Chapter 4
Crops and Their Environment

4.1 Radiation and Energy

The primary energy source for almost all ecosystems is solar energy, which reaches the Earth continuously. At the boundaries of the Earth's atmosphere, the sun's radiation efficiency is approximately 1,360 W m^{-2}. This value is nearly constant and is, therefore, termed the **solar constant**. The portion of the radiation that reaches the Earth's surface, the so-called **insolation (in**coming **so**lar radia**tion**), is lower, because approximately half of the solar energy is lost by absorption and reflection in the atmosphere. Another factor that determines the insolation of a particular site is the angle at which the sun's rays meet the Earth. Therefore, the insolation is significantly higher at the equator than at the poles. The worldwide highest values (>250 W m^{-2} annual average) are reached in tropical and subtropical region rarely covered by clouds (e.g. the Sahara desert). The mean annual insolation in the temperate latitudes is approximately half of that value and amounts to 127 W m^{-2}. In Stuttgart-Hohenheim in Germany, for example, the value is highest in July (230 W m^{-2}) and lowest in December (50 W m^{-2}).

4.1.1 *Photosynthesis*

The sun's electromagnetic radiation covers a range of wavelengths from 100 to 5,000 nm (nanometres) and can be divided into three parts (Fig. 4.1): ultraviolet radiation (100–380 nm), light visible to humans (380–740 nm), and near infrared radiation (740–5,000 nm). The visible region of the electromagnetic spectrum is nearly identical with the spectrum that plants can utilize for photosynthesis and is termed **photosynthetically active radiation (PAR)**.

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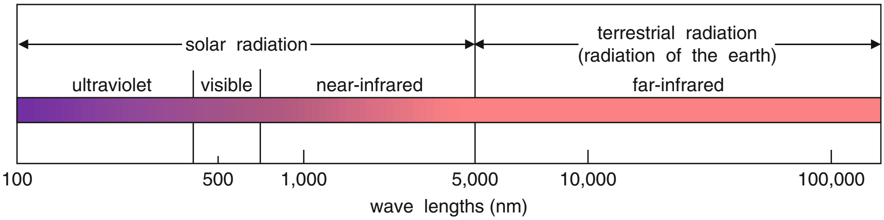

Fig. 4.1 The electromagnetic spectrum (solar and terrestrial radiation). 1 nanometre (nm) = 10^{-9} (one billionth) metre

Photosynthesis is a process that enables green plants and some bacteria to produce carbohydrates (i.e. biomass), from carbon dioxide and water by use of light energy (Box 4.1). This process releases oxygen (O_2):

$$6CO_2 + 12H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2$$

Box 4.1 Carbohydrates

The basic units of carbohydrates are the simple sugars (monosaccharides), for example glucose and fructose. By condensation of two monosaccharides, a disaccharide is formed. Sucrose is made up of glucose and fructose and is the most important disaccharide produced by plants. Carbohydrates that are made up of more than four monosaccharides are termed polysaccharides. The starches are included in this group. Starches are made up of 200–1,000 glucose molecules and serve as carbohydrate reservoirs for plants. Starch is also the most important carbohydrate in human nutrition and serves as an energy source. The daily requirement of carbohydrates is 5–6 g kg^{-1} body weight. In the body, starches are broken down by enzymes into glucose, which is taken up by the blood and cells.

Numerous crops are cultivated for the production of starch, which can be derived from different plant parts. Examples:

Plant part	Crop species (examples)
Seed	Cereals, buckwheat (*Fagopyrum esculentum*)
Root	Sweet potato (*Ipomoea batatas*), cassava (*Manihot esculenta*), yam (*Dioscorea* species)
Tuber	Potato (*Solanum tuberosum*)
Rhizome	Taro (*Colocasia esculenta*)
Stem	Sago palm (*Metroxylon sagu*), ensete (*Ensete ventricosum*)
Fruit	Plantain (*Musa* species), breadfruit (*Artocarpus altilis*; Fig. 4.2)

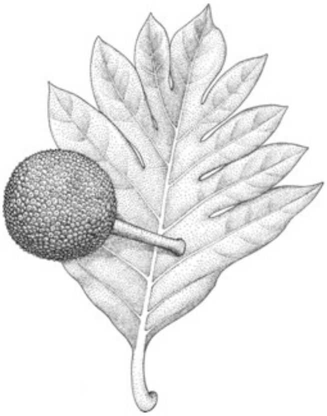

Fig. 4.2 Breadfruit tree (*Artocarpus altilis),* fruit and leaf

Plant photosynthesis takes place in the chloroplasts. These cell organelles contain pigment systems, the chlorophylls, which absorb light energy and transform it into chemical energy. The chlorophylls of plants have two absorption peaks within the visible light spectrum, one of which lies, approximately, between 400 and 500 nm and the other between 600 and 700 nm. Light in the intermediate region (i.e., 500–600 nm) can be used to a limited extent only. In contrast, cyanobacteria, which are also capable of photosynthesis, have other pigments with their absorption peak at wavelengths between 500 and 600 nm.

The CO_2 that is required for photosynthesis and taken from the air must be fixed by the plants, which means it must be incorporated into a molecule before it can be utilized for production of carbohydrates. Fixation of CO_2 does not occur in the same way in all plants and is associated with particular physiological and morphological characteristics of specific species. Overall, three photosynthetic types are identified; the C_3, C_4, and CAM plants.

4.1.1.1 C_3-Plants

For 95% of all plant species, the CO_2 taken from the air is fixed as phosphoglycerate. Because this molecule is made up of three C atoms, plants that perform synthesis in this way are termed C_3 plants. Binding of the CO_2 occurs via the enzyme ribulose-1,5-biphosphate-carboxylase/oxygenase (RuBisCo). However, this molecule has only low affinity for CO_2 and can also bind oxygen (O_2). Because of other reactions, some of the bound carbon (approximately 20–30%) is lost as of CO_2, which therefore reduces the effectiveness of photosynthesis. Because this process occurs in light, it is called **photorespiration**. With increasing light intensity and temperature, the associated carbon loss increases. The optimum temperature for CO_2 fixation by C_3 plants is between 15 and 25°C.

If the concentration of CO_2 is increased, the photosynthetic performance of C_3 plants can be increased by up to 30%. This "CO_2 fertilization effect" is used in greenhouse cultivation (e.g. of cucumbers and tomatoes) to achieve higher yields.

As a result of the increasing CO_2 content of the Earth's atmosphere, this effect will, in the future, probably also become relevant to the production of field crops (Sect. 8.1.3.2).

The gas exchange of plants occurs via the stomata (Greek s*toma* = mouth, opening) in the epidermis. For uptake of CO_2 and release of O_2, the stomata of C_3 plants are usually open during the day. At the same time, the stomata regulate plant transpiration, i.e. release of water or water vapour.

With increasing temperature, the rate of transpiration increases and, as a result, loss of water. When these losses cannot be compensated by water uptake through the roots, then the plant will suffer from water stress. Plants react to this by contracting or closing their stomata, which simultaneously results in a reduction in photosynthetic performance.

The photosynthetic performance of C_3 plants is not only affected by light and CO_2 availability, but also to a great extent by temperature and by water availability.

4.1.1.2 C_4-Plants

In approximately 2% of all plant species, fixation of atmospheric CO_2 does not occur via the enzyme RuBisCo, but instead via the enzyme phosphoenolpyruvate-carboxylase (PEPC). This process produces, depending on the plant species, either malate or aspartate. Because these acid compounds are each made up of four carbon atoms, plants with this mechanism are called C_4 plants. Fixation of CO_2 through PEPC occurs in the mesophyll cells of the leaves. The C_4 acids produced in the mesophyll cells are transferred into the bundle sheath cells. There, the respective acid (malate or aspartate) is chemically broken down into a smaller organic molecule, and CO_2 is released. This carbon dioxide then enters the chloroplast of the bundle sheath cell and is fixed a second time in the same way as in the C_3 plants (i.e. by RuBisCo).

Thus, in the C_4 plants initial CO_2 fixation occurs that is spatially separated from the other photosynthetic processes. The advantage of this mechanism is the significantly higher CO_2 affinity of PEPC in comparison with that of RuBisCo. Therefore, the carbon losses associated with photorespiration are substantially lower in C_4 plants than in C_3 plants. In other words, with higher light intensity, the net photosynthetic rate of the C_4 plants is significantly higher than in C_3 plants. Furthermore, high temperatures do not lead to significant reductions in the photosynthetic performance of C_4 plants. The optimum temperature of CO_2 fixation in C_4 plants is between approximately 30 and 40°C. As a result of the greater CO_2 affinity of PEPC, C_4 plants are capable of utilizing relatively low CO_2 concentrations. They can, therefore, perform effective photosynthesis with contracted stomata, thus limiting water losses through transpiration.

Because of these properties, C_4 plants are found primarily in warm and relatively dry areas of the tropics and subtropics. C_4 plants include, among others, many tropical grass species (including such important crop species as maize, sugar cane, sorghum, and pearl millet) and species of the Amaranthaceae (amaranth family).

In respect of photosynthetic performance, the C_4 plants have advantages over the C_3 plants at sites with high solar radiation, higher temperatures, and relatively lower water availability.

4.1.1.3 CAM-Plants

Another pathway of CO_2 utilization occurs in the CAM plants. CAM means *crassulacean acid metabolism*, because it was first discovered amongst species of the Crassulaceae (orpine family). However, this mechanism is also found in numerous other plant families—in approximately 3% of all plant species. These plants have the same two carbon-fixing steps as are present in C_4 plants, that is, initial CO_2 fixation occurs via PEPC and malate is produced, from which the CO_2 is later released and subsequently bound by RuBisCo. However, in the CAM plants there is no spatial separation of these processes, but rather a temporal separation between day and night. At night, the stomata are open to take up CO_2. As a result of the accumulation of malate, the pH inside the cells declines substantially (the term *acid* metabolism refers to this). During the day, the stomata are closed and photosynthesis is performed with the previously fixed carbon. Because photosynthesis and transpiration are largely decoupled, the CAM plants can prevent high water losses under high solar radiation. Although the advantages of the C_4 mechanism are primarily evident under conditions of high solar radiation, the CAM mechanism is, to a greater extent, an adaptation to reduce water loss. Many typical representatives of the CAM plants can therefore be found in the subtropical deserts and semi-deserts (Sect. 7.2.2.1), for example, the Cactaceae (spine plant family) and the Agavaceae. The best-known CAM crop plant is pineapple (*Ananas comosus*; Fig. 4.3), of the Bromeliaceae family.

Figure 4.4 shows an overview of the mechanisms of CO_2 fixation of the C_3, C_4, and CAM plants.

4.1.1.4 Solar Radiation in Agroecosystems

An important condition required for crop plants to achieve high biomass production and yields is optimum utilization of the available radiation energy. Because not all species have the same photosynthetic performance under the same conditions, the site of cultivation must meet the requirements of the species or variety. For production of C_4 plants, suitable sites include regions in which the optimum

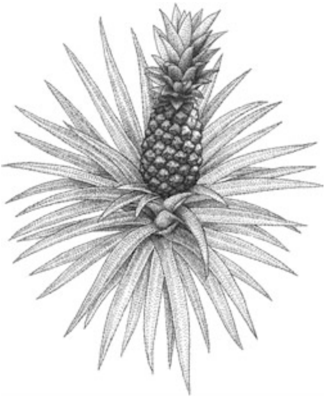

Fig. 4.3 Pineapple (*Ananas comosus*)

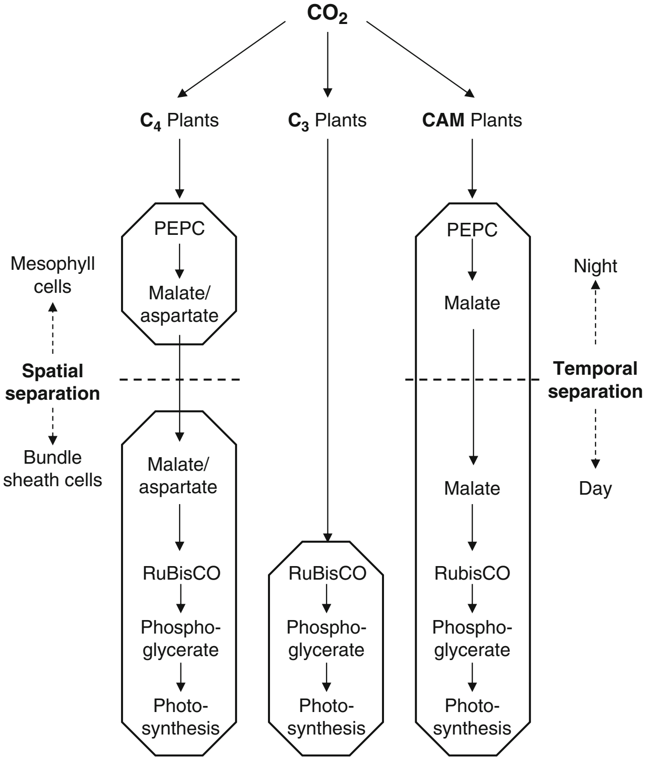

Fig. 4.4 CO_2 fixation in C_3, C_4, and CAM plants

temperatures for photosynthesis (>30°) and high radiation intensities are found. In contrast, C_3 plants have the best photosynthetic performance under relatively cool and moist conditions.

The distribution of solar radiation within a plant stand also affects photosynthetic performance. The light that reaches the plants is partially reflected by the leaves, to a large part absorbed, and partially passes through the plants. Overall, intensity is reduced as the radiation passes through a plant stand to the ground. The proportion of the radiation entering the stand that can actually be absorbed by the plants depends on the leaf area index and the architecture or type of plant. The **leaf area index (LAI)** describes the relationship between the total upper leaf area of a plant stand and the surface area of the ground of the stand (i.e., leaf area per unit land area). However, a high LAI alone does not guarantee optimum use of solar radiation, because the photosynthetic performance of plants is limited by hanging leaves and the shading of leaves within the same plant. For cereals, especially, varieties were therefore bred that better absorb solar radiation. The upper leaves of such plants stand upright so the solar radiation that enters the stand can also be utilized by leaves located further down the plant.

It is not only available solar radiation but also day length, or **photoperiod**, that affects the growing conditions of plants. The photoperiod is determined by latitude and season and is of crucial importance in inducing the formation of flowers by many plant species. The insolation ($W\ m^{-2}$) plays a much less important role, in other words, it makes very little difference to the plants whether there is sunshine or clouds during the photoperiod.

For the so-called **long-day plants**, a particular minimum of day length must be reached for the flowering of the plant. The required day length varies from species to species, but most often lies between 12 and 14 h. These conditions are met in Central Europe from approximately April to September. Important long-day crop plants include wheat, barley, potato, canola, and peas. Their sowing date must be chosen such that the flowering period falls within the long day phase. For other long-day crop plants, for example lettuce (*Lactuca sativa*), spinach (*Spinacia oleracea*), and Chinese cabbage (*Brassica pekinensis*), which are used as leafy vegetables, flowering is not desired. To prevent flowering, the crop's growing period must lie in a phase during which the days become shorter.

Flowering of the **short-day plants** is only, or primarily, induced when day length falls below a specific minimum, i.e. the days may not be longer than approximately 12–14 h. Species in this group include rice, soybean, sugar cane (Fig. 4.5), and coffee. However, there are many plant species that flower independent of day length (e.g. tomato and sunflower); these are called **day-neutral plants**. Variety-specific differences with regard to photoperiod are observed for some crops. Thus, there are short and long-day varieties of tobacco, maize, and potato.

The relationships between day length and flower formation are essentially determined by the climate of the plant's habitat. In the Mediterranean climate, where dry periods predominate in the summer, many plants flower and develop seeds in the long-day conditions of spring. Also most of the crop plants that originate from the Middle East are long-day plants. In areas of dry winters in the temperate latitudes, short-day plants are primarily found, including soybean, which originates from China. Plant species from the tropics are short-day plants and day-neutral because in these latitudes a day length of approximately 14 h is not exceeded at any point in the year.

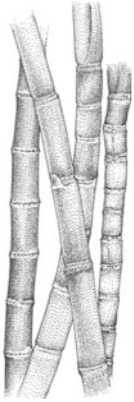

Fig. 4.5 Sugar cane (*Saccharum officinarum*)

4.1.2 Heat Energy

Only approximately 0.01% of the solar radiation that reaches the Earth's surface is used for photosynthesis. Most global radiation is absorbed by the Earth's surface and transformed into long-wave (infrared) radiation, which subsequently heats the air layers close to the ground. Some of the radiation emitted from the surface is absorbed by the atmosphere and reflected; another portion is released into space (Fig. 4.6). The reflected radiation is the so-called counter-radiation and is primarily determined by the water vapour content of the air and of clouds, and by the concentration of CO_2 and other trace gases. On clear nights with low humidity, the counter-radiation is low, which is why the ground's surface cools substantially. At the global level, the counter-radiation is responsible for the natural greenhouse effect (Sect. 8.1.3). Because of the relationship between latitude and global insolation, heating of the air by long-wave radiation is higher at the equator than at the poles. However, via air and ocean currents the energy is transported from the equator to the higher latitudes (Sect. 7.1).

4.1.2.1 Temperature and Location

The suitability of a location for the production of crops is not only affected by the average temperature of the site, but also to a great extent by the maximum and minimum temperatures. In particular, the occurrence of late frosts in spring limits production in regions that are characterized by an overall mild climate. The local temperature conditions are, therefore, not only affected by the latitude but also by additional factors. These include:

Topography. In a valley, the temperature can decline significantly more overnight than in higher locations, because of the sinking of cool, heavy air. The differences can, at temperate latitudes, amount to 10°C or more in summer.

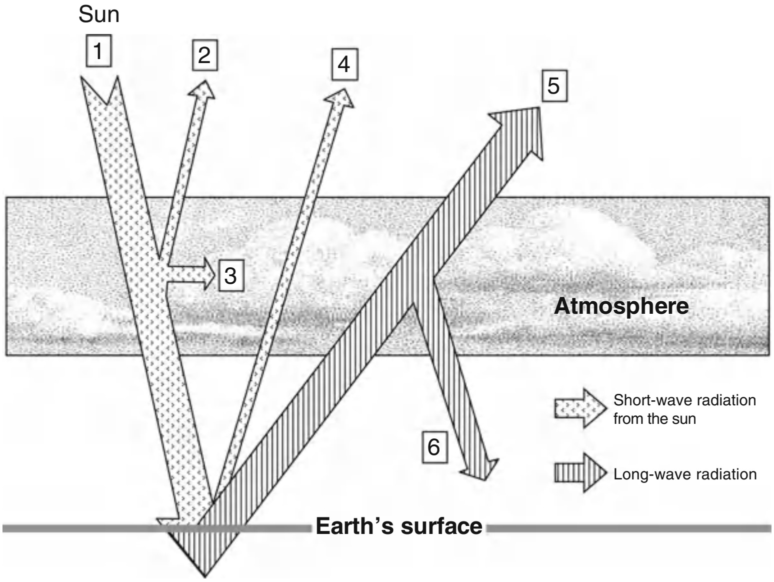

Fig. 4.6 Schematic presentation of the radiation budget of the Earth. **1**=solar radiation, **2**= reflection by the atmosphere, **3** = absorption by the atmosphere, **4** = reflection at the Earth's surface, **5** = long-wave radiation emitted from the Earth's surface, **6** = counter-radiation

Because of the threat of frost damage, valley bottoms of Central Europe are suitable for the production of specific crop plants only (e.g. fruit trees).

Altitude. There is a temperature gradient between the air layers close to the ground surface and those at higher elevations. That is why the average temperature decreases in mountainous areas with increasing altitude at a rate of 0.6–1.0°C per 100 m. In tropical and subtropical mountainous regions, it is, therefore, possible to cultivate crops that are otherwise only suitable for higher latitudes (Fig. 4.7).

Continent–ocean distribution. Oceans and continents differ in their heat budgets. Land surfaces are characterized by their strong warming in summer and strong cooling in winter. In contrast, oceans warm slowly and also cool slowly. Because of this, in winter the large land masses of the northern hemisphere are far colder than the oceans of the same latitude. In July, the opposite situation is found. The oceans have a balancing effect on the temperature of coastal regions and islands, i.e. temperature differences throughout the year are less extreme than in the continental regions at the same latitudes (Sect. 7.2.3).

4.1.2.2 Effect of Temperature on the Development of Crops

Plants are **ectothermic** (gr. e*ktos* = outside, *thermos* = warm) organisms, which means they must derive most of heat energy required for metabolism from their surroundings. Endothermic (gr. e*ndon* = inside) organisms, which include

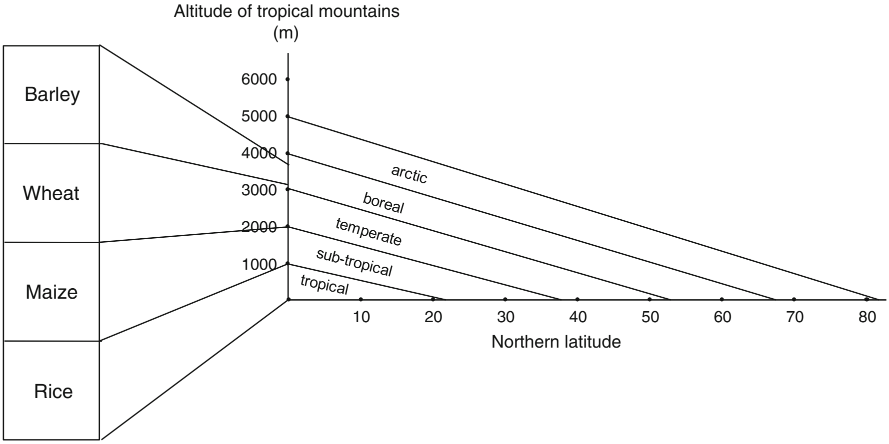

Fig. 4.7 Temperature-based suitability of different altitudes of tropical mountainous regions and different latitudes and/or climate zones for cultivation of particular crop species

mammals and birds, can maintain their body temperature by internal heat production, with a high energy turnover. The life processes of ectothermic organisms are subject to the **van't Hoff rule**. This rule states that the rate of biochemical reactions doubles with a 10°C increase in temperature (up to a point when proteins break down). As a result, a close relationship exists between the surrounding temperature and the time required by an ectothermic organism to develop (e.g. the time a plant requires to reach the flowering stage or to develop mature seeds, or that an insect requires for the completion of its larval stage). The time required for such a process is determined by the temperature sum that is reached over a period of time. For a development process to occur at all, a threshold temperature in the surrounding environment, the so-called base temperature, must be exceeded. When the temperature falls below a species-specific minimum, development in individuals of this species ceases.

The time required by an organism for its development can be expressed in degree-days (measured in °C). Degree-days (T_n) are calculated by use of the formula:

$$T_n = \sum T'$$

where n is the number of days and T' is the temperature sum reached in one day:

$$T' = [(T_{\text{max}} + T_{\text{min}})/2] - T_{\text{b}}$$

T_{max} = daily maximum temperature

T_{min} = daily minimum temperature

T_{b} = base temperature

Table 4.1 Example of the calculation of degree-days

	Days						
	1	2	3	4	5	6	T_n
T_b (°C)	5	5	5	5	5	5	
T_{min} (°C)	8	9	6	8	7	9	
T_{max} (°C)	14	17	16	20	19	15	
T' (°C)	6	8	6	9	8	7	44

Fig. 4.8 Faba bean (*Vicia faba*)

An example of the calculation of degree-days is given in Table 4.1.

In agricultural practice, measurement of growing degree days (GDD) and temperature sums can be used to predict the period of time required between sowing and flowering or harvest for different growing periods.

Example: In the Mediterranean countries, faba bean (*Vicia faba*; Fig. 4.8) makes an important contribution to the protein supply for human and animal nutrition, and to improvement of soil fertility.

Sowing is usually performed in September or October, just before the start of the winter rainy season. On sites far from coastal areas with cold winters, for example northwest Syria, frost damage to flowering faba beans can result in significant yield losses. The threat is greatest in December and January. The risk of frost damage for particular sowing dates can be estimated by predicting the time of flowering of faba bean with the help of a simulation model that uses the concept of temperature sums, with temperature and day length data. This method shows that the risk decreases the further the sowing date is shifted into wintertime (Fig. 4.9). With sowing dates in January, the plants flower in April when there is no longer any risk of frost. As a result of the increasing temperature, the time span between sowing and flowering is significantly lower than for early sowing dates (Grenz 2004). However, with the end of the winter rains in May, the risk of yield losses increases because of water stress during the pod-filling stage. Therefore, to determine the optimum sowing date, more complex plant-development models are needed.

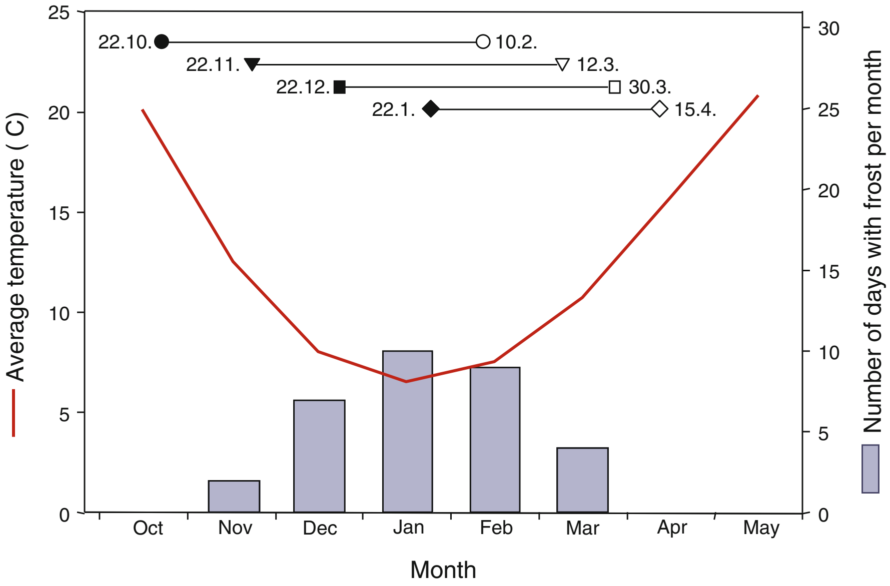

Fig. 4.9 Average monthly temperatures and number of days with frost (temperature below 0°C) per month, and the periods between sowing (*black symbols*) and flowering (*white symbols*) of faba bean in Tel Hadya, northwest Syria. The weather data are based on measurements from the years 1979 to 2000 and the flowering dates are based on computer simulation (Based on Grenz 2004)

4.2 Water

There is a close relationship between plant growth and water consumption. The **transpiration coefficient** serves as a measure of the water requirements of plants. The coefficient indicates how many litres of water are required to produce 1 kg of plant dry mass (DM). This value is species and variety-specific and is between 200 and 800 $\mathrm{l\,kg^{-1}}$ DM for C_3 plants and between 200 and 350 $\mathrm{l\,kg^{-1}}$ DM for C_4 plants.

An important criterion in the selection of a production site for a crop is, therefore, the water requirement of that species or variety. However, it is not only the precipitation conditions and the possibility for irrigation that are important for the water supply, but also particular properties of the soil which determine the soil water balance.

4.2.1 *Soil Water Balance*

Temporal changes in the water content of the soil, which depend on the absorption, storage, and release of water, are referred to as the soil water balance.

4.2.1.1 Infiltration

The percolation of surface water into soil is termed **infiltration**. Some of the infiltration water drains through the soil and reaches the groundwater as percolation water. Another portion, the **capillary water**, is held in the soil by capillarity and by binding to soil particles. The **field capacity** is the water content or soil moisture held by a soil after excess water has drained away and the downward movement of water has slowed. The field capacity is expressed in ml H_2O per 100 ml soil volume and depends primarily on the size of soil pores, in other words on the space that can be filled with water. Sandy soils have the lowest field capacity (because a large portion of the infiltrating water flows through the soil via the relatively large spaces). Clay soils, which have the smallest pores, have the largest field capacity (compare Sect. 4.3.1). The smaller a pore, the greater the potential with which the water is held, i.e., soil water tension. These conditions determine the ability of plants to utilize the water present in the soil. The portion of soil water that can be taken up by plants via their roots is termed the **plant-available water**. In those areas of the soil from which a root takes up water, water-free zones occur. As a result, a matrix potential gradient emerges between the connected soil pores. Consequently, water flows out of water-saturated areas of the soil into water-free zones and continuously supplies roots with water.

Specific quantities of water, which differ depending on the type of soil, are held by the solid surfaces of soil particles with greater force than can be overcome by the roots. This water, which is not available to the plants, is called **hygroscopic water**. When a plant has removed all the available water from a soil, it begins to wilt irreversibly, i.e., the **permanent wilting point** has been reached.

The movement of water through the soil of a field is shown schematically in Fig. 4.10.

4.2.1.2 Evaporation

Evaporation is the transformation of water from the fluid to the gaseous state. When this occurs from soil and water surfaces free from vegetation, the process is called **evaporation**. Evaporation from the surface of plants is called **transpiration**. In dense plant stands, transpiration is often significantly higher than evaporation. Together, these two forms of water release constitute the **evapotranspiration**. With regard to this, two aspects must be distinguished:

- The **potential evapotranspiration** indicates how high the annual evapotranspiration would be under the climate conditions of a given site, if an unlimited supply of water were available.
- The **actual evapotranspiration** is the actual annual quantity of water released to the atmosphere.

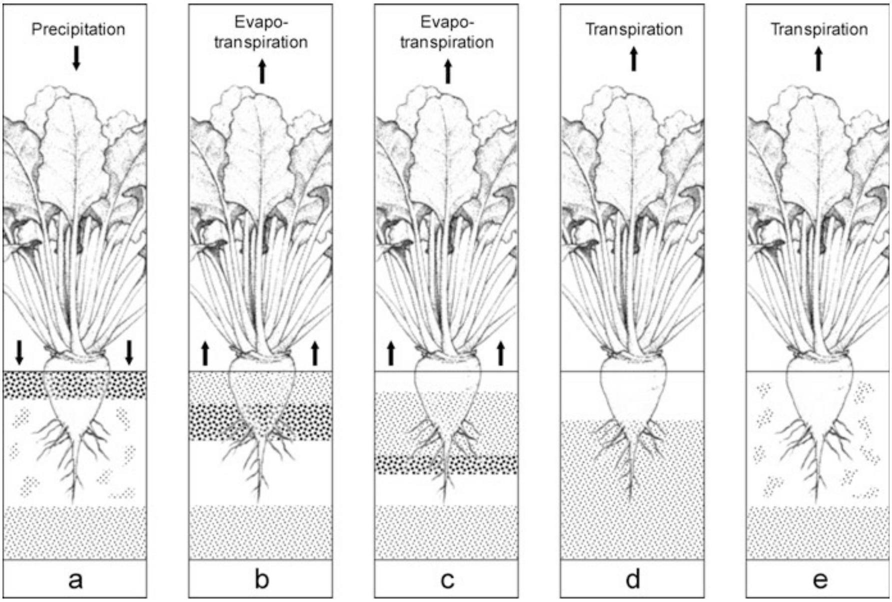

Fig. 4.10 Movements of water in an agricultural soil. (**a**) Precipitation water infiltrates a dry soil. (**b**) As percolation water, it reaches lower soil layers. Above this, capillary water is held back (field capacity). Simultaneously, water is removed from the soil via evapotranspiration. (**c**) As the percolation water moves deeper into the soil, the soil surface begins to dry out. (**d**) The percolation water reaches the groundwater, and capillary water is still present in the soil. (**e**) The plants remove the available water from the soil until the permanent wilting point is reached (Based on Gliessman 2000 and Daubenmire 1974)

Regions in which the potential evapotranspiration is higher than the average precipitation are defined as **arid**. Regions in which the quantity of water released to the atmosphere is less than that deposited by precipitation are called **humid**. In such areas, accumulation of groundwater occurs.

4.2.2 Irrigation

The climatic water balance, defined as the difference between precipitation and potential evapotranspiration, also determines the conditions of crop production in the different climate zones.

In the humid tropics, precipitation is usually sufficient for year-round production of most crop species. In regions with strongly seasonal rainfall, rain-fed crop production is limited to the phases of high precipitation, which is primarily the situation in the wet-dry tropics (Sect. 7.2.1.2) and the winter rainfall regions of the Mediterranean climate (Sect. 7.2.2.2). In regions with long dry periods or periods of limited or irregular precipitation, it is, at best, possible to utilize the water stored in the soil after rainfall for the production of crops. To increase yields, however, or even to make agricultural production possible at all in such regions, it is usually necessary to irrigate the land. In such cases, the water supply is secured via reservoirs in which rain water is captured, or from rivers, or from aquifers. The last of these may contain either renewable groundwater or fossil groundwater which accumulated during periods of high precipitation in the past and is not renewable.

Globally, the area that is irrigated has increased sixfold since the beginning of the twentieth century. Irrigation is applied to approximately 20% of the total available cropland, but is responsible for delivering more than one third of all food produced. Nearly two-thirds of irrigated crop land is found in India, China, the United States, Central Asia, and Pakistan. The most important crops grown on irrigated land are rice and wheat. Without irrigation, global cereal production would decrease by approximately 20%, so more land would be required to produce the same amount of food (Siebert and Döll 2010).

Approximately 90% of global rice production takes place on irrigated land, which is primarily found in south and Southeast Asia. Although rice can be grown under rain-fed conditions, the best production conditions are found on flooded fields. This explains the high water requirement of rice production which cannot usually be met solely by precipitation even in the humid tropics. In the wet–dry monsoon regions of south Asia (Sect. 7.1), rice production is primarily found in valley bottoms that are flooded once per year (e.g. Ganges, Mekong). In some areas of the humid tropics of Southeast Asia, terraces are used for rice production (Fig. 4.11).

On the one hand, irrigated agriculture contributes substantially to the global food supply and to the development of rural areas. On the other hand, it also contributes to major environmental problems. In many regions, more water is used for irrigation than is delivered by precipitation. As a result, in some regions of India and China the groundwater level is sinking by more than 1 m year^{-1}. This not only affects agricultural production, but also threatens natural ecosystems.

Another problem is salinization which primarily affects arid regions. In such areas irrigation results in higher rates of evaporation which leads to a gradual increase in the salt content of the soil, even if the water used has a low salt content. This process can only be prevented by sufficient drainage, by constructing drainage canals, or by installing drainage pipes, which ensures that excess water and the dissolved salts therein are drawn off.

“No irrigation without drainage” is the principle for irrigated agriculture in arid areas.

In Iraq, 20% of irrigated areas have had already to be abandoned because of soil salinization. In Pakistan, salinized soils have led to a 30% decline in yields. The salt content of soils impairs crops primarily as a result of osmotic effects (reduced water uptake), toxic effects of particular ions (e.g. chlorides and sulfates of sodium and

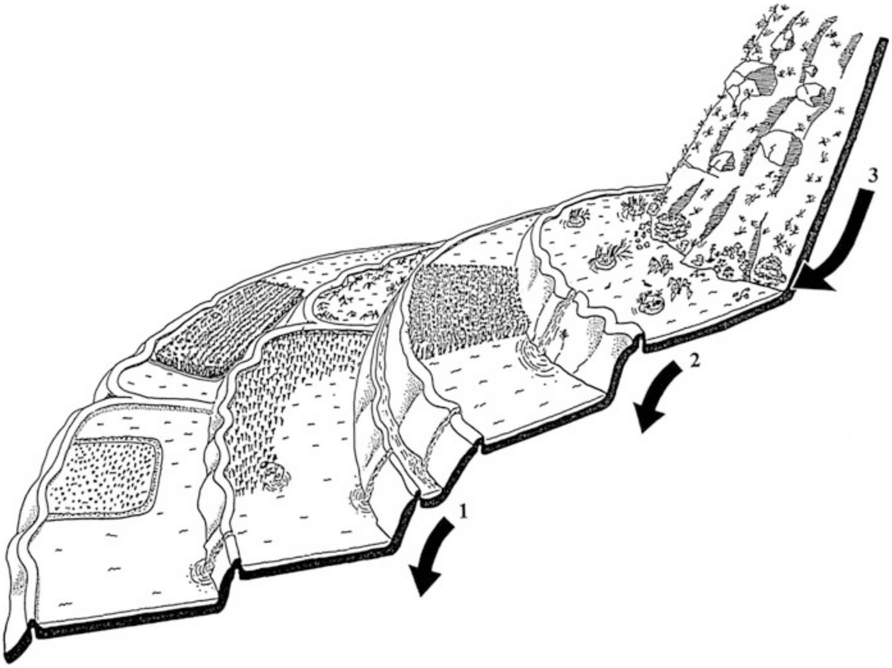

Fig. 4.11 Water supply in rice terraces of the traditional production system of Ifugao (Northern Luzon, Philippines). **1** = from diverted brooks, **2** = from field to field, **3** = with percolating spring water from the mountain side (From Martin 1994; drawn by Ch. Allgaier)

magnesium), and changes in soil properties (e.g. soil aeration and rooting ability). Individual crop species and varieties have different sensitivity to the salt concentration in soil solutions. Relatively tolerant species include barley and cotton whereas potatoes, wheat, and many legumes have low tolerance to salt. By breeding measures, including genetic engineering, attempts are being made to increase the salt tolerance of crop species.

The efficiency of irrigation methods is relatively small and amounts to, on average, less than 50%, which means that more than half of the applied water is not used by the plants, but rather percolates into the groundwater, runs off the surface, or evaporates. With special irrigation techniques, however, the quantity of water lost and, hence, the quantity of water used may be reduced. One way is to repeatedly use the water that flows out of an irrigated area for further irrigation; however, this leads to accumulation of salt in the water and thus to a reduction in its usability. Another method of water conservation is drip irrigation. In drip irrigation, pipes are laid either above or below ground, which then deliver water drop-wise to the plant roots through small openings in the pipes (sometimes nutrients are also delivered to the plants via the water, called fertigation). With such methods, water use efficiency of 95% can be achieved. The danger of soil salinization is only slight with this method because of the targeted delivery of the water. Drip irrigation is used primarily in fruit and vegetable production.

4.3 Soil

The upper layer of the Earth's crust, which is formed above the bedrock, is called **soil**. This layer is the product of the transformation of mineral materials and organic substances and is created by the effects of abiotic and biotic factors. Litho, bio, hydro, and atmosphere interpenetrate in the soil and form a unique component of the terrestrial ecosystem, the **pedosphere** (Greek *pedos* = soil; Fig. 4.12).

Soils fulfil numerous ecological functions:

- Soils are habitats for organisms. In this function, they directly serve the soil biotic community and the plants, which depend on the soil for rooting space and for uptake of nutrients and water. Indirectly, soils thus serve as the nutrient supplier for heterotrophic animal species and humans; the latter require soils for crop production.
- Soils are important in the regulation of different ecological cycles. By transformation and decomposition of organic and inorganic substances, soils significantly contribute to the cycling of carbon, nitrogen, and other elements.
- Soils serve as reservoirs, filters, buffers, and transformers of materials. An important function of soils is absorption of precipitation and its release to the atmosphere, to surface waters, and to groundwater. Related to this is the soil's ability to hold pollutants (e.g. pesticides, heavy metals) either mechanically or via adsorption by soil particles and thus to prevent or reduce the input of pollutants to water bodies. This function also includes the transformation of pollutants into non-hazardous compounds. The buffer action of soils is based primarily on the neutralization of introduced acids, which, e.g., originate from the atmosphere or fertilizers.

4.3.1 Soil Development and Soil Properties

The development and properties of soils are primarily determined and shaped by the parent material, topography or relief (e.g. slope), climate (temperature and precipitation), and organisms (Fig. 4.13). Soils are subject to constant change via transformation and translocation processes.

Rocks on the Earth's surface are subject to weathering, which means they are physically broken down into smaller pieces (e.g. by frost bursting) and chemically transformed (e.g. by oxidation and the action of acids). Through these processes nutrients are released, which enable the colonization of the rocks by organisms and the succession of communities. Subsequently, detritus, primarily from plant residues (litter), is increasingly deposited. From this litter, the activities of organisms produce the organic material of the soil, which is referred to as **humus**. Part of the humus is found as a more or less decomposed layer on top of the soil, and the remainder is

gaseous	air		
liquid	water		
solid	organic	living	underground plant parts
			soil organisms
		dead	detritus, humus
	inorganic	ions	
		minerals	

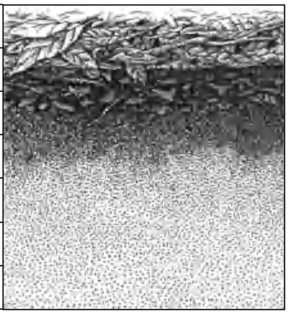

Fig. 4.12 Composition of the pedosphere

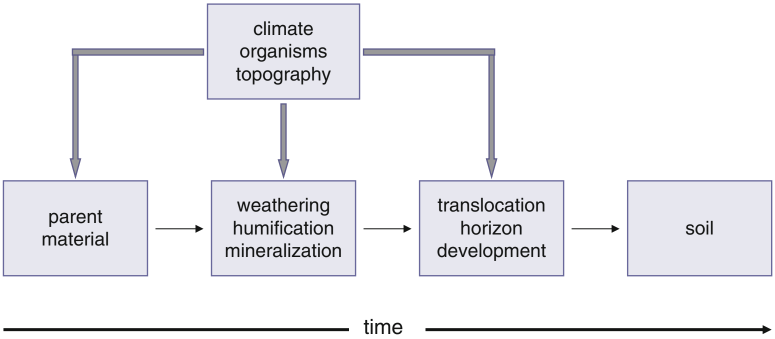

Fig. 4.13 Soil development (pedogenesis)

incorporated into the mineral soil. Depending on biotic and abiotic conditions, different types of humus are formed:

- **Mor** originates primarily from the litter of coniferous trees at relatively low temperatures and high precipitation.
- **Moder** forms primarily from the litter of deciduous forests under cool and moist conditions.
- **Mull** forms primarily from the easily decomposable litter of herbaceous plants of meadows and fields, and steppe vegetation under continental climate conditions.

Organic material that accumulates under wet conditions is called **peat** and is the raw material for peat soils.

Depending on the site conditions and the stage of development, soils depths may range from just a few centimetres to several metres. The development of deep and differentiated soils which are suitable for agriculture requires several thousand years. A fertile agricultural soil in Central Europe has a humus-rich upper layer that extends approximately 20 cm.

Table 4.2 Properties of different soil types

	Water infiltration and aeration	Water-holding and absorption capacity	Nutrient content	Root permeability	Soil condition for cultivation
Soils with a high sand content	High	Low	Low	Good	Good
Soils with a high clay content	Low	High	High	Moderate–poor	Poor
Soils with a high silt content	Medium	Medium	Medium–high	Moderate	Moderate–good

Soil development in Central Europe began at the end of the last ice age. Under moderate climate conditions, 100–300 years are required to build up a 1-cm layer of humus.

In addition to organic components, soils contain mineral materials that occur with a variety of particle sizes (grain sizes). The grains are differentiated into coarse (>2 mm) and fine soil fragments; the latter are further divided into sand (2–0.063 mm), silt (0.063–0.002 mm), and clay (<0.002 mm). The proportions and mixture of the fine soil fragments determine the **soil type**. In most soils, fragments of the different classes are found together. Depending on the proportion of each fragment class and on the soil texture, soil types are classified more specifically (e.g. loamy sand or silty clay). Loam is a mixture of the three classes sand, silt, and clay.

Depending on the mixture of fragments and their texture, soils have specific properties (Table 4.2) of different suitability for cultivation of crops. For root and tuber crops, for example potato, yam, and manioc, sandy, well-drained soils are usually favourable because the underground plant parts are less susceptible to diseases and are easier to harvest. Rice and taro (*Colocasia esculenta*) are adapted to clay-rich, waterlogged, or flooded soils. These plants have aerenchyma in their tissue (intercellular spaces or air channels which enable exchange of gases between the shoot and the root); this guarantees the supply of oxygen to the roots.

The physical properties of different soil types and the respective dominant climate conditions affect the growth conditions of plants in different ways. Sandy soils with large pores have a low water-storage capacity, which can lead to a drying of the soil in periods of low precipitation. Clay soils with small pores have a high field capacity which enables plants to avoid the danger of drought damage during longer periods without precipitation. Such conditions are found primarily in humid regions. In arid regions, the low precipitation, which occurs at great temporal intervals, often only supplies the upper layers of the soil with water. Because of different field capacities, the same quantity of water percolates deeper into sandy soils than into clay soils. By evaporation, the water at the surface of clay soils is rapidly lost whereas the moisture found deeper in sandy soils remains available longer and can be better utilized by plant roots (Walter and Breckle 1999).

In humid regions, favourable water conditions for plants are found on clay soils whereas in arid regions favourable water conditions are found on sandy soils.

4.3.2 Identification and Classification of Soils

In the course of their development, soils produce zones with different structures, which are termed **soil horizons** and are visible in a vertical section of the soil (soil profile).

The most important main soil horizons of naturally developed soils, by their position from top to bottom within the soil profile, are:

- **L** (litter) and **O** (organic) horizons above the mineral soil (organic layers of more or less decomposed plant residues)
- **A** horizon (mineral topsoil containing organic material, i.e. humus)
- **B** horizon (mineral subsoil of weathered parent material and accumulations from upper layers)
- **C** horizon (parent material, little affected by the soil-forming processes)

All of these categories can be further subdivided for more detailed description of the layer characteristics. The type, number and arrangement of horizons are criteria used for identification and classification of soils. However, there is no generally accepted system. Rather, various national and international systems based on different traditions exist for classification of soils. Important examples are:

- For the purpose of a global soil map, the FAO-UNESCO developed a soil classification system that differentiates between 30 major groups of soil (Table 4.3). The system is based on diagnostic horizons in consideration of specific characteristics and materials. All soil types and units described in this book are based on the FAO system.
- In North America, a classification system for soils (soil taxonomy) has become established that is defined by the presence or absence of defined diagnostic horizons and divides soils into 12 orders.
- In the German soil classification system, soils are primarily classified on the basis of the effect of different factors (e.g. parent material, vegetation, moisture, anthropogenic effects) on the development of the soil (Scheffer and Schachtschabel 2002).

Table 4.3 FAO-UNESCO (1988) soil classification

Major group	Characteristics	Etymology
Acrisols	Soils with subsurface accumulation of low-activity clays and low base saturation	Lat. *acris*, acidic, sour
Albeluvisols	Acid soils with a bleached horizon penetrating into a clay-rich subsurface horizon	Lat. *albus*, white Lat. *luvi*, eluviate
Alisols	Soils with subsurface accumulation of high activity clays, rich in exchangeable aluminium	Lat. *alumen*, Alum
Andosols	Young soils in volcanic deposits	Jap. *an do*, black earth
Anthrosol	Soils that have been formed or heavily modified by long-term human activity	Gr. *anthropos*, human
Arenosols	Sandy soils featuring very weak or no soil development	Lat. *arena*, sand
Calcisols	Soils with accumulation of secondary calcium carbonates	Lat. *calx*, lime
Cambisols	Weakly to moderately developed soils	Lat. *cambiere*, change
Chernozems	Soils with thick, blackish topsoil, rich in organic matter with calcareous subsoil	Russ. *cherny*, black; *zemlja*, earth
Cryosols	Soils with permafrost within 1 m depth	Gr. *kryos*, cold, ice
Durisols	Soils with accumulation of secondary gypsum	Lat. *durus*, firm, hard
Ferralsols	Deep, strongly weathered soils with a chemically poor, but physically stable subsoil	Lat. *ferrum*, iron; al from aluminum
Fluvisols	Young soils in alluvial deposits	Lat. *fluvius*, river
Gleysols	Soils with permanent or temporary wetness near the surface	Rus. *glej*, moist, heavy soil
Gypsisols	Soils with accumulation of secondary gypsum	Gr. *gypsos*, gypsum
Histosols	Soils composed of organic materials	Gr. *histos*, tissue
Kastanozems	Soils with thick, dark brown topsoil, rich in organic matter and calcareous or gypsum-rich subsoil	Lat. *castanea*, chestnut
Leptosols	Very shallow soils over hard rock or in unconsolidated very gravelly material	Gr. *leptos*, thin/ shallow
Lixisols	Soils with subsurface accumulation of low-activity clays and high base saturation	
Luvisols	Soils with subsurface accumulation of high-activity clays	Lat. *luvi*, eluviate
Nitisols	Deep, dark red, brown or yellow clayey soils having a pronounced shiny, nut-shaped structure	Lat. *nitidus*, shiny
Phaeozems	Soils with a thick, dark topsoil rich in organic matter and evidence of removal of carbonates	Gr. *phaios*, dark grey
Planosols	Soils with bleached, temporarily water-saturated topsoil on slowly permeable subsoil	Lat. *planus*, flat
Plinthosols	Wet soils with an irreversibly hardening mixture of iron, clay, and quartz in the subsoil	Gr. *plinthos*, brick
Podzols	Acid soils with blackish/brownish/reddish subsoil with alluvial iron–aluminium–organic compounds	Russ. *pod zola*, under ash
Regosols	Soils with very limited soil development	Gr. *rhegos*, cover
Solonchaks	Strongly saline soils	Rus. *sol*, salt
Solonetz	Soils with subsurface clay accumulation, rich in sodium	Rus. *sol*, salt
Umbrisols	Acid soils with a thick, dark topsoil rich in organic matter	Lat. *umbra*, shadow/ dark
Vertisols	Dark-coloured cracking and swelling clays	Lat. *vertere*, turn

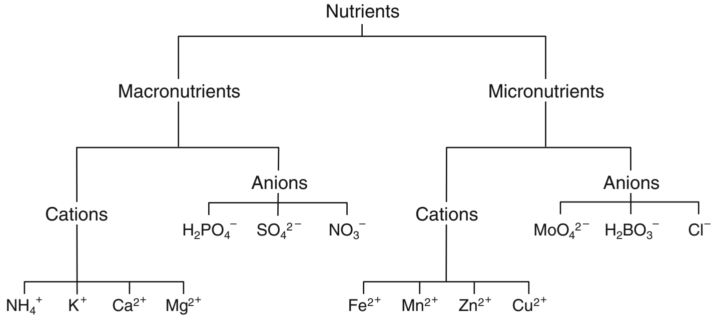

Fig. 4.14 Macro- and micronutrients of plants in the forms in which they are taken up by the plants

4.3.3 Plant Nutrients

In addition to sun's energy, CO_2, and water, mineral nutrients are also necessary for the growth and development of plants. These must be taken up by the plants as ions, and are usually drawn from the soil solution via the plant roots.

Plants have a relatively high requirement for the elements nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg). These are the **macronutrients**. The elements iron (Fe), manganese (Mg), boron (B), zinc (Zn), copper (Cu), molybdenum (Mo), and chlorine (Cl) are required in smaller amounts and belong to the **micronutrients** (Fig. 4.14). Together, these nutrients are the essential (necessary for life) nutrients. They act either as components of organic substances or are required for particular physiological processes. Other elements, for example sodium (Na), selenium (Se), cobalt (Co), and nickel (Ni), are important for at least some plants as **trace elements**.

In agroecosystems, nutrients are rarely present in balanced proportions and in the necessary quantities. Not only a deficit but also excess of an essential nutrient can negatively affect the development of a plant. In addition to the essential nutrients, other elements are also found in the soil, in particular such heavy metals as cadmium (Cd), lead (Pb), mercury (Hg), and chromium (Cr). At high concentrations these elements are toxic to organisms because they inhibit physiological processes and the activity of enzymes.

When all essential nutrients are available in the quantities necessary for plants, development of the plant proceeds regularly. As soon as the plant is lacking one of these nutrients, signs of deficiencies will emerge and growth will be depressed. On the basis of this observation, Justus von Liebig (1803–1873) formulated the **Law of the Minimum**. It states that plant growth is controlled not by the total amount of nutrients available, but by the scarcest nutrient. In other words, yield is proportional to the amount of the most limiting nutrient, whichever it may be.

4.3.3.1 Availability of Nutrients

In the soil, the nutrients required by the plants are predominantly present in diverse bound forms, from which they are released by the following processes:

- bound in minerals of the parent material and released by weathering of the parent material,
- organically bound in detritus and humus and released during decomposition by soil organisms,
- adsorbed on soil colloids and released by ion exchange (see below).

Not only the quantities of nutrients in the soil, but also spatial and temporal availability are crucial in the growth and development of plants.

Because nutrients must be taken up by plants from the soil solution, they are only usable when the root zone is sufficiently moist. Lack of water can therefore limit uptake of nutrients by plants. The clay and humus content of the soil also has a significant effect on nutrient availability. Of greatest importance are particles with sizes less than 0.001 mm (**soil colloids**). In interaction with calcium, these also form the so-called clay–humus complexes. The surfaces of clay colloids have electrostatic negative charges on which cations (positively charged particles) from the soil solution become attached (adsorption). On humus colloids and oxidized particles, positive charges are found on which anions (negatively charged particles) are adsorbed. Conversely, release of adsorbed ions to the soil solution may occur (desorption) by displacement or exchange of ions. Ion exchange can occur only between ions of equivalent charge, for example 6 H^+ for 3 Mg^{2+} or 3 Ca^{2+}.

The ions that may be exchanged on colloids, which are, in part, of importance as plant nutrients, include the cations Ca^{2+}, Mg^{2+}, K^+, Na^+, H^+, and Al^{3+}, and the anions PO_4^{3-} and SO_4^{2-}. There are almost no specific binding sites for NO_3^- and Cl^-, which is why these ions are most often found in the soluble form.

Ion exchange in the soil, which is also of great importance to the nutrient status of plants, involves exchange processes between colloids, the soil solution, and the roots (Fig. 4.15). Roots release ions, primarily H^+ and HCO_3^-, which are formed during cell respiration, into the soil solution. This enables uptake of an equivalent quantity of nutrient ions. As a consequence, further ion-exchange processes occur between the soil solution and the soil colloids.

The total quantity of exchangeable cations and anions, in other words the maximum amount of ions that may be adsorbed in the soil, is termed the exchange capacity. In clay and humus-rich soils, largely cation exchange sites are present, and anion exchange sites are of minor importance only. Because many important plant nutrients are cations, usually only the **cation-exchange capacity (CEC)** is used as a measure of nutrient supply for plants. The CEC is expressed in charge

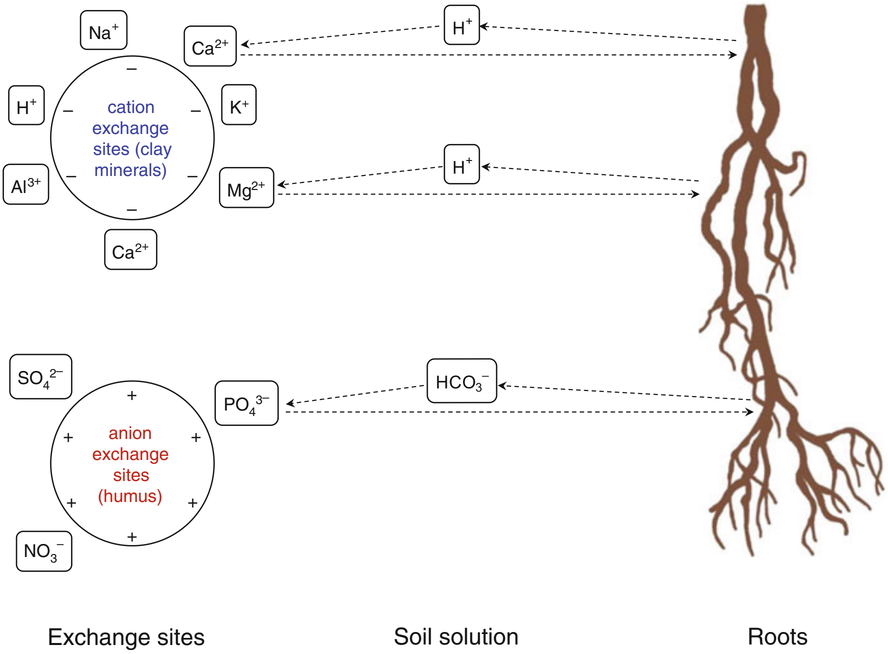

Fig. 4.15 Ion-exchange processes in the soil

equivalents or milligram equivalents (mol$_c$ or centimol$_c$ = cmol$_c$) per kilogram dry soil. The higher the CEC, the better is the ability of the soil to hold and exchange cations. The CEC is primarily dependent on the soil's content of mineral and organic exchange sites and, in most soils with approximately 2–3% humus, this lies between 5 cmol$_c$ (sandy soils) and 40 cmol$_c$ (clay soils).

The amount of Ca^{2+}, Mg^{2+}, K^+, and Na^+ ions with an alkaline effect on the exchange sites is termed the **base saturation**. The remaining amount comprises H^+ and Al^{3+} ions, which determine soil acidity (see below). A base saturation of, for example, 60% means that 60% of the ions adsorbed by the exchange sites are Ca^{2+}, Mg^{2+}, K^+, and Na^+ ions, and 40% are H^+ and Al^{3+} ions.

4.3.4 Soil Reaction (pH)

The acidic and alkaline effects of the soil solution are termed the **soil reaction**. This depends on the quantity of acidic H^+ ions and alkaline OH^- ions and is measured, on the basis of hydrogen ion concentration, as the **pH value** [Latin p = *pondus* (weight), H = *Hydrogenium* (hydrogen)]. pH is defined as the negative logarithm of the H^+ ion concentration in grams (g) per litre (l) solution (pH $x = 10^{-x}$ g H^+ l^{-1}). pH 7 means that 10^{-7} g H^+ ions are found in 1 l of soil solution. Because the quantity of OH^- ions is the same in this case, the soil solution is said to be neutral at pH 7. The pH scale ranges from 0 to 14. The higher the H^+ ion concentration, the lower the pH. When the pH is below 7, the soil solution is acidic; when the pH is more than 7 the soil solution is alkaline (basic). The range of pH values in Central Europe ranges from approximately 3 to 8. Most soils are slightly acidic (around pH 5–6.5).

pH significantly affects the amounts of nutrients adsorbed, and thus their availability. The availability of most nutrients is highest under slightly acidic to neutral conditions (pH 5.5–7), which means that this range may also be regarded as optimum for most agricultural soils. Under nearly neutral conditions, the effect of the pH is also particularly favourable for soil structure, i.e. high Ca^{2+} and Mg^{2+} content. In strongly acidic soils ($pH < 4.5$), high concentrations of Al^{3+} ions are found in the soil solution, which may damage plants (aluminum toxicity). Low pH also negatively affects soil bacteria (see below). Legumes are directly affected by this, because they live in symbiotic relationships with nitrogen-fixing bacteria (Sect. 3.7.4.1), which are impaired by acidic conditions.

pH affects many soil properties, and thus the growth conditions of plants and the living conditions and performance of soil organisms.

An increase in soil acidity (acidification) can be caused by a variety of factors. Widespread acidification and loss of bases has occurred in the upper soils of Central Europe in recent years, largely as the result of acid rain (Sect. 3.7.4.2). A decrease in pH can also result from development of acidic humus materials from litter, and as a result of the respiration of soil organisms, including soil roots (production of carbonic acid: $CO_2 + H_2O \leftrightarrow HCO_3^- + H^+$)

In agricultural soils, specific fertilizers (e.g. ammonium sulfate, liquid manure, superphosphate) can also lead to a decline in pH.

The extent of the effects of these on soil pH depends primarily on lime content, cation-exchange capacity, and base saturation on the exchange sites. The higher these are, the better is the buffer capacity of the soil, i.e., the soil's ability to bind H^+ ions and thus counteract soil acidification. This ability is, in turn, affected by the alkali content of the parent material, which is particularly high for carbonate rocks (calcite and dolomite). By application of calcium and/or magnesium carbonate, the buffering capacity of the soil can be improved, in other words the pH of acidic soils can be increased.

4.3.5 Soil Organisms

All the organisms living in the soil are known as the *Edaphon* (Greek: living in the soil). The most important function of the soil biological community is decomposition and transformation of dead remains of organisms in terrestrial ecosystems. These processes include the development of humus and the release of organic and inorganic compounds, including plant nutrients.

4.3.5.1 Composition and Function of the Soil Community

Traditionally, soil organisms are divided into two main groups:

1. The **soil flora** primarily consists of bacteria and fungi, which are the smallest organisms of the soil community and are also termed microflora. The soil flora also includes algae and lichens, and, in the broadest sense, subterranean plant organs.
2. The **soil fauna** is composed of the animals in the soil community, which are subdivided according to body size:

    - The microfauna primarily includes the protozoa (single-celled animals). Their most important groups in the soil are amoebae, ciliates, and flagellates.
    - The mesofauna comprises the smallest representatives of the soil arthropods, of which the most important groups are the Acari (mites) and Collembola (springtails). In addition, Nematodes (roundworms or eelworms) and the Enchytraeidae belonging to the Annelida (segmented worms) are also included in the mesofauna.
    - The macrofauna especially includes the Lumbricidae (earthworms), some insects, Chilopoda (centipedes), Diplopoda (millipedes), Isopoda (woodlice), some Arachnida (spiders), and Gastropods (snails and slugs).
    - The term megafauna is primarily applied to mammals, for example voles (Arvicolidae) and moles (Talpidae), which interact with the soil by construction of burrows and tunnels.

Little is known about the diversity of the Edaphon. It can be assumed that in most ecosystems the number of species living in the soil is several times the number of species found above-ground. This is primarily because of the species diversity of bacteria and fungi that live in the soil. Currently, probably only 10% of all species of the soil community have been described (Hawksworth and Mound 1991).

Beside classification according to size, the organisms of the soil community can also be divided into functional groups, which are defined by their position in the food web, in other words by their source of food. The major groups are, thus, detritivores, bacterivores (feed on bacteria), fungivores (feed on fungi), phytophages (primarily feeders on roots), predators, and omnivores. Figure 4.16 shows the food web of an agricultural soil, on the basis of this classification.

The most important resource on which the soil food web builds is dead organic material (detritus), which is primarily made up of plant residues (above-ground litter and dead root materials). Under the action of different groups of detritivores, the process of the transformation of organic materials is as follows:

- **Wash-out phase**: First, the readily soluble molecules, primarily sugars, are washed out by precipitation. These can then be used directly by microorganisms.
- **Break-down phase**: Soil animals, for example earthworms, roundworms, and springtails transform the remaining material by breaking it down into smaller pieces, ingesting it, and excreting most of it.

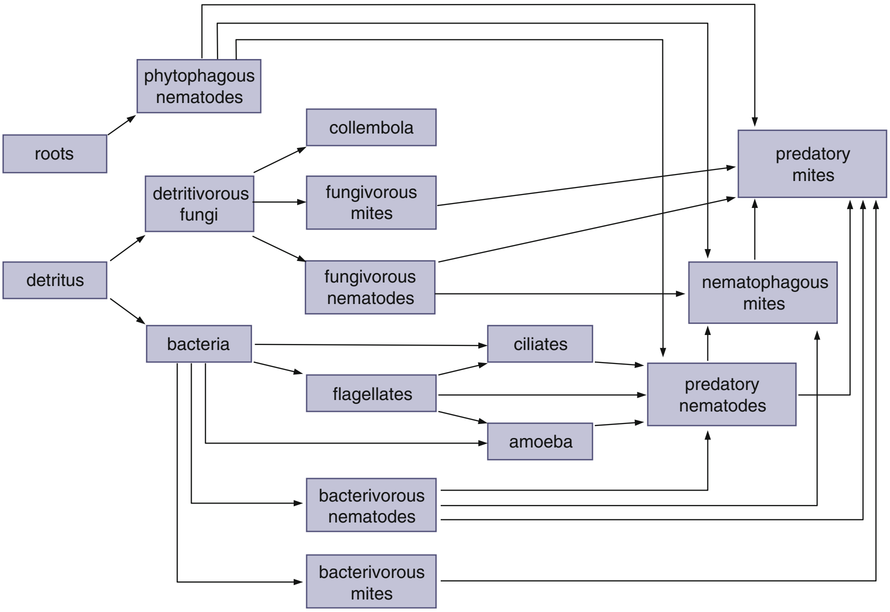

Fig. 4.16 Food web of the soil biological community in an intensively cultivated field of winter wheat in the Netherlands (Based on Moore and De Ruiter 1991)

- **Microbial phase**: The size-reduced and transformed residues are readily susceptible to the enzymes of fungi and bacteria and are used by them as a source of energy and nutrients. Thus, some of the material is decomposed into inorganic products in a relatively short period of time (between months and a few years). This process is called **mineralization**. In addition to CO_2 and water, diverse mineral nutrients are released in the process, and are then available to plants. Another portion of the materials (e.g. lignin, cellulose, resins, waxes, chitin) is decomposed more slowly and is transformed by the microorganisms into new organic intermediate products. Such **humic substances** can remain in the soil for hundreds of years.

The rate and extent of decomposition of organic substances is affected by, in addition to the abiotic conditions (including temperature, moisture, pH), primarily the composition of the materials themselves. An important factor is the carbon-to-nitrogen ratio of the material. The lower the **C/N ratio**, the faster is the decomposition, because then the organisms have a relatively large quantity of nitrogen compounds available for food. The litter of herbaceous plants has a C/N ratio of approximately 20–30:1. The autumn leaf litter of many trees often has a ratio of approximately 40–60:1; for straw it is 60–100:1. The rate of decomposition decreases in the same order. Coniferous litter is, because of its high resins content, very hard to decompose.

4.3.5.2 Factors Affecting the Soil Community

Most of the biomass of soil organisms is usually fungi and bacteria. Among the representatives of the soil fauna earthworms and protozoa usually predominate. The total biomass, and the proportions of the individual groups of organisms in the community, can, however, vary substantially in different soils. In addition to climatic conditions, the following factors strongly affect the composition of the soil community:

Pore spaces in the soil. Most representatives of the microflora are found in soil pores as small as 1–25 μm in diameter, and many species of microflora and mesofauna require pores with a diameter of 25–100 μm (1 μm = micrometre = 10^{-6} m = one thousandth of a millimetre). The composition of the soil community shifts with a decline in the pore size of a soil, to the benefit of the organisms with small body sizes, and therefore varies with soil type.

Water and air content of the soil. The availability of water is a precondition for the existence and activity of soil organisms. They also require oxygen, however, so water and air, in balanced quantities, must be present in the soil. The ideal conditions for microflora are when approximately 60% of the pore volume is filled by water. Many organisms (e.g. bacteria, protozoa, and nematodes) require a water film on the soil particles to be able to move. Extreme deviations from the balanced conditions (water saturation or drought) have a negative effect on the entire soil community.

Soil pH. Bacteria biomass is usually highest in neutral or slightly acidic soils and declines with more acidic or alkaline pH values. The reason for this is primarily that the activity of many bacterial enzymes is dependent on pH. This relationship is usually not evident for fungi and the soil fauna. Some of those species reach their highest density in relatively acidic sites whereas others reach this level in sites with neutral pH (Fig. 4.17).

Vegetation. The composition of the vegetation of a site determines the quantity and quality (e.g. C/N ratio) of the litter. This material serves as the food resource of the detritivores and thus affects the structure of the soil food web. For many soil organisms, the living biomass of plant roots is also important. This is true not only for plant feeders but also for fungi (mycorrhiza, Box 3.2) and bacteria, which can use root excretions (especially amino acids and sugars) as a food source (cf. Sect. 3.7.4.1). In addition, the vegetation has indirect effects on the environmental conditions of the soil, which can include effects on water balance (e.g. by shading, and water use of the plants) and on pH.

In agroecosystems, the soil organisms and their activities are also affected by the following factors:

Fertilization. The nutrient content of agroecosystems is directed by natural processes in only a limited way. Because a large part of the produced biomass is removed with harvest, the quantity of organic material that originates from plants is usually less than that found in natural ecosystems. The nutrient supply of plants is, instead,

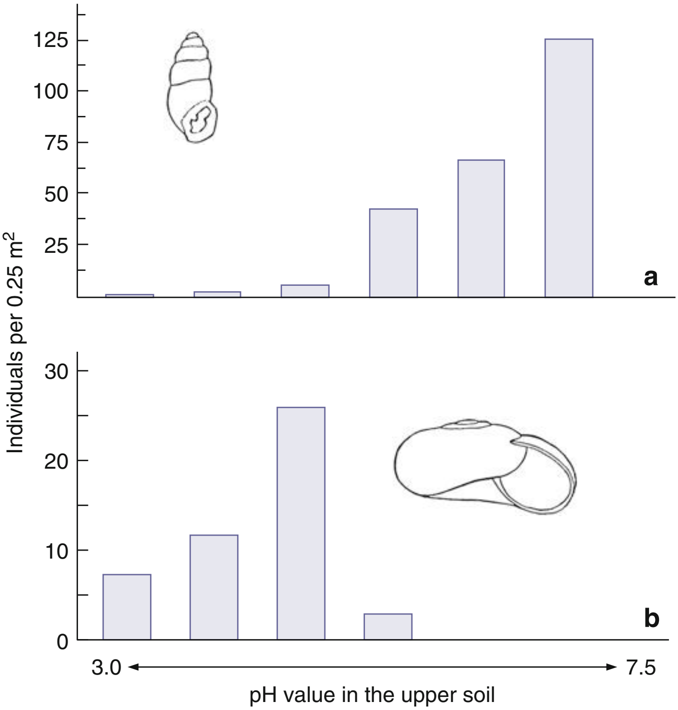

Fig. 4.17 Relationships between the pH of the upper soil and the number of individuals of two snail species in woodlands of southwest Germany. (**a**) *Carychium tridentatum*, (**b**) *Nesovitrea hammonis* (Based on Martin and Sommer 2004; drawings by Ch. Allgaier)

met with mineral or organic fertilizers. The qualitatively and quantitatively different resource supply of agroecosystems, in comparison with natural systems, can have diverse and complex effects on the biomass and composition of the soil community, on the abundance of individual groups of organisms, and on the structure of the soil food web. No broad generalizations can be made about the extent of such changes; they are affected not only by the type and quantity of fertilizer used but also by the individual abiotic site conditions.

Soil cultivation (Box 4.2). Ploughing causes inversion of the soil, which changes the soil structure and the soil microclimate conditions (temperature and moisture). These factors affect the organisms of the soil community in different ways. Negative effects result for many soil animals found in the soil (e.g. earthworms and some insect larvae) or on the soil's surface (e.g. ground beetles and some species of spider). On the other hand, the activities of the microorganisms and, thereby, the decomposition of humus are promoted by ploughing. In the long term, this type of soil cultivation therefore leads to a loss of organic matter in the upper soil. As a result of regular ploughing a plough pan may also form in the soil. The associated decline in pore volume, with changes in soil water content, also affect the living conditions of soil organisms.

Box 4.2 Soil Cultivation

Conventional tillage involves ploughing, whereby compact layers of the upper soil are broken up and turned upside down. Ploughing improves plant root penetration, water infiltration and storage capacity, and soil aeration. Ploughing is also a means of incorporating harvest residues and contributing to weed management (Sect. 5.1.3). After this so-called primary cultivation, the seed bed is prepared in which the soil material is broken down into smaller pieces and levelled with a variety of equipment. On this prepared area, sowing is conducted. However, this process is accompanied by several disadvantages, primarily negative effects on the soil fauna, loss of humus, increased risk of erosion, and development of a ploughpan.

As an alternative to conventional soil cultivation, **conservation tillage** can be used to avoid or minimize the disadvantages mentioned. In contrast with the effect of the plough, conservation tillage does not turn harvest and green manure residues into the soil, instead these residues are mixed with the soil close to the surface. This is achieved by use of equipment for soil-loosening (e.g. a cultivator), rather than soil-turning. Thus, the structure of the soil is maintained, in other words “conserved”.

An additional form of tillage in agroecosystems is **direct seeding or no-till**, in which there is no soil tillage. Seed bed preparation and mechanical weeding are also omitted. Sowing solely involves creation of a furrow in the soil. In direct seed systems, the soil is permanently covered with plant residues, which can hinder the even distribution of seeds.

Conservation tillage, and to a greater extent direct seeding, have positive effects on some properties of the soil. In particular these include conservation or increase of the organic matter content of the soil, avoidance of soil compaction, and reduction of soil losses via erosion. Furthermore, with both methods the costs of machinery use and energy, and labour requirements, are lower than with conventional soil tillage. Because no-till and conservation tillage methods are only rarely accompanied by declines in yield, they are increasingly being used.

Pesticides and herbicides. The chemical and biological substances used to protect crops from pests, phytopathogens, or weeds not only affect the target organisms but can also often directly or indirectly damage species of the soil biological community.

4.3.5.3 The Importance of Humus in Agroecosystems

In principle, it is possible to replace the soil, as rooting space for plants, with a synthetic substrate (e.g. rock wool or coconut fibres) and grow such plants as tomatoes, cucumbers, or courgettes in a nutrient solution that is produced to meet the requirements of the plants. This soil-free method of production is used in greenhouses where, under controlled temperature and light conditions, production can be conducted irrespective of season. Complete de-coupling of plant production from natural nutrient cycles, including the delivery of organic materials and their transformation (the release of nutrients and the building of humus) by soil organisms, should not be the intention of farming, nor is it achievable. A nutrient-rich, entirely mineral soil is only of limited use for agricultural purposes because particular functions, which depend on the delivery of organic materials and the activity of soil organisms, are not, or only partially, fulfilled. Humus, which in agricultural soils originates from harvest residues (roots, straw, leaves) and, eventually, organic fertilizers (green manure, manure, liquid manure, compost), is of crucial importance in these functions and to **soil fertility**, which means the ability of the soil to facilitate plant growth and produce yields, i.e. the productivity of a site. In addition to organic substance, soil fertility is also determined by diverse abiotic factors (e.g. parent material, climate, weathering, water balance). Depending on the quality and quantity of humus, other soil properties that are important in agroecosystems are, in turn, affected. These include root penetration, ease of tillage, field capacity, rate of infiltration, aeration, and soil erodibility. Conditions suitable for high agricultural productivity are found in a soil which has approximately 45% mineral components, 5% organic substances, and a pore volume of approximately 50%.

Important agricultural measures for conservation and promotion of the humus content of an agricultural soil are:

- providing the soil with a sufficient supply of organic substances to compensate for humus loss;
- balanced and need-based application of mineral and organic fertilizers, pesticides, and herbicides;
- site-adapted crop rotation, as diverse as possible; and
- site-adapted and appropriate soil tillage that avoids soil compaction and erosion.

4.3.6 Soil Erosion

Soil erosion is removal of soil materials by water or wind. In principle, soil erosion is a natural process; it may, however, be strengthened or initiated in particular sites by some types of land use.

The extent and the form of **water erosion** (Fig. 4.18) depend primarily on:

- the intensity, frequency, and duration of rainfall. With increasing precipitation and energy of the raindrops, the effect on the soil surface increases (rain-splash erosion).
- the water-absorption capacity of the soil, which is affected by the infiltration rate, the water transfer capacity, and the current storage capacity of the soil (in other