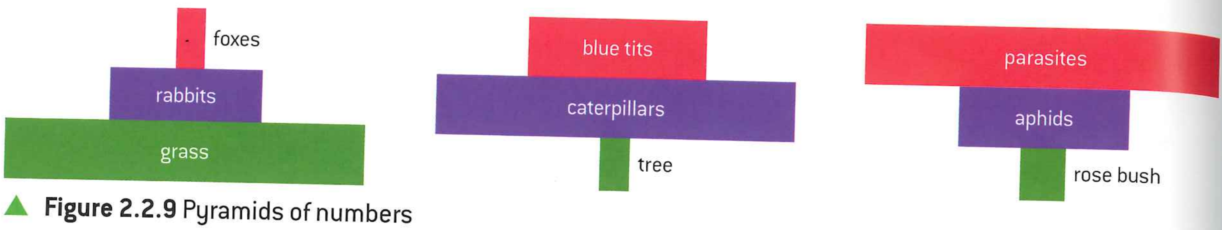


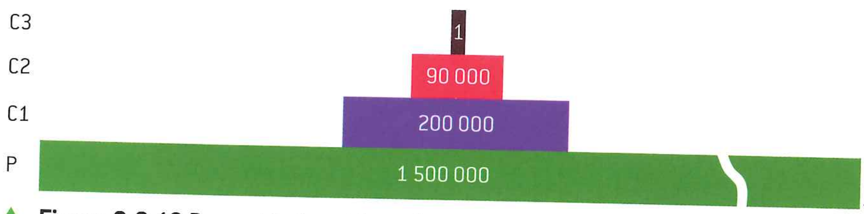
Figure 2.2.8

A **pyramid of numbers** shows the number of organisms at each trophic level in a food chain at one time – the **standing crop**. The units are number per unit area.

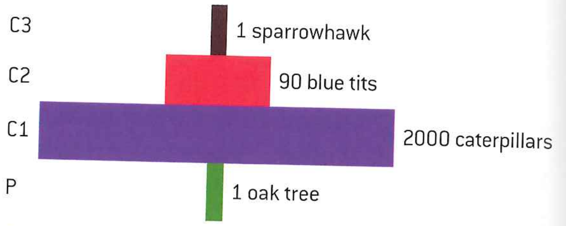


▲ **Figure 2.2.9** Pyramids of numbers

The length of each bar gives a measure of the relative numbers. Most pyramids are broad at their base and have many individuals in the producer (P) level. But some may have a large single plant, a tree, as the producer so the base is one individual which supports many consumers.



▲ **Figure 2.2.10** Pyramid of numbers for a grazing ecosystem



▲ **Figure 2.2.11** Pyramid of numbers for an oak wood

Advantage

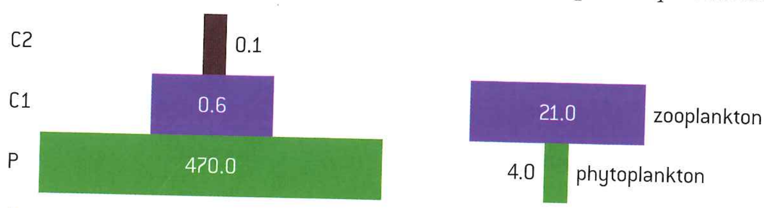
- This is a simple, easy method of giving an overview and is good at comparing changes in population numbers with time or season.

Disadvantages

- All organisms are included regardless of their size, therefore a pyramid based on an oak tree would be inverted (have a small bottom and get larger as it goes up the trophic levels).
- Does not allow for juveniles or immature forms.
- Numbers can be too great to represent accurately.

A **pyramid of biomass** contains the biomass (mass of each individual × number of individuals) at each trophic level. Biomass is the quantity of (dry) organic material in an organism, a population, a particular trophic level or an ecosystem.

The units of a pyramid of biomass are in units of mass per unit area, often grams per square metre ($g\ m^{-2}$) or kilograms per water volume (eg, $kg\ km^{-3}$). A pyramid of biomass is more likely to be a pyramid shape but there are some exceptions, particularly in oceanic ecosystems where the producers are phytoplankton (unicellular green algae). Phytoplankton reproduce fast but are present only in small amounts at any one time. As a pyramid represents biomass at one time only, eg in winter, the phytoplankton bar may be far less than that of the zooplankton which are the primary consumers.



▲ **Figure 2.2.12** Pyramids of biomass (units gm^{-2})

▲ **Figure 2.2.13** Pyramid of biomass for a lake

Advantage

- Overcomes some of the problems of pyramids of numbers.

Disadvantages

- Only uses samples from populations, so it is impossible to measure biomass exactly.
- Organisms must be killed to measure dry mass.
- The time of the year that biomass is measured affects the result. In the case of algae, their biomass changes by large amounts during the year therefore the shape of the pyramid would depend on the season. The giant redwood trees of California have accumulated their biomass over many years yet algae in a lake at the equivalent trophic level may only have needed a few days to accumulate the same biomass. This pyramid will not show these differences.
- Pyramids of total biomass accumulated per year by organisms at a trophic level would usually be pyramidal in shape. But two organisms with the same mass do not have to have the same energy content. A dormouse stores a large amount of fat, around 37 kJ g^{-1} of potential chemical energy yet a carnivore of equivalent mass would contain larger amounts of carbohydrates and proteins, around 17 kJ g^{-1} potential energy. Some organisms contain a high proportion of non-digestible parts such as in the exoskeletons of marine crustaceans.

Pyramids of numbers and biomass are snapshots at one time and place. Depending on when the pyramid was investigated, for the same food web in the same ecosystem, the pyramid can vary with season and year. In the spring, there will be more producers growing, in autumn, perhaps more consumers living on the producers. Pyramids of numbers may sometimes be inverted (figure 2.2.9).

A **pyramid of productivity** shows the rate of flow of energy or biomass through each trophic level. It shows the energy or biomass being generated and available as food to the next trophic level during a fixed period of time. So, unlike pyramids of numbers and biomass, which are snapshots at one time, these pyramids show the flow of energy over time. They are always pyramid-shaped in healthy ecosystems as they must follow the second law of thermodynamics (1.3). They are measured in units of energy or mass per unit area per period of time, often Joules per square metre per year (J m^{-2} yr^{-1}). Productivity values are rates of flow, whereas biomass values are stores existing at one particular time.

Supermarket analogy

The turnover of two supermarkets cannot be compared by just looking at the goods displayed on the shelves; the rate at which goods are being stocked and sold needs to be known. Both shops may have well stocked shelves but the rate of removal of goods from a city centre shop may be considerably more than a village shop. In the same way, pyramids of biomass simply represent the stock on the shelves, whereas pyramids of productivity show the rate at which that stock is being removed by customers and restocked by shop assistants.

The bars are drawn in proportion to the total energy utilized at each trophic level. As only about 10% of the energy in one level is passed on to the next, in pyramids of productivity, each bar will be about 10% of the lower one. Sometimes the term pyramid of energy is used which can be either the standing stock (biomass) or productivity. We shall avoid it here as it is confusing.

Pyramid	Units
Numbers (standing crop)	N m^{-2}
Biomass (standing crop)	g m^{-2}
Productivity (flow of biomass/energy)	g $m^{-2}yr^{-1}$ J $m^{-2}yr^{-1}$

▲ **Figure 2.2.14** Pyramid units. Note the notation: N = numbers, g = grams, J = joules, the negative indices replace / , eg N/m^2

Advantages

- Most accurate system, shows the actual energy transferred and allows for rate of production.
- Allows comparison of ecosystems based on relative energy flows.
- Pyramids are not inverted.
- Energy from solar radiation can be added.

Disadvantages

- It is very difficult and complex to collect energy data as the rate of biomass production over time is required.
- There is still the problem (as in the other pyramids) of assigning a species to a particular trophic level when they may be omnivorous.

To do

On graph paper, draw and label pyramids from the data in the table. Comment on these.

	Number pyramid	Biomass pyramid / kJ m^{-2}	Productivity pyramid / 000 kJ m^{-2} yr^{-1}
Primary producers	100,000	2,500	500
Primary consumers	10,000	200	50
Secondary consumers	2,000	15	5
Top consumers	500	1	–

To think about

Consequences of pyramids and ecosystem function

1. The concentration of toxic substances in food chains.
2. The limited length of food chains.
3. The vulnerability of top carnivores.

Bioaccumulation and biomagnification

If a chemical in the environment (eg a pesticide or a heavy metal) breaks down slowly or does not break down at all, plants may take it up and animals may take it in as they eat or breathe. If they do not excrete or

egest it, it accumulates in their bodies over time. If the chemical stays in the ecosystem for a prolonged period of time the concentration builds up. Eventually, the concentration may be high enough to cause disease or death. This is **bioaccumulation**.

If a herbivore eats a plant that has the chemical in its tissues, the amount of the chemical that is taken in by the herbivore is greater than that in the plant that is eaten – because the herbivore grazes many plants over time. If a carnivore eats the herbivores, it too will take in more of the chemical than each herbivore contained as it eats several herbivores over time. In this way the chemical's concentration is magnified from trophic level to trophic level. While the concentration of the chemical may not affect organisms lower in the food chain, the top trophic levels may take in so much of the chemical that it causes disease or their death. This is **biomagnification**.

A serious problem with pesticides is how long they last in the environment once they are sprayed. Some decompose into harmless chemicals as soon as they touch the soil. Glyphosate (first sold by Monsanto as Roundup) is one of these: once it touches the soil, it is inactivated. Others are persistent and do not break down in this way. They enter the food web and move through it from trophic level to trophic level as they do not break down even inside the bodies of organisms. They are non-biodegradable (POPs, see sub-topic 1.5). Many early insecticides such as DDT, dieldrin and aldrin fall into this group and they are stored in the fat of animals. Seals and penguins in Antarctica and polar bears in the Arctic have been found with pesticides in their tissues. The nearest land where the pesticides have been used is thousands of kilometres away. How may the pesticides have reached them?

To do

In this food web, the smaller fish (minnows) eat plankton (microscopic plants and animals) in the water. The minnow is eaten by the larger fish called pickerel. These are eaten by herons, ospreys and cormorants and herons eat the minnows as well. The numbers give the percentage concentration of DDT.

1. How many trophic levels are in this food web?
2. How many times more concentrated is the DDT in the body of the cormorant than the water? Explain how this happens.
3. In which species does bioaccumulation occur?
4. In which species does biomagnification occur?

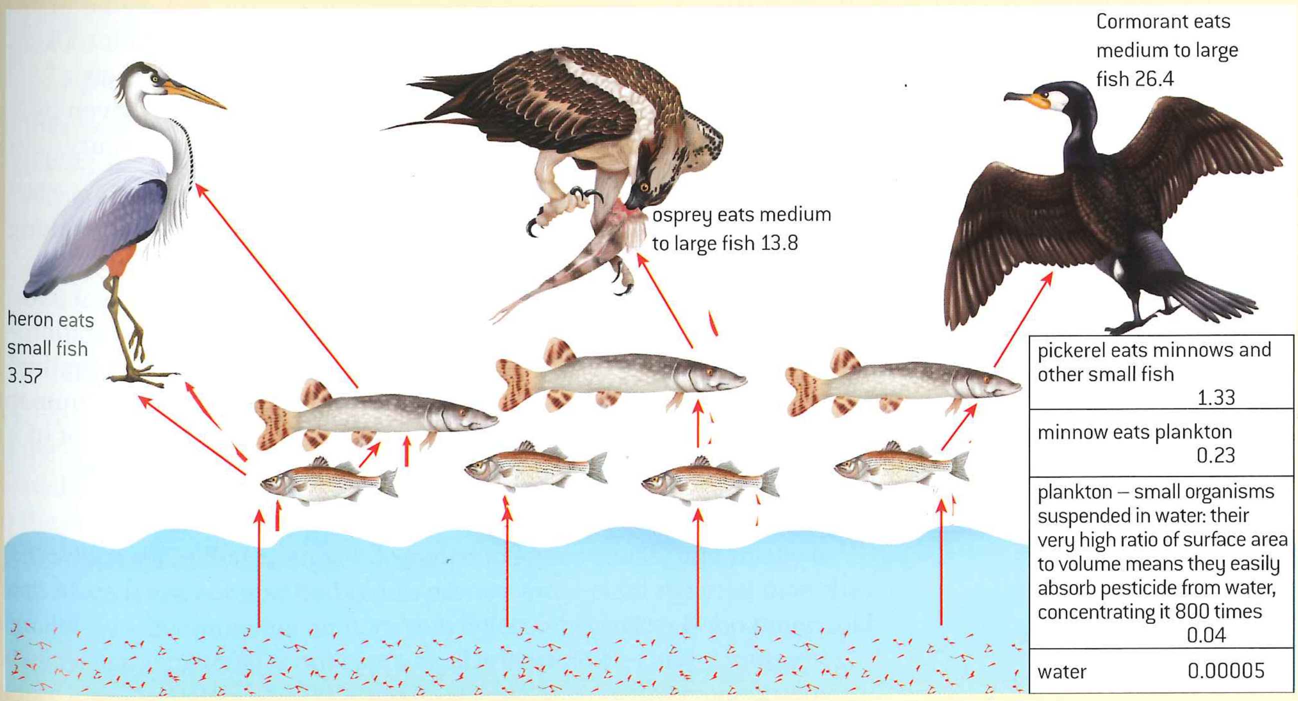
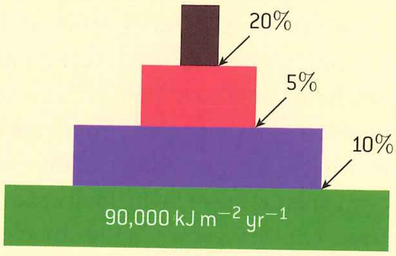


Figure 2.2.15 Food web in a freshwater ecosystem

To do

1. An ecosystem consists of one oak tree on which 10,000 herbivores are feeding. These herbivores are prey to 500 spiders and carnivorous insects. Three birds are feasting on these spiders and carnivorous insects. The oak tree has a mass of 4,000 kg, the herbivores have an average mass of 0.05 g, the spiders and carnivorous insects have an average mass of 0.2 g and the three birds have an average mass of 10 g.
   a. Construct a pyramid of numbers.
   b. Construct a pyramid of biomass.
   c. Explain the differences between these two pyramids.
2. Explain whether the energy 'loss' between two subsequent trophic levels is in contradiction with the first law of thermodynamics (see 1.3).
3. Assuming an ecological efficiency of 10%, 5% and 20% respectively (see figure 2.2.16), what will be the energy available at the tertiary consumer level (4th trophic level), given a net primary productivity of 90,000 kJ m^{-2} yr^{-1}? What percentage is this figure of the original energy value at the primary producer level?



▲ **Figure 2.2.16**

CASE STUDY

Story of Minamata Bay

Minamata is a small factory town in Japan, dominated by one factory, the Chisso factory. Chisso make petrochemical-based substances from fertilizer to plastics. Waste water containing methylmercury from this process was released into Minamata Bay. Between 1932 and 1968 Chisso released an estimated 24 tonnes of mercury and methylmercury into Minamata Bay. Beginning in the 1950s, several thousand people living locally started to suffer from mercury poisoning.

What had happened? Waste water containing elemental mercury and methylmercury from this process was released into Minamata Bay. Also, some bacteria can change elemental mercury to the modified form called methylmercury. Methylmercury is easily absorbed into the bodies of small organisms such as shrimp. When the shrimp are eaten by fish, the methylmercury enters the fish. The methylmercury does not break down easily and can stay in the fish bodies for a long time. As the fish eat more and more shrimp, the amount of methylmercury increases. The same increase in concentration happens when people then eat the fish. Mercury bioaccumulated in the food chain. People of Minamata ate a lot of shellfish and were poisoned by mercury. It took over 30 years to recognize the cause of their illnesses and compensation is still being given by the Chisso Corporation although the mercury release stopped in 1968.

There is a slow orders-of-magnitude build-up along the food chain: very many bacteria absorb very small amounts of mercury – many shrimp eat a lot of bacteria building up the mercury concentration – lots of fish eat lots of shrimp again building up the concentration and finally a small number of humans at the top of the food chain eventually eat a lot of fish and absorb high levels of methylmercury.

Why top carnivores are in trouble

It is often the highest trophic level in a food chain (the top carnivore) that is the most susceptible to alterations in the environment. In the UK, the population of the peregrine falcon (a bird of prey) crashed in the late 1950s probably due to agricultural chemicals such as DDT accumulating and then magnifying in the food chain. This appeared to cause egg-shell thinning and reduced breeding success. These chemicals were banned and from the mid 1960s, the peregrine population began to slowly recover despite persecution and the threat from egg collectors.

The top of the food chain is always vulnerable to the effects of changes further down the chain. Top carnivores often have a limited diet so a change in their food prey has a knock-on effect. Their population numbers are low because of the fall in efficiency along a food chain, therefore their ability to withstand negative influences is more limited than species lower in the food chain with larger populations.

Practical Work

* Construct a pyramid of numbers of for a local ecosystem.
* Build up a food chain for local ecosystem.

To think about

Polar bears and the new DDT

Figure 2.2.17 Polar bears

The new DDT could be polybrominated diphenyl ether (PBDE). It is manufactured in the United States and was widely used in the 1990s as a flame retardant to coat electrical appliances, sofas, carpets and car seats. The problem is that this chemical was designed to last the lifetime of the product, but in fact it lasts much longer. When sofas, carpets and car seats were thrown away, PBDE entered the rivers, the oceans and the atmosphere. The Arctic, where all the world's polar bears live, is one of the great sinks of the planet. Chemical pollutants such as PBDE are carried towards the Arctic Ocean by the great rivers of Russia and Canada. PBDE already in the sea is taken north by ocean currents and carried by the wind. As it moves through the food chain from plankton to predator, PBDE bioaccumulates and is biomagnified so that long-lived top carnivores such as the polar bear accumulate the most concentrated amounts of them. High amounts of PBDE have now been found in the body tissue of polar bears and killer whales. The long-term environmental effect of PBDE is unknown, but it will probably damage immune systems, brain functions and bone strength. It also messes up the polar bear's sex hormones. One female bear on Spitzbergen had both male and female organs, a condition called imposex and often linked to chemical pollution.

The length of food chains

As a rule of thumb, only 10% of the energy in one trophic level is transferred to the next – the **trophic efficiency** is 10%. A major part of the energy is used in respiration to keep the organism alive and is finally lost as heat to the environment. This is a result of the second law of thermodynamics (1.3) which states that energy is degraded to lower quality and finally to heat. More is lost because herbivores destroy more plant material than they actually eat – by trampling on it, or they reject it because it is too tough, old or spiky. Some material is not eaten at all and some dies and decomposes before it can be eaten. The 90% loss of energy in going from one trophic level to the next means there is very little energy available after about four trophic levels in terrestrial ecosystems and five in aquatic ecosystems.