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prolific the species is. The large numbers of seed (up to 14 million/ha) are most commonly found in the top 7 cm of the soil where, under conditions of light, fluctuating temperatures and nitrate ions, they may overcome the dormancy mechanism and germinate to form the seedling. Many seeds, however, survive up to the second, third and occasionally fourth years. Figure 13.6 shows that germination can occur at any time of the year, with April and September as peak periods. Chickweed is an alternate host for many aphid transmitted viruses (e.g. cucumber mosaic), and the stem and bulb nematode.

Spread. The seeds are normally released as the fruit capsule opens during dry weather; they survive digestion by animals and birds and may thus be dispersed over large distances. Irrigation water may carry them into channels and ditches.

Control. This weed is controlled by a combination of methods. Physical controls include partial sterilization of soil in greenhouses while hoeing in the spring and autumn periods prevents the seedling from developing and flowering. Mulching is effective against germinating weeds.

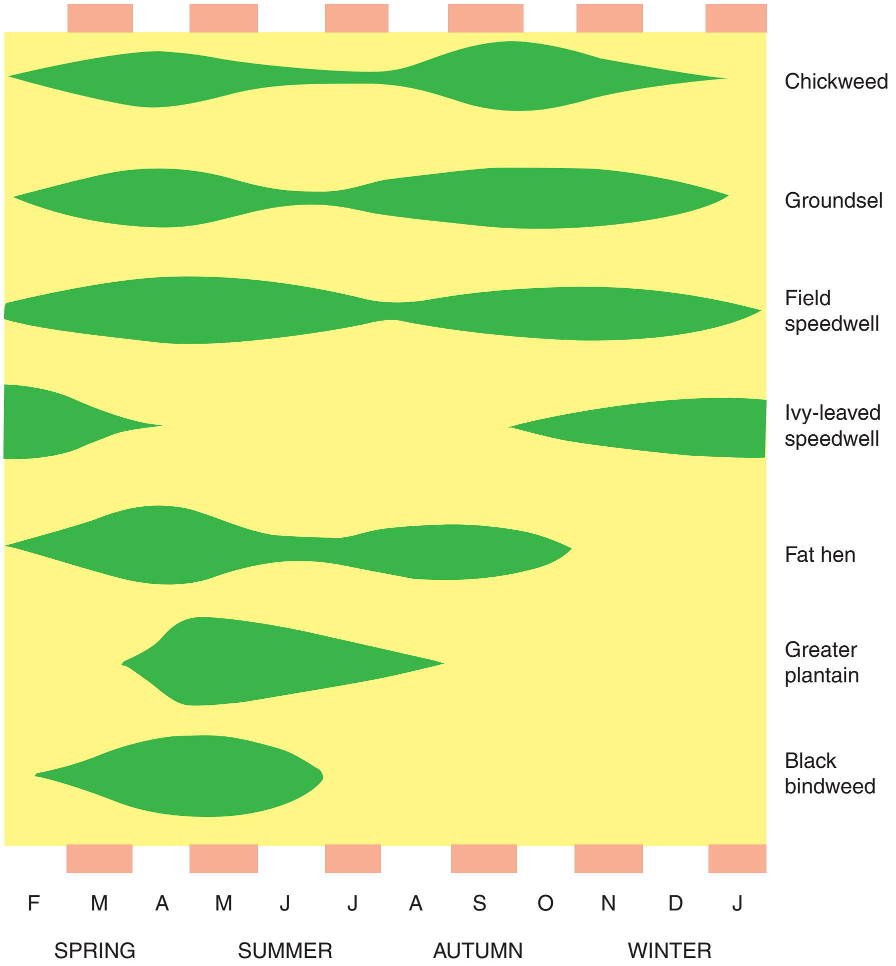


Figure 13.6 **Annual and perennial weeds**: periods of seed germination. Note that chickweed, groundsel and field speedwell seeds germinate throughout the year. Many other species are more limited. (Reproduced by permission of Blackwell Scientific Publications)

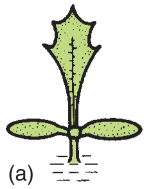
Amateur gardeners can use the non-selective, non-persistent herbicide, **glufosinate-ammonium plus fatty acids** for control in such situations as ornamental beds containing woody perennials, and in cane fruit.

Professional horticulturalists use pre-emergent contact sprays such as **paraquat** applied before a crop emerges. A soil-applied root-acting herbicide such as **propachlor** is used on a crop such as strawberries before weeds germinate. A foliage-acting herbicide such as **linuron** is applied for chickweed control in potatoes.

Groundsel (*Senecio vulgaris*). Plant family – Asteraceae (Compositae)

Damage. This is a very common and important weed, particularly on heavy soil. Its high level of seed production and the ability of its seed to germinate soon after release lead to dense mats of the weed. It grows on both rich and poor soils up to almost 600 m in altitude.

Life cycle. The seedling cotyledons are narrow, purple underneath, and the first true leaves have step-like teeth (see Figure 13.7). The adult plant has an upright habit, and produces as many as 25 yellow, small-petalled flower heads. Flowering occurs in all seasons of the year. Produces about 45 column-shaped seeds, 2 mm in length densely packed in the fruit head. As can be seen in Figure 13.5, the seeds may germinate at any time of the year, with early May and September as peak periods. Since there may be more than three generations of groundsel per year (the autumn generation surviving the winter), and each generation may give rise to a thousand seeds, it is clear why groundsel is one of the most successful colonizers of cultivated ground. Its role as a symptomless carrier of the wilt fungus, *Verticillium*, increases its importance in certain crops, e.g. tomatoes and hops.



(b)

Figure 13.7 (a) **Groundsel seedling** (b) **Groundsel plant**

Spread. The seeds bear a mass of fine hairs. These hairs, in dry weather, can parachute seeds along on air currents for many metres. In wet weather the seeds become sticky and may be carried on the feet of animals, including humans. The seeds survive digestion by birds, and thus can be transported in this way.

Control. A combination of control methods may be necessary for successful control. Physical control is by hoeing or by mechanical cultivation, particularly in spring and autumn to prevent developing seedlings from flowering. Care should be taken not to allow uprooted flowering groundsel plants to release viable seed.

The ***amateur*** gardener can use the herbicide, **glufosinate-ammonium plus fatty acids**, for control in such situations as ornamental beds containing woody perennials, and in cane fruit.

The ***professional*** horticulturalist can use contact herbicides, such as **paraquat** to control the weed in all stages of growth on paths or in fallow soil (but never on garden plants or turf). Soil-acting chemicals such as **propachlor** on brassicas kill off the germinating seedling. An established groundsel population, especially in a crop such as lettuce (a fellow member of the Asteraceae family) requires careful choice of herbicide to avoid damage to the crop (see also **propyzamide**, p279).

Annual weeds

While there are at least 50 successful annual weed species in horticulture, this book can cover only a few examples that illustrate the main points of life cycles and control. Two species, annual meadow grass and speedwell, are described.

Annual meadow grass (*Poa annua*). Plant family – Poaceae (Graminae)

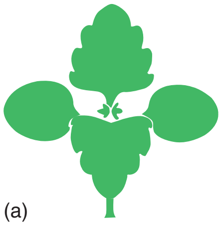
Damage. This species is a quite small annual (or short-term perennial) found on a range of ornamental and sports grass surfaces, on paths and in vegetable plots (see Figure 13.8). It is able to establish quickly on bare ground. It does not thrive on acid soils or those low in phosphates. Despite its relatively small size, it often emerges in sufficient quantities to smother crop seedlings. Its seed may be present as an impurity in commercial grass seed. Special selections of this species are used in seed mixtures for lawns.

Life cycle. Flowers can occur at any time of year and are usually self-pollinated. About 2000 seeds per plant are produced from April to September. Plants will flower and seed even when mown regularly. Seeds germinate from February to November with the main peaks in early spring and autumn. Some seed will germinate soon after their release; others can remain viable in soil for at least 4 years. This weed species can be the host of a number of nematode species that also attack important crops.

Spread. There is no obvious dispersal mechanism. Most seeds fall around the parent plant and become incorporated into the soil. Seeds may be carried around on boots and wheels of machinery. Worms may bring seeds to the soil surface in worm casts.

Control is achieved by a variety of methods. The physical action of hoeing normally controls the weed especially when it is in the young stage. Deep digging-in of seedlings and young plants is also usually effective. Mulching is effective against germinating weeds in flower beds and fruit areas. The ***amateur*** gardener can use the non-selective, non-residual herbicide, **glufosi-nate-ammonium plus fatty acids**, for control in situations such as ornamental beds containing woody perennials and in cane fruit. The ***professional*** horticulturalist may use **paraquat** or **glyphosate** for total chemical control, but these two chemicals should never be sprayed in the vicinity of growing crops. Care should be taken not to walk on grass after application of these chemicals. **Chlorpropham** may be used as a soil applied chemical on crops such as currants, onions and chrysanthemum.

Figure 13.8 Annual meadow grass plant



(a)

(b)

Figure 13.9 (a) **Field speedwell seedling** (b) **Field speedwell plants**

Speedwells (*Veronica persica* and *V. filiformis*). Plant family – Scrophulariaceae

Damage. The first species, the large field speedwell (*V. persica*) is an important weed in vegetable production, crowding out young crop plants and reducing growth of more mature stages. The second species, the slender or round-leaved speedwell (*V. filiformis*), once considered a desirable rock garden plant introduction from Turkey, has become a serious turf problem.

Life cycle. The seedling cotyledons are spade shaped, while the true leaves are opposite, notched and hairy (see Figure 13.9) in both species. The adult plants have erect, hairy stems and rather similar broad-toothed leaves. *V. persica* produces up to 300 bright blue flowers, 1 cm wide, per plant. The flowers are self-fertile and occur throughout the year, but mainly between February and November. The adult plant produces an average of 2000 light brown boat-shaped seeds 2 mm across. The seeds of this species germinate below soil level all year round, but most commonly from March to May (see Figure 13.5), the winter period being necessary to break dormancy. Seeds may remain viable for more than 2 years. *V. filiformis* produces self-sterile purplish-blue flowers between March and May, and spreads by means of prostrate stems which root at their nodes to invade fine and coarse turf, especially in damp areas. Segments of this weed cut by lawnmowers easily root and further increase the species. Seeds are not important in its spread.

Spread. Seeds of *V. persica* falling to the ground may be dispersed by ants. Seed of this species can be spread as contaminants of crop seed. *V. filiformis* does not produce seed. Its slow spread is mainly by means of grass-cutting machinery.

Control. Field speedwell (*V. persica*) is controlled by a combination of methods. The physical action of hoeing or mechanical cultivation, particularly in spring, prevents developing seedlings from growing to mature plants and producing their many seeds.

The ***amateur*** gardener can use the herbicide, **glufosinate-ammonium plus fatty acids** for control in situations such as ornamental beds containing woody perennials and in cane fruit.

For the ***professional*** grower, total contact herbicides, such as **paraquat**, may be sprayed to control the weed on paths or in fallow soils. Soil-acting chemicals such as **chlorpropham** on crops such as lettuce, onions and chrysanthemums kill off the germinating weed seedling. A contact, foliar chemical such as **clopyralid**, may be sprayed on to brassicas, young onions, and strawberries to control emerging seedlings.

The slender speedwell (*V. filiformis*) represents a different problem for control. Physical controls such as regular close mowing and spiking of turf removes the high humidity necessary for this weed's establishment and development.

The ***amateur*** gardener has difficulty controlling this weed with the turf herbicides available. The ***amateur*** or ***professional*** grower can control the weed in a turf seedbed using a total, contact chemical such as **glufosinate-ammonium plus fatty acids**, a few weeks before sowing the turf seed. This '**stale seed bed**' method leaves the turf to establish relatively undisturbed by weeds. Organic growers may remove stale seedbed weeds by hoeing. Professional growers can use a selective contact chemical such as **chlorthal dimethyl** which is effective against this weed in established grass.

Perennial weeds

Five species (creeping thistle; couch; yarrow; dandelion and broad-leaved dock) are described below to demonstrate the different features of their biology (particularly the perennating organs) that make them successful weeds. The flowering period of these weeds is mainly between June and October (see Figure 13.10), but the main problem for gardeners and growers is the plant's ability to survive and reproduce vegetatively.

Creeping thistle (*Cirsium arvense*). Plant family – Asteraceae (Compositae)

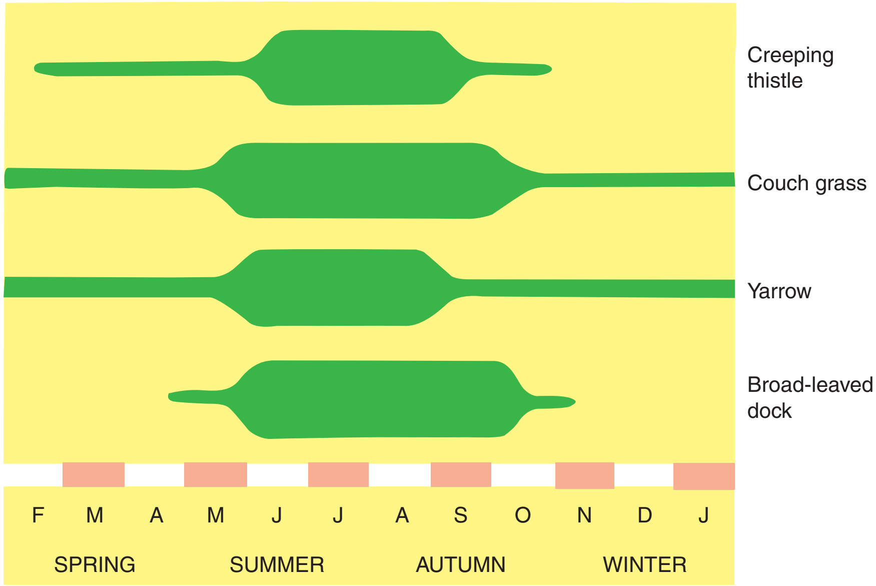


Figure 13.10 **Perennial weeds**: periods of flowering. Most flowers and seeds are produced between June and October. Annual weeds commonly flower throughout the year. However the slender speedwell flowers only between March and May

Damage. This species is a common weed in grass and perennial crops, e.g. apples, where it forms dense clumps of foliage, often several metres across.

Life cycle. The seedling cotyledons are broad and smooth, the true leaves are spiky (see Figure 13.11). The mature plant is readily recognizable by its dark green spiny foliage growing up to 1 m in height. It is found in all areas, even at altitudes of 750 m, and on saline soil. The species is dioecious, the male plant producing spherical and the female slightly elongated purple flower heads from July to September. Only when both sexes of the plant are within about 100 m of each other does fertilization occur in sufficient quantities to produce large numbers of brown, shiny fruit, 4 mm long. The seeds may germinate beneath the soil surface in the same year as their production, or in the following spring, particularly when soil temperatures reach 20°C. The resulting seedlings develop into a plant with a taproot which commonly reaches 3 m down into the soil.

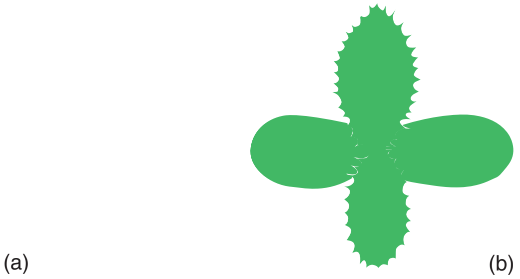


Figure 13.11 **Creeping thistle plant** showing (a) lateral roots, (b) seedling

Spread. Seeds are wind-borne using a parachute of long hairs. The mature plant produces lateral roots which grow out horizontally about 0.3 m below the soil surface and may spread the plant as much as 6 m in one season. Along their length adventitious buds are produced that, each spring, grow up as stems. Under permanent grassland, the roots may remain dormant for many years. Soil disturbance, such as ploughing, breaks up the roots and may result in a worse thistle problem.

Control. The seedling stage of this weed is not normally targeted by the gardener/grower. The main control strategy is primarily against the perennial root system. For both ***amateur*** and ***professional*** horticulturalist, cutting down plants at the flower bud stage when sugars are being transferred from the roots upwards is a physical control measure that partly achieves this objective.

The ***amateur*** gardener can use another physical control, removing roots by deep digging. The amateur gardener is also able to use herbicide products which contain a mixture of dicamba, MCPA and mecoprop-P (all of these are translocated down to the roots).

The ***professional*** grower can use the technique of deep ploughing to expose and dry off roots. Products containing the three active ingredients mentioned in the last paragraph are also available to the professional. Effectiveness of herbicide translocation to the roots is greatest when applied in autumn, at a time when plant sugars are similarly moving down the plant.

Couch grass (*Agropyron repens*). Plant family – Poaceae (Graminae)

Damage. This grass, sometimes called ‘twitch’, is a widely distributed and important weed found at altitudes up to 500 m. It is able to quite rapidly take over plots growing ornamentals, vegetables or fruit.

Life cycle. The dull-green plant is often confused, in the vegetative stage, with the creeping bent (*Agrostis stolonifera*). However, the small 'ears' (ligules) at the leaf base characterize couch. The plant may reach a metre in height and often grows in clumps. Flowering heads produced from May to October resemble perennial ryegrass, but, unlike ryegrass, the flat flower spikelets are positioned at right angles to the main stem in couch. Seeds (9 mm long) are produced only after cross-fertilization between different strains of the species, and the importance of the seed stage, therefore, varies from field to field. The seed may survive deep in the soil for up to 10 years.

Spread. Couch seeds may be carried in grass seed batches over long distances. From May to October, stimulated by high light intensity, overwintered plants produce horizontal rhizomes (see Figure 13.12) just under the soil; these white rhizomes may spread 15 cm per year in heavy soils, 30 cm in sandy soils. They bear scale leaves on nodes that, under apical dominance, remain suppressed during the growing period. In the autumn, rhizomes attached to the mother plant often grow above ground to produce new plants that survive the winter. If the rhizome is cut by cultivations such as digging or ploughing, fragments containing a node and several centimetres of rhizome are able to grow into new plants. The rapid growth and extension of couch plants provides severe competition for light, water and nutrients in any infested crop.

Figure 13.12 **Couch grass plant** showing rhizomes

Control is achieved by a combination of physical and chemical methods. In fallow soil, deep digging or ploughing (especially in heavy land) exposes the rhizomes to drying. Further control by rotavating the weed when it reaches the one or two leaf stage disturbs the plant at its weakest point, and repeated rotavating will eventually cut up couch rhizomes into such small fragments that nodes are unable to propagate.

The ***amateur*** gardener can use the herbicide, **glufosinate-ammonium plus fatty acids** for control in such situations as ornamental beds containing woody perennials and in cane fruit.

For the ***professional*** horticulturalist, a translocated herbicide such as **glyphosate**, sprayed onto couch in fallow soils during active weed vegetative growth, kill most of the underground rhizomes. In established fruit, **glufosinate-ammonium** is recommended.

Yarrow (*Achillea millifolium*). Plant family – Asteraceae (Compositae)

Damage. This strongly scented perennial, with its spreading flowering head (Figure 13.13), is a common hedgerow plant found on most soils at altitudes up to 1200 m. Its persistence, together with its resistance to herbicides and drought in grassland, makes it a serious turf weed.

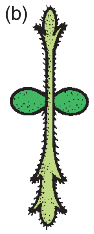


Figure 13.13 **Yarrow plant** showing (a) stolons, (b) seedling

Life cycle. The seedling leaves are hairy and elongated, with sharp teeth (Figure 13.3). The mature plant has dissected pinnate leaves produced throughout the year on wiry, woolly stems, which commonly reach 45 cm in height, and which from May to September produce flat-topped white-to-pink flower heads. Each plant may produce 3000 small, flat seeds annually. The seeds germinate on arrival at the soil surface.

Spread. Seeds are dispersed by birds. When not in flower, this species produces below-ground and above-ground stolons which can grow up to 20 cm long per year. In autumn, rooting from the nodes occurs.

Control. Control of this weed may prove difficult. Routine scarification of turf does not easily remove the roots. For the ***amateur*** and ***professional***, products containing **2,4-D** and **mecoprop** are used against yarrow.

Figure 13.14 **Dandelion plant** growing in turf

Dandelion (*Taraxacum officinale*). Plant family – Asteraceae (Compositae)

Damage. This species is a perennial with a stout taproot. It is a weed in lawns (see Figure 13.14), orchards and on paths. Several similar species such as mouse-ear hawkweed (*Hieracium pilosella*) and smooth hawk's beard (*Crepis capillaris*) present problems similar to dandelion in turf.

Life cycle. Seedlings emerge mainly in March and April. Flowers are produced from May to October. An average of 6000 seeds is produced by each plant. Most seeds survive only one year in the soil, but a few may survive for five years. Mature plants can survive for 10 years.

Spread. Seeds are wind dispersed by means of tiny 'parachutes' and may travel several hundred metres. They are also able to spread in the moving water found in ditches and by animals through their digestive systems. The plant may regenerate from roots, after being chopped up by spades or rotavators.

Control. Physical removal of the deep root by a sharp trowel is recommended, but this leaves bare gaps in turf for invasion by other weeds. For the ***amateur*** gardener and ***professional*** groundsman, products containing the two translocated ingredients, **2,4-D** and **dicamba**, are able to kill the stout penetrating root of the dandelion.

Broad-leaved dock (*Rumex obtusifolius*). Plant family – Polygonaceae

Damage. This is a common perennial weed of arable land, grassland and fallow soil.

Life cycle. The seedling cotyledons are narrow (see Figure 13.3). Seedling true leaves are often crimson coloured. The mature plant is readily identified by its long (up to 25 cm) shiny green leaves (see Figure 13.15), known to many as an antidote to 'nettle rash'. The plant may grow 1 m tall, producing a conspicuous branched inflorescence of small green flowers from June to October. The seed represents an important stage in this perennial weed's life cycle, surviving many years in the soil, and most commonly germinating in spring. Like most *Rumex* spp, the seedling develops a stout, branched taproot (see Figure 13.15), which may penetrate the soil down to 1 m in the mature plant, but most commonly reaches 25 cm. Segments of the taproot, chopped by cultivation implements are capable of producing new plants.

Spread. The numerous plate-like fruits (3 mm long) may fall to the ground or be dispersed by seed-eating birds such as finches. They are sometimes found in batches of seed stocks.

Control. High levels of seed production, a tough taproot and a resistance to most herbicides present a problem in the control of this weed. For the ***amateur*** gardener, in turf, physical removal of the deep root by a sharp trowel is recommended, but this leaves bare gaps in turf for invasion by other weeds. A product containing **dicamba, MCPA**, and **mecoprop-P** is effective against young plants.

Figure 13.15 **Broad-leaved dock** showing (a) swollen taproot, (b) seedling

For the ***professional*** horticulturalist, attempts in fallow soils to exhaust the root system by repeated ploughing and rotavating have proved useful. Young seedlings are easily controlled by translocated chemicals such as **2,4-D**, but the mature plant is resistant to all but a few translocated chemicals, e.g. **asulam**, which may be used on grassland (not fine turf), soft fruit, top fruit and amenity areas, during periods of active vegetative weed growth when the chemical is moved most rapidly towards the roots.

Mixed weed populations

In the field a wide variety of both annual and perennial weeds may occur together. The horticulturalist must recognize the most important weeds in their holding or garden, so that a decision on the precise use of chemical control with the correct herbicide is achieved. Particular care is required to match the concentration of the herbicide to the weed species present. Also, the grower must be aware that continued use of one chemical may induce a change in weed species, some of which may be tolerant to that chemical.

Mosses and liverworts

These simple plants may become weeds in wet growing conditions. The small cushion-forming moss (*Bryum* spp.) grows on sand capillary benches and thin, acid turf that has been closely mown. Feathery moss

(*Hypnum* spp.) is common on less closely mown, unscarified turf. A third type (*Polytrichum* spp.), erect and with a rosette of leaves, is found in dry acid conditions around golf greens. Liverworts (*Pellia* spp.) are recognized by their flat (thallus) leaves growing on the surface of pot plant compost (see Figure 13.16).

These organisms increase only when the soil and compost surface is excessively wet, or when nutrients are so low as to limit plant growth. Cultural methods such as improved drainage, aeration, liming, application of fertilizer and removal of shade usually achieve good results in turf. Control with contact scorching chemicals, e.g. alkaline ferrous sulphate, may give temporary results. Moss on sand benches becomes less of a problem if the sand is regularly washed.

Figure 13.16 **Pot plant compost** covered with moss and liverwort

Check your learning

1. Define the term ‘weed’.
2. Describe five ways in which weeds reduce plant productivity.
3. Describe how weeds may harbour pests and diseases.
4. Define the term ‘ephemeral weed’. Give an example.
5. Describe the characteristics of ephemeral weeds.
6. Describe a physical control appropriate to this type of weed.
7. Describe a named chemical used for control of the weed example given.
8. Describe the mode of action of this herbicide, stating in which horticultural situation(s) it is used.
9. Describe four methods by which weeds spread.
10. Describe three ways of reducing moss on lawns.

Further reading

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Chapter 14
Horticultural pests

Summary

This chapter includes the following topics:

- **Definition of the term 'pest'**
- **Life cycles of pests**
- **Damage caused by pests**
- **Relationship between life cycle and control**
- **Methods of limiting the effects of pests on plant growth**

Figure 14.1 **Red spider mite** symptoms on palm

Mammal pests

Pest. A mammal, bird, insect, mite or nematode that is damaging to plants.

A small selection of important mammal pests is included here.

The rabbit (*Oryctolagus cuniculus*)

The rabbit is common in most countries of central and southern Europe. It came to Britain around the eleventh century with the Normans, and became an established pest in the nineteenth century.

Damage. The rabbit may consume 0.5 kg of plant food per day. Young turf and cereal crops are the worst affected, particularly winter varieties that, in the seedling stage, may be almost completely destroyed. Rabbits may move from cereal crops to horticultural holdings. Stems of top fruit may be **ring barked** by rabbits, particularly in early spring when other food is scarce. Vegetables and recently planted garden-border plants are a common target for the pest, and fine turf on golf courses may be damaged, thus allowing lawn weeds, e.g. yarrow, to become established.

Life cycle. The rabbit's high reproductive ability enables it to maintain high populations even when continued control methods are in operation. The doe, weighing about 1 kg, can reproduce within a year of its birth, and may have three to five litters of three to six young ones in 1 year, commonly in the months of February to July. The young are blind and naked at birth, but emerge from the underground 'maternal' nest after only a few weeks to find their own food. Large burrow systems (**warrens**), penetrating as deep as 3 m in sandy soils, may contain as many as 100 rabbits. Escape or **bolt holes** running off from the main burrow system allow the rabbit to escape from predators.

Control. Rabbit control is, by law, the responsibility of the land owner. **Preventative** measures, available to both ***amateur*** and ***professional*** horticulturists are effective. **Wire fencing**, with the base 30 cm **underground** and facing outwards, represents an effective barrier to the pest, while thick plastic sheet **guards** are commonly coiled round the base of exposed young trees (see Figure 16.2). Repellant chemicals, e.g. **aluminium ammonium sulphate**, may be sprayed on bedding displays and young trees.

Small spring traps placed in the rabbit hole, winter **ferreting** or **long nets** placed at the corner of a field to catch herded rabbits are methods used as **curative** control. **Shotguns** are used on large horticultural holdings by holders of gun licences.

Gassing is an effective method, but must be applied only by trained operators. Crystals of powdered **sodium cyanide** are introduced into the holes of warrens by means of long-handled spoons or by power operated machines. On contact with moisture hydrocyanic acid is released as a gas and, in well-blocked warrens, the rabbits are quickly killed. Care is required in the storage and use of powdered cyanide, where an **antidote**, amyl nitrite, should be readily available.

Myxamatosis, a flea-borne virus disease of the rabbit, causing a swollen head and eyes, was introduced into Britain in 1953, and within a few years greatly reduced the rabbit population. The development of weaker virus strains, and the increase in rabbit resistance, has combined to reduce this disease's effectiveness in control, although its importance in any one area is constantly fluctuating.

The brown rat (*Rattus norvegicus*)

The brown rat, also called the common rat, is well known by its dark-brown colour, blunt nose, short ears and long, scaly tail.

Damage. Its diet is varied; it will eat **seeds**, **succulent stems**, **bulbs and tubers**, and may grind its teeth down to size by the unlikely act of gnawing at plastic **piping** and electric cables. A rat's average annual food intake may reach 50 kg, a large amount for an animal weighing only about 300 g.

Life cycle. This species has considerable reproductive powers. The female may begin to breed at 8 weeks of age, producing an average of six litters of six young ones per year. Its unpopular image is further increased by its habit of fouling the food it eats, and by the potentially lethal human bacterium causing **Weil's disease**, which it transmits through its urine.

Control. ***Amateur*** gardeners are able to use products containing **aluminium ammonium sulphate** to deter rats. **Sonic** devices are sometimes used to disturb the animal and provide a round-the-clock deterrent.

Baiting with rat poison should be performed by trained operatives. This method is best achieved by a preliminary survey of rat numbers in buildings and fields of the horticultural holding, and by the identification of the 'rat-runs' along which the animals travel. Baits containing a mixture of **anticoagulant** poison and food material such as oatmeal are placed near the runs, inside a container that, while attracting the rat, prevents access by children and pets. Drainage tiles or oil drums drilled with a small rat-sized hole often serve this purpose. The poison, e.g. **difenacoum**, takes about three days to kill the rat and, since the other rats do not associate the rat's death with the chemical, the whole family may be controlled. The bait should be placed wherever there are signs of rat activity, and repeated applications every three days for a period of three weeks should be effective.

Strains of rat resistant to some anticoagulants are found in some areas, and a range of chemicals may need to be tried before successful control is achieved. The poison, when not in use, should be safely stored away from children and pets. Dead rats should be burnt to avoid poisoning of other animals.

The grey squirrel (*Sciurus carolinensis*)

This attractive-looking 45 cm long creature was introduced into Britain in the late nineteenth century, at a time when the red squirrel population was suffering from disease. The grey squirrel became dominant in most areas, with the red squirrel surviving in isolated areas such as the Isle of Wight.

Damage. The horticultural damage caused by grey squirrels varies with each season. In spring, germinating **bulbs** may be eaten, and the **bark** of many tree species stripped off (see **ring barking**, p95). In summer, **pears**, **plums** and **peas** may suffer. Autumn provides a large wild food source, although **apples** and **potatoes** may be damaged. In winter, little damage is done. Fields next to wooded areas are clearly prone to squirrel damage.

Life cycle. Squirrels most commonly produce two litters of three young ones from March to June, in twig platforms (**dreys)** high in the trees. The female may become pregnant at an early age (6 months). As the squirrels have few natural enemies, and this species lives high above ground, control is difficult.

Control. ***Amateur*** and ***professional*** horticulturists may need to reduce grey squirrel numbers. During the months of April–July, when most damage is seen, **cage traps** containing desirable food, e.g. maize seed, reduce the squirrel population to less damaging levels. **Spring traps** placed in natural or artificial tunnels achieve rapid results at this time of year if placed where the squirrel moves. ***Professional*** horticulturists are able to use **poisoned bait** containing a formulation of anticoagulant chemical, e.g. **warfarin**, when placed in a well-designed ground-level **hopper** (one hopper per 3 ha). This can achieve successful squirrel control without affecting other small wild mammal numbers. In winter and early spring, the destruction of squirrel nests by means of long poles may achieve some success.

The mole (*Talpa europea*)

The mole is found in all parts of the British Isles except Ireland.

Damage. This dark-grey, 15 cm long mammal, weighing about 90 g, uses its shovel-shaped feet to create an underground system 5–20 cm deep and up to 0.25 ha in extent. The tunnel contents are excavated into mole hills (see Figure 14.2). The resulting **root disturbance** to grassland and other crops causes wilting, and may result in serious losses.

Figure 14.2 **Mole hill** in grass

Life cycle. In its dark environment, the solitary mole moves, actively searching for earthworms, slugs, millipedes and insects. About 5 hours of activity is followed by about 3 hours of rest. Only in spring do males and females meet. In June, one litter of two to seven young ones are born in a grass-lined underground nest, often located underneath a dense thicket. Young moles often move above ground, reach maturity at about 4 months, and live for about 4 years.

Control. Natural predators of the mole include tawny owls, weasels and foxes. The main control methods are **trapping** and **poison baiting**, usually carried out between October and April, when tunnelling is closer to the surface. ***Amateur*** or ***professional*** horticulturalists can use pincer or half barrel **traps** placed in fresh tunnels and inserted carefully so as not to greatly change the tunnel diameter. The soil must be replaced so that the mole sees no light from its position in the tunnel. The mole enters the trap, is caught and starves to death. In serious mole infestations, trained operators use **strychnine** salts mixed with earthworms at the rate of 2 g ingredient per 100 worms. Single worms are carefully inserted into inhabited tunnels at the rate of 25 worms per hectare. DEFRA authority is required before purchasing strychnine, a highly dangerous chemical, which must be stored with care.

Deer

Deer may become pests in land adjoining woodland where they hide. Muntjac and roe deer **ring-bark** (see p95) trees and eat succulent crops. High fences and regular shooting may be used in their control.

Bird pests

A couple of important bird pests are included here.

The wood-pigeon (*Columba palumbus*)

Damage. This attractive-looking, 40 cm long, blue-grey pigeon with white underwing bars is known to horticulturists as a serious pest on most outdoor edible crops. In **spring**, seeds and seedlings of crops such as brassicas, beans and germinating turf may be systematically eaten. In **summer**, cereals and clover receive its attention; in **autumn**, tree fruits may be taken in large quantities, while in **winter**, cereals and brassicas are often seriously attacked, the latter when snowfall prevents the consumption of other food. The wood-pigeon is invariably attracted to **high protein** foods such as seeds when they are available.

Life cycle. Wood-pigeons lay several clutches of two eggs per year from March to September. The August/September clutches show highest survival. The eggs, laid on a nest of twigs situated deep inside the tree, hatch after about 18 days, and the young ones remain in the nest for 20–30 days. Predators such as jays and magpies eat many eggs, but the main population-control factor is the availability of food in winter. Numbers in the British Isles are boosted a little by migrating Scandinavian pigeons in April, but the large majority of this species is resident and non-migratory.

Control. The wood-pigeon spends much of its time feeding on wild plants, and only a small proportion of its time on crops. Control of the whole population, therefore, seems ethically unsound and is both costly and impracticable. Physical control involves the protection of particular fields by means of **scaring devices** which include scarecrows, bangers (firecrackers or gas guns), artificial hawks on wires, or rotating orange and black vanes, all which disturb the pigeons. Changing the **type** and **location** of the device every few days helps prevent the pigeons from becoming indifferent. The use of the **shotgun** by licenced operators from hidden positions such as hides and ditches (particularly when plastic decoy pigeons are placed in the field) is an important additional method of scaring birds and thus protecting crops.

The bullfinch (*Pyrrhula pyrrhula*)

This is a strikingly-coloured, 14 cm long bird, characterized by its sturdy appearance and broad bill. The male has a rose-red breast, blue-grey back and black headcap. The female has a less striking pink breast and yellowish-brown back.

Damage. From April to September the bird progressively feeds on seeds of wild plants, e.g. chickweed, buttercup, dock, fat hen and blackberry. From September to April, the species forms small flocks that, in addition to feeding on buds and seeds of wild species, e.g. docks, willow, oak and hawthorn, turn their attention to **buds of soft and top fruit**. Gooseberries are attacked from November to January, apples from February to April and blackcurrants from March to April. The birds are shy, preferring to forage on the edges of orchards, but as winter advances they become bolder, moving towards the more central trees and bushes. The birds nip buds out at the rate of about 30 per minute, eating the central meristem tissues. Leaf, flower and fruit development may thus be seriously reduced, and since in some plums and gooseberries there is no regeneration of fruiting points, damage may be seen several years after attack.

Life cycle. The bullfinch produces a platform nest of twigs in birch or hazel trees, and between May and September lays two to three clutches of four to five pale blue eggs, with purple-brown streaks. It can thus quickly re-establish numbers reduced by lack of food or human attempts at control. They are mainly resident, only rarely migrating.

Control. ***Amateur*** and ***professional*** horticulturists can use fine mesh **netting** or **cotton** or synthetic **thread** draped over trees. ***Professional*** horticulturists spray bitter chemicals such as **ziram** on to shrubs and trees at the time of expected attack to limit bird numbers. Some additional control is achieved by catching birds (usually immature individuals) in specially designed **traps**, which close when the bird lands on a perch to eat seeds. Trapped birds are then taken to a non-horticultural location. Trapping may be started as early as September. Large-scale reinvasion by the same birds in the same season is unlikely as they are territorial, rarely moving more than two miles throughout their lives. Bullfinch trapping is permitted only in scheduled areas of wide-scale fruit production, e.g. Kent.

Mollusc pests

Slugs

This group of serious pests belongs to the phylum Mollusca, a group including the octopus and whelk and the slug's close relatives, the snails, which cause some damage to plants in greenhouses and private gardens.

Damage. The slug lacks a shell and this permits movement into the soil in search of its food source: seedlings, roots, tubers and bulbs. It feeds by means of a file-like tongue (**radula)**, which cuts through plant tissue held by the soft mouth, and scoops out cavities in affected plants (see Figure 14.3). In moist, warm weather it may cause above-ground damage to leaves of plants such as border plants, establishing turf, lettuce and Brussels sprouts. Slugs move slowly by means of an undulating foot, the slime trails from which may indicate the slug's presence. Horticultural areas commonly support populations of 50 000 slugs per hectare.

Figure 14.3 Slug damage on carrot

Life cycle. Slugs are **hermaphrodite** (bearing in their bodies both male and female organs), mate in spring and summer, and lay clusters of up to 50 round, white eggs in rotting vegetation, the warmth from which protects this sensitive stage during cold periods. Slugs range in size from the black keeled slug (*Milax*) 3 cm long, to the garden slug (*Arion)* which reaches 10 cm in length. The mottled carnivorous slug (*Testacella)* is occasionally found feeding on earthworms.

Control. ***Private*** gardeners use many non-chemical forms of control, ranging from baits of grapefruit skins and stale beer to soot sprinkled around larger plants. A nematode (*Phasmarhabditis hermaphrodita*) is increasingly being used to limit slug numbers. The most effective methods available to both amateur and professional horticulturists at the moment are three chemicals, **aluminium sulphate** (an irritant), **metaldehyde** (which dehydrates the slug) and **methiocarb** (which acts as a stomach poison). The chemicals are most commonly used as small-coloured **pellets** (which include food attractants such as bran and sugar), but metaldehyde may also be applied as a drench. Some growers estimate the slug population using small heaps of pellets covered with a tile or flat stone (to prevent bird poisoning) before deciding on general control. Use of **metaldehyde** and **methiocarb** in gardens has recently been claimed as a major contribution to the decline of the thrush numbers. A simple device such as that seen in Figure 16.2, using a modified plastic milk carton (containing slug pellets) prevents the entry of mammals and birds.

Insect pests

Belonging to the large group of **Arthropods**, which include also the **woodlice**, **mites**, **millipedes** and **symphilids** (see Table 14.1), insects are horticulturally the most important arthropod group, both as pests, and also as beneficial soil animals.

Structure and biology

The body of the adult insect is made up of segments, and is divided into three main parts: the head, thorax and abdomen (see Figure 14.4). The **head** bears three pairs of moving **mouthparts**. The first, the mandibles in insects (such as in caterpillars and beetles) have a **biting** action (see Figure 14.5). The second and third pairs, the maxillae and labia in these insects help in pushing food into the mouth. In the aphids, the mandibles and maxillae are fused to form a delicate tubular stylet, which **sucks** up liquids from the plant phloem tissues. Insects remain aware of their environment by means of compound eyes which are sensitive to movement (of predators) and to colour (of flowers). Their antennae may have a touching and smelling function.

The **thorax** bears three pairs of legs and, in most insects, two pairs of wings. The **abdomen** bears breathing holes (spiracles) along its length, which lead to a respiratory system of tracheae. The blood is colourless, circulates digested food and has no breathing function. The digestive system, in addition to its food absorbing role, removes waste cell products from the body by means of fine, hair-like growths (malpighian tubules) located near the end of the gut.

Since the animal has an **external skeleton** made of tough chitin, it must shed and replace its ‘skin’ (**cuticle**, see Figure 14.4) periodically by a process called **ecdysis**, in order to increase in size.

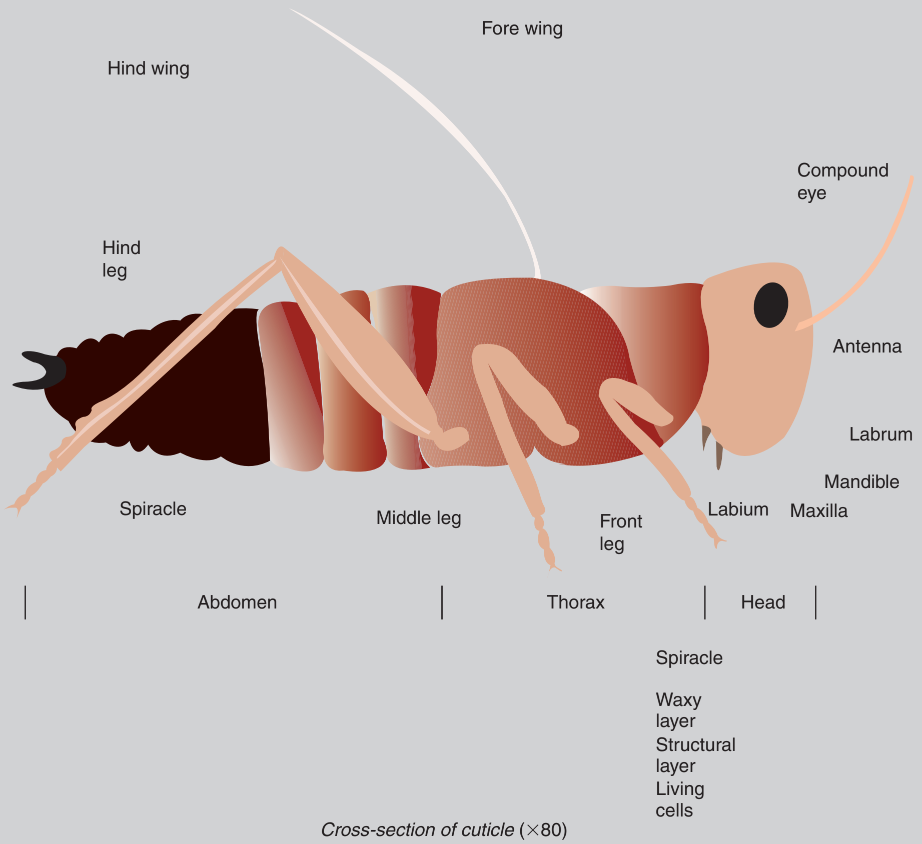


Figure 14.4 **External appearance of an insect**. Note the mouthparts, spiracles and cuticle, the three main entry points for insecticides

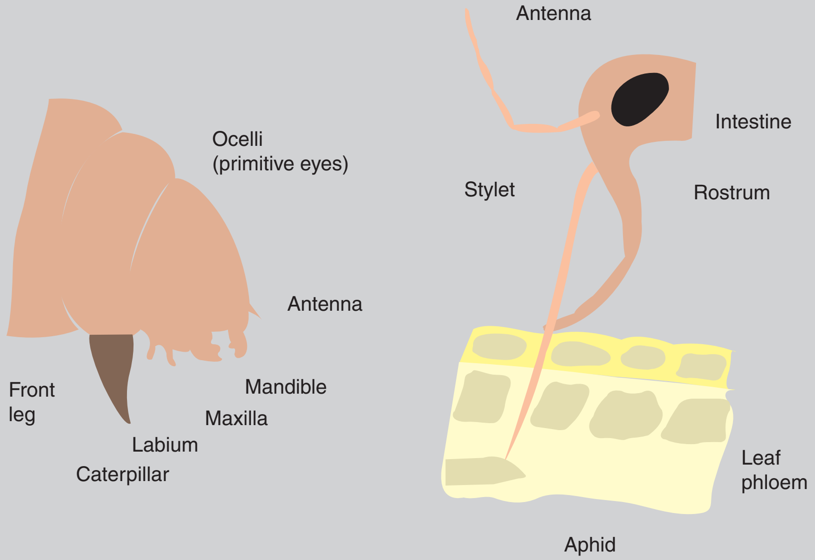


Figure 14.5 **Mouthparts of the caterpillar and aphid**. Note the different methods of obtaining nutrients. The aphid selectively sucks up dilute sugar solution from the phloem tissue

The two main groups of insect develop from egg to adult in different ways. In the first group (Endopterygeta), typified by the aphids, thrips and earwigs, the egg hatches to form a first stage, or instar, called a **nymph**, which resembles the adult in all but size, wing development and possession of sexual organs. Successive nymph instars more closely resemble the adult. Two to seven instars (growth stages) occur before the adult emerges (see Figure 14.6). This development method is called **incomplete metamorphosis**.

In contrast, the second group of insects ‘Endopterygota’ including the moths, butterflies, flies, beetles and sawflies undergo a **complete metamorphosis**. The egg hatches to form a first **instar**, called a **larva** which usually differs greatly in shape from the adult. For example the larva (caterpillar) of the cabbage white bears little resemblance to the adult butterfly. Some other dam aging larval stages are shown in Figure 14.7 and these can be compared with the often more familiar adult stage. The great change (**metamorphosis**) necessary to achieve this transformation occurs inside the pupa stage (see Figure 14.6).

The method of **overwintering** differs between insect groups. The aphids survive mainly as the eggs, while most moths, butterflies and flies survive as the pupa. The **speed** of increase of insects varies greatly between groups. Aphids may take as little as 20 days to complete a life cycle in summer, often resulting in vast numbers in the period June–September. On the other hand, the wireworm, the larva of the click beetle, usually takes four years to complete its life cycle.

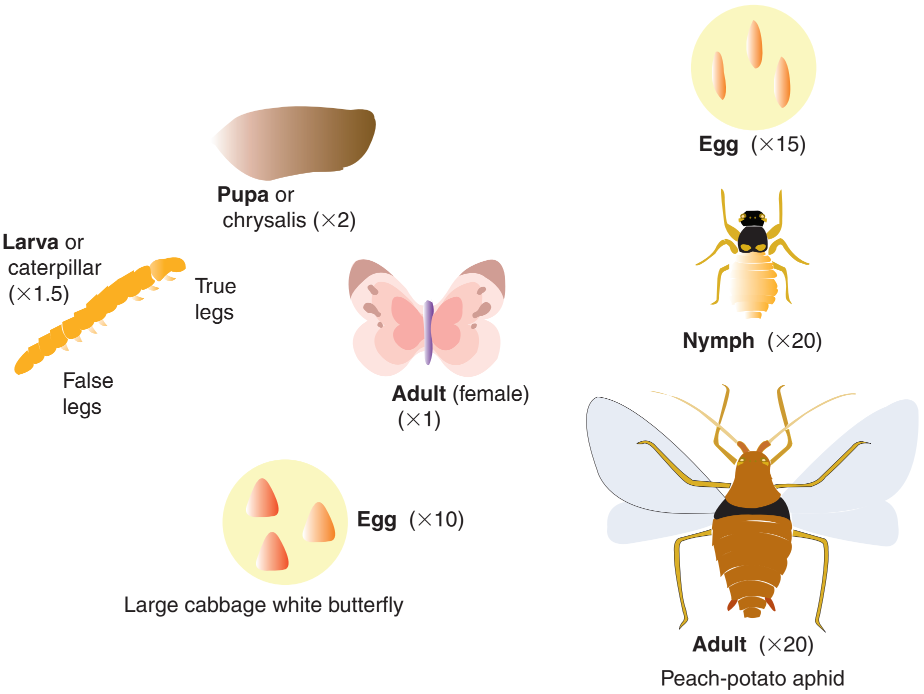


Figure 14.6 **Life cycle stages of a butterfly and an aphid pest**. Note that all four stages of the butterfly's life cycle are very different in appearance. The nymph and adult of the aphid are similar

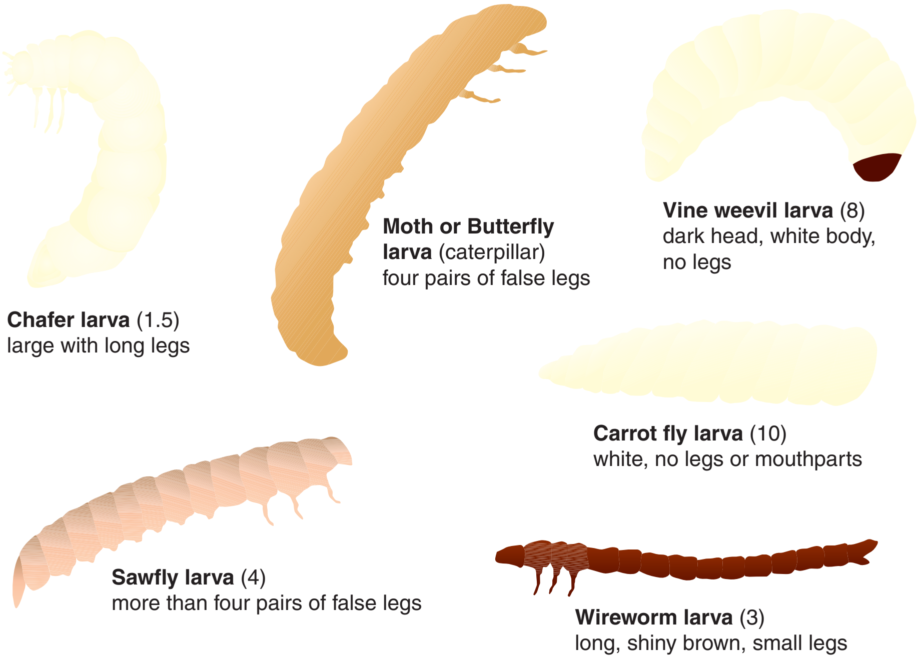


Figure 14.7 **Insect larvae** that damage crops. Identification into the groups above can be achieved by observing the features of colour, shape, legs and mouthparts

Insect groups are classified into their appropriate order (Table 14.1) according to their general appearance and life cycle stages. There follows now a selection of insect pests in which each species' particular features of life cycle are given. Whilst comments on control are mentioned here, the reader should also refer to Chapter 16 for details

Table 14.1 Arthropod groups found in horticulture

Group	Key features of group	Habitat	Damage
Woodlice (*Crustacea*)	Grey, seven pairs of legs, up to 12 mm in length	Damp organic soils	Eat roots and lower leaves
Millipedes (*Diplopoda*)	Brown, many pairs of legs, slow moving	Most soils	Occasionally eat underground tubers and seed
Centipedes (*Chilopoda*)	Brown, many pairs of legs, very active with strong jaws	Most soils	Beneficial
Symphilids (*Symphyla*)	White, 12 pairs of legs, up to 8 mm in length	Glasshouse soils	Eat fine roots
Mites (*Acarina*)	Variable colour, usually four pairs of legs (e.g. red spider mites)	Soils and plant tissues	Mottle or distort leaves, buds, flowers and bulbs; soil species are beneficial
Insects (*Insecta*)	Usually six pairs of legs, two pairs of wings		
Springtails (*Collembola*)	White to brown, 3–10 mm in length	Soils and decaying humus	Eat fine roots; some beneficial
Aphid group (*Hemiptera*)	Variable colour, sucking mouthparts, produce honeydew (e.g. greenfly)	All habitats	Discolour leaves and stems; prevent flower pollination; transmit viruses
Moths and butterflies (*Lepidoptera*)	Large wings; larva with three pairs of legs, four pairs of false legs and biting mouthparts (e.g. cabbage-white butterfly)	Mainly leaves and flowers	Defoliate leaves (stems and roots)
Flies (*Diptera*)	One pair of wings, larvae legless (e.g. leatherjacket)	All habitats	Leaf mining, eat roots
Beetles (*Coleoptera*)	Horny front pair of wings which meet down centre; well-developed mouthparts in adult and larva (e.g. wireworm)	Mainly in the soil	Eat roots and tubers (and fruit)
Sawflies (*Hymenoptera*)	Adult like a queen ant; larvae have three pairs of legs, and more than four pairs of false legs (e.g. rose-leaf curling sawfly)	Mainly leaves and flowers	Defoliation
Thrips (*Thysanoptera*)	Yellow and brown, very small, wriggle their bodies (e.g. onion thrips)	Leaves and flowers	Cause spotting of leaves and petals
Earwigs (*Dermaptera*)	Brown, with pincers at rear of body	Flowers and soil	Eat flowers

of specific types of control (cultivations, chemicals, etc.) and for explanations of terms used.

Aphids and their relatives (*Order Hemiptera*)

This important group of insects has the egg–nymph–adult life cycle and sucking mouthparts.

Peach-potato aphid (Myzus persicae)

This and similar species are often referred to by the name 'greenfly' (Figure 14.8).

Damage. It is common in market gardens and greenhouses. The nymph and adult of this aphid may cause three types of damage. Using its sucking stylet, it may inject a digestive juice into the plant phloem, which in young organs may cause severe **distortion**. Having sucked up sugary phloem contents, the aphid excretes a sticky substance called **honey-dew**, which may block up leaf stomata and reduce photosynthesis, particularly when dark-coloured fungi (sooty moulds) grow over the honeydew. Thirdly, the aphid stylets may **transmit viruses** such as virus Y on potatoes and tomato aspermy virus on chrysanthemums.

Life cycle. The aphid varies in colour from light green to orange, measures 3 mm in length (see Figure 14.9) and has a complex life cycle, shown in Figure 14.8, alternating between the winter host (peach) and the many summer hosts such as potato and bedding plants. In spring and summer, the females give birth to nymphs directly without any egg stage (a process called vivipary), and without fertilization by a male (a process called parthenogenesis). Spread is by the summer flighted females. Only in autumn, in response to decreasing daylight length and outdoor temperatures, are both sexes produced, which having wings, fly to the winter host, the peach. Here, the female is fertilized and lays

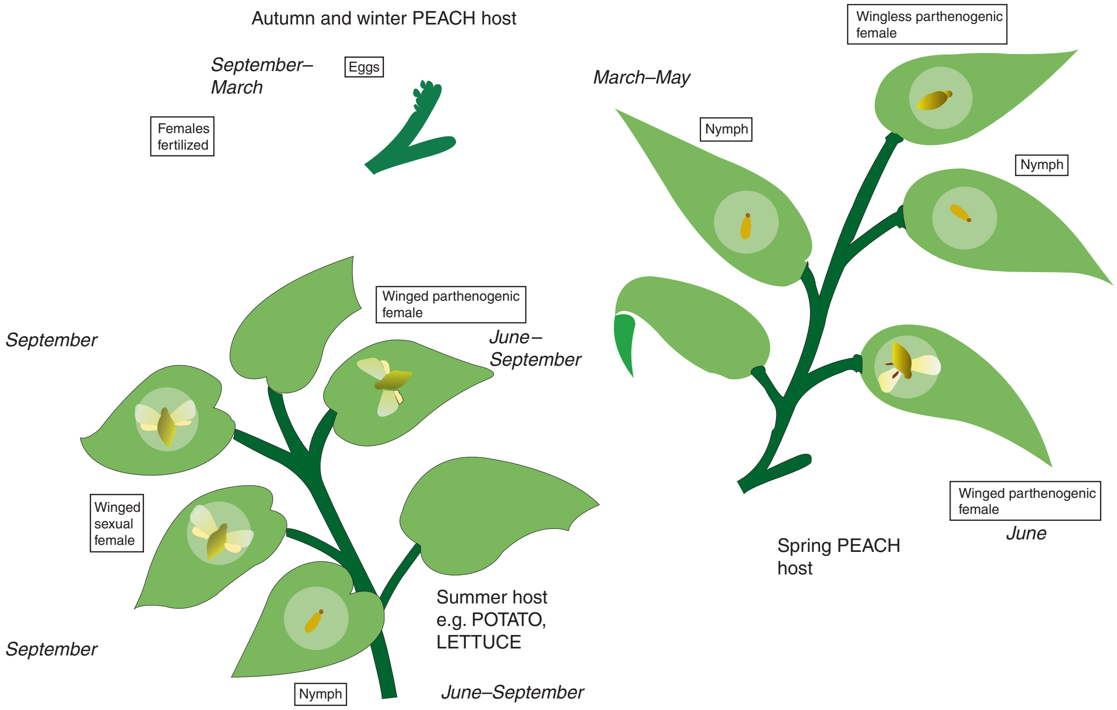


Figure 14.8 **Peach-potato aphid life cycle** throughout the year. Female aphids produce nymphs on both the peach and summer host. Winged females develop from June to September. Males are produced only in autumn. Eggs survive the winter. In greenhouses the life cycle may continue throughout the year

thick-walled black eggs. In glasshouses, the aphid may survive the winter as the nymph and adult female on plants such as begonias and chrysanthemums, or on weeds such as fat hen.

Spread occurs in early summer and autumn by winged females.

Control. The peach-potato aphid can be controlled in several ways. In outdoor crops, several organisms, e.g. ladybirds, lacewings, hoverflies and parasitic fungi (see **biological control**, Chapter 16), naturally found in the environment, may reduce the pest's importance in favourable seasons. In the greenhouse, an introduced parasitic wasp (*Aphidius matricariae*) is available to amateurs and professionals.

Figure 14.9 Rose aphid

The ***amateur*** gardener uses an aphicide containing **pyrethrins.** Two other chemicals are used by both amateur and professional horticulturists: a contact chemical **bifenthrin** and a soap concentrate containing **fatty acids**.

For the ***professional***, there is a biological control using the fungus *Verticillium lecanii*, and many chemical controls, including **pirimicarb** used outdoors and in glasshouses as a spray, and **nicotine** used as a smoke in glasshouses.

There are many other horticulturally important aphid species. The black bean aphid (*Aphis fabae*), which overwinters on *Euonymus* bushes, may seriously damage broad beans, runner beans and red beet. The rose aphid (*Macrosiphum rosae*) attacks young shoots of rose.

Spruce-larch adelgid (Adelges viridis)

This relative of the aphid may cause serious damage on spruce grown for Christmas trees.

Damage. Although nursery trees less than four years of age are rarely badly damaged, early infestation in the young plant may result in serious damage as it gets older. In June–September the adults move to **larch**, acquire woolly white hairs and may cause defoliation of the leaves.

Life cycle. The green female adult develops from overwintering nymphs on spruce, and in May (year 1) lays about 50 eggs on the dwarf shoots. The emerging nymphs, injecting poisons into the shoots, cause abnormal growth into pineapple galls, which spoil the tree's appearance. After a further year (year 2) on this host, the female adelges returns to the spruce, where it lives for another year (year 3) before the gall-inducing stages are produced.

Spread is by flighted females.

Control. In Christmas tree production, the adelges may be controlled by sprays of **deltamethrin** in May, when the gall-inducing nymphs are developing.

Glasshouse whitefly (Trialeurodes vaporariorum)

This small insect, looking like a tiny moth, was originally introduced from the tropics, but now causes serious problems on a range of glasshouse food and flower crops. It should not be confused with the very similar, but slightly larger cabbage whitefly on brassicas.

Damage. All stages after the egg have sucking stylets, which extract a sugary liquid from the phloem, often causing large amounts of honeydew and sooty moulds on the leaf surface. Plants that are seriously attacked include fuchsias, cucumbers, chrysanthemums and pelargoniums. Chickweed, a common greenhouse weed, may harbour the pest over winter in all stages of the pest's life cycle.

Life cycle. The adult glasshouse whitefly (Figure 14.10) is about 1 mm long and is able to fly from plant to plant. The fertilized female lays about 200 minute, white, elongated oval eggs in a circular pattern on the **lower leaf surface** over a period of several weeks. After turning black, the eggs hatch to produce nymphs (crawlers), which soon become flat immobile scales. The last scale instar is thick-walled and called a ' pupa' from which the male or female adult emerges. Three days later, the female starts to lay eggs again. The whole life cycle takes about 32 days in spring, and about 23 days in the summer.

Spread is mainly by introduced plants, or more rarely by chance arrivals of adult through doors or vents.

Figure 14.10 **Adult glasshouse whitefly**, actual size is about 1 mm long

Control of glasshouse whitefly is achieved in several ways.

Amateur and ***professional*** horticulturalists should remove weeds (such as chickweed or sowthistle) harbouring the pest from crop to crop. Careful inspection of the lower leaves of introduced plants achieves a similar aim.

There is a reliable form of biological control. This involves a minute wasp (*Encarsia formosa)* which lays an egg inside the last scale stage of the white-fly. The developing whitefly is eaten away by the wasp grub and the scale turns black and soon releases the next generation of wasps (see Chapter 16 for more details). Control is usually most effective when whitefly numbers are low.

Amateur gardeners can use spray products containing specially formulated **fatty acids** to control young and adult pest stages. ***Professional horticulturists*** can choose between an insecticide that physically blocks the insect's breathing holes (see p204) such as **alginate/polysaccharide**, or a contact insecticide such as deltamethrin, or the above-mentioned **fatty acids**.

It is suggested that serious infestations of this pest receive a regular weekly chemical spray to catch the more sensitive scale and adult stages.

Greenhouse mealy bug (Planococcus citri)

Damage. This pest, a distant relative of the aphid, spoils the appearance of glasshouse crops, particularly orchids, *Coleus* species, cacti and *Solanum* species. All of the stages except the egg suck phloem juices by means of a tubular mouthpart (**stylet)**, and when this pest is present in dense masses it produces **honey dew** and may cause leaf drop (see Figure 14.11).

(a) (b)

Figure 14.11 (a) Mealy bug (b) Brown scale

Life cycle. Being a tropical species, it develops most quickly in high temperatures and humidities, and at 30°C completes a life cycle within about 22 days. The adult measures about 3 mm in length and produces fine waxy threads.

Spread. Adults have wings, but the most important spread is by introduction of plant material newly infested with small nymphs, or from plant to plant when leaves are touching.

Control. Mealy bugs are difficult pests to control, as the thick cuticle resists chemical sprays, and the droplets fall off the waxy threads. An introduced tropical ladybird, *Cryptolaemus montrouzieri*, is commercially available for controlling the pest and is most effective at temperatures above 20°C. Spray products containing pure **fatty acids** are effective against this pest and are available to both ***amateur*** and ***professional*** horticulturists.

A recently reported related problem on beech has been the woolly beech aphid (*Phyllapis fagi*).

Brown scale (Parthenolecanium corni)

The female scale, measuring up to 6 mm, is tortoise shaped (see Figure 14.11) and has a very **thick cuticle**. It may be a serious pest outdoors on vines, currants, top fruit and cotoneasters, sucking phloem sugars out of the plants. It is also found in greenhouses on vines, peaches and Amaryllis, causing stunted growth and leaf defoliation. The nymphs are mobile, but do not spread far. Transport of infested plant material is the main cause of outbreaks in greenhouses. As with mealy-bug, control is made more difficult because of the thick cuticle, but products containing **fatty acids** give good control. A recently reported scale problem is soft brown scale (*Coccus hesperidum*) in greenhouses.

Leaf hoppers (Graphocephala fennahi)

These slender, light green insects, about 3 mm long, well known in their nymph stage as ‘cuckoo spit’, are found on a wide variety of crops, e.g. potato, rose, *Primula* and Calceolaria. The adults can fly from plant to plant. They live on the **undersurface** of leaves, causing a mottling of the upper surface. In strawberries, they are vectors of the **green-petal** disease, while in rhododendron they carry the serious **bud blast** disease that kills off the flower buds (see Figure 14.12). August and September sprays of products containing **fatty acids** prevent egg laying inside buds of rhododendron, and thus reduce the entry points for the fungus disease.

Common green capsid (Lygocoris pabulinus)

This very active, light green pest measuring 5 mm in length and resembling a large aphid, occurs on fruit trees and shrubs and flower crops, most commonly outdoors. Owing to the poisonous nature of its salivary juices, young foliage shows distorted growth with small holes, even when relatively low insect numbers are present and fruit is scarred (see Figure 14.12). The adult flies from plant to plant. The chemicals used against aphids control this pest.

Thrips (*Order Thysanoptera*)

Whilst classified under the broad grouping of the Exopterygota (like the aphids), thrips also produce a survival stage which is often soil borne, and is loosely called a pupa (a life cycle stage normally reserved for members of the other main insect group, the Endopterygota). Due to their increased activity during warm humid weather, thrips are sometimes called ‘ thunder flies’ (and are known for their ability to get into human’s hair in sultry summer weather and cause itching).

(a)

(b)

(c)

Figure 14.12 (a) **Bud blast on rhododendron** transmitted by a leafhopper (b) **Capsid damage on apple**.(c) **Capsid damage on potato leaf**

Onion thrips (Thrips tabaci)

Damage. Thrips’ mouthparts are modified for piercing and sucking, and the toxic salivary juices cause silvering in onion leaves, straw-brown spots several mm in diameter on cucumber leaves, and white streaks on carnation petals.

Life cycle. The 1 mm long, narrow-bodied insect has feather-like wings. The last instar of the life cycle, called the **pupa**, descends to the soil, and it is this stage which overwinters. In greenhouses there may be seven generations per year, while outdoors one life cycle is common.

Spread. Adults may be blown considerable distances from nursery to nursery in the wind. (The occurrence in Britain of Western flower thrip (*Frankliniella occidentalis*) on both greenhouse and outdoor flower and vegetable crops has created serious problems for the industry, particularly because it transmits the serious tomato spotted wilt virus, and is able to pupate on the plant, deep within dense flowers such as carnation.)

Control. Thrips infestations may be reduced in greenhouses by the use of fine screens over vents, and by a double door system.

Amateur gardeners are able to use a recently introduced product for thrip control containing **natural plant extracts** which block the insect's breathing holes.

Professional growers use the predatory mite *Neoseiulus cucumeris*, and the predatory bug *Orius laevigatus.* Chemicals used include the ingredient **abamectin** and the above named **natural plant extract**. Western flower thrip has shown greater resistance to chemical control than the other thrips and a careful rotation of chemical groups has proved necessary.

Earwigs (Forficula auricularia)

These pests belong to the order Dermaptera, and bear characteristic 'pincers' (cerci) at the rear of the 15 mm long body. They gnaw away at leaves and petals of crops such as beans, beet, chrysanthemums and dahlias, usually from July to September, when the nymphs emerge from the parental underground nest. They usually **spread** by crawling on the surface of the soil, but they can also fly. Upturned flower pots containing straw are sometimes used in greenhouses for trapping these shy nocturnal insects. The professional grower may use **pirimiphos-methyl** as a spray or smoke.

Moths and butterflies

This group of insects belongs to the large grouping, the Endopterygota (see p205) which has different life cycle details from the aphid group. The order (Lepidoptera) characteristically contains adults with four large wings and curled feeding tubes. The larva (**caterpillar**), with six small legs and eight false legs, is modified for a leaf-eating habit (see Figures 14.6 and 14.7). Some species are specialized for feeding inside fruit (codling moth on apple, see Figure 14.15), underground (cutworms), inside leaves (oak leaf miner), or inside stems (leopard moth). The gardener may find large webbed caterpillar colonies of the lackey moth (*Malacosoma neustria*) on fruit trees and hawthorns, or the juniper webber (*Dichomeris marginella*) causing webs and defoliating junipers.

Large cabbage-white butterfly (Pieris brassicae)

Damage. Leaves of cabbage, cauliflower, Brussels sprouts and other hosts such as wallflowers and the shepherd's-purse weed are progressively eaten away. The defoliating damage of the larva may result in skeletonized leaves.

Life cycle. This well-known pest on cruciferous plants emerges from the overwintering pupa (chrysalis) in April and May and, after mating, the females (see Figure 14.13) lay batches of 20 to a 100 yellow eggs on the underside of leaves. Within a fortnight, groups of first instar larvae emerge and soon moult to produce the later instars, which reach 25 mm in length and are yellow or green in colour, with clear black markings. They have well-developed mandibles. Pupation occurs usually in June, in a crevice or woody stem, the pupa (chrysalis) being held to its host by silk threads. A second generation of the adult emerges in July, giving rise to more damaging larval infestation than the first. The second pupa stage overwinters.

Spread. The species is spread by the adults. (Care should be taken not to confuse the cabbage-white larva with the large smooth green or brown larva of the cabbage moth, or the smaller light green larva of the diamond-backed moth, both of which may enter the hearts of cabbages and cauliflowers, presenting greater problems for control.)

Control. There are several forms of control against the cabbage-white butterfly. A naturally occurring small wasp (*Apantales glomeratus)* lays its eggs inside the pest larva (see p273). A virus disease may infect the pest, causing the larva to go grey and die. Birds such as starlings eat the plump larvae. When damage becomes severe, amateur gardeners and professional growers can use spray products containing **bifenthrin**.

(a)

(b)

Figure 14.13 (a) **Cabbage-white adult**. (b) **Yellow underwing moth** with cutworm larva and brown

Winter moths (Operophthera brumata)

Damage. These are pests which may be serious on top fruit and ornamentals, especially woody members of the Rosaceae family. The caterpillars eat away leaves in spring and early summer and often form other leaves into loose webs, reducing the plant's photosynthesis. They occasionally scar young apple fruit.

Life cycle. This pest's timing of life cycle stages is unusual. The pest emerges as the adult form from a soil-borne pupa in November and December. The male is a greyish-brown moth, 2.5 cm across its wings, while the female is wingless. The female crawls up the tree to lay 100–200 light-green eggs around the buds. The eggs hatch in spring at bud burst to produce green larvae with faint white stripes. These larvae move in a characteristic looping fashion and when fully grown, descend on silk threads at the end of May before pupating in the soil until winter.

Spread is slow because the females do not have wings.

Control. A common control is a **grease band** wound around the main trunk of the tree in October which is effective in preventing the flightless female moth's progress up the tree. In large orchards, professional growers use springtime sprays of an insecticide such as **deltamethrin** to kill the young caterpillars.

Cutworm (e.g. Noctua pronuba)

Damage. The larvae of the **yellow underwing moth**, unlike most other moth larvae, live in the soil, nipping off the stems of young plants and eating holes in succulent crops, e.g. bedding plants, lawns, potatoes, celery, turnips and conifer seedlings. The damage resembles that caused by slugs.

Life cycle (see Figure 14.13). The adult moth, 2 cm across, with brown fore-wings and yellow or orange hind wings, emerges from the shiny soil-borne chestnut brown pupa from June to July, and lays about 1000 eggs on the stems of a wide variety of weeds. The first instar caterpillars, having fed on weeds, descend to the soil and in the later instars cause the damage described above, eventually reaching about 3.5 cm in length. They are grey to grey-brown in colour, with black spots along the sides. Several other cutworm species such as **heart and dart moth** (*Agrotis exclamationis*) and **turnip moth** (*Agrotis segetum*) may cause damage similar to that of the yellow underwing. In all three species, their typical caterpillar-shaped larvae should not be confused with the legless leatherjacket which is also a common underground larva. The cutworm species normally have two life cycles per year, but in hot summers this may increase to three.

Spread. The larvae are able to crawl from plant to plant, but most spread is by the actively flying adults.

Control. ***Amateur*** gardeners remove a good proportion of the cutworm larvae as they dig plots over. Good weed control reduces cutworm damage. A soil-directed spray of ***bifenthrin*** will achieve some control of cutworm.

For the ***professional*** horticulturist, soil drenches of residual insecticides such as **chlorpyrifos** have proved successful against the larva stage of this pest.

Leopard moth (Zeuzera pyrina)

Damage. The caterpillar of this species tunnels into the branches and trunk of a wide range of tree species, such as apple, ash, birch, and lilac. The tunnelling may weaken the branches of trees which in high winds commonly break.

Life cycle. The Leopard moth has an unusual life cycle. The moth is large, 5–6 cm across, and is white with black spots. In early summer the female lays dark-yellow eggs on the bark of the tree. The emerging caterpillar (see Figure 14.14) enters the stem by a bud, and then tunnels for 2–3 years in the heartwood. It has bacteria in its gut which help to digest the xylem tissue that it eats. It eventually reaches 5 cm in length, pupating in the tunnel, and finally emerging from the branch the following summer as the adult. Spread is only by adults.

Control. Where tunnels are observed, a piece of wire may be pushed along the tunnel to kill the larva.

Other moths worthy of mention here are the fruit-invading species such as codling moth (*Cydia pomonella*) on apple, plum moth (*Cydia funebrana*) and pea moth (*Cydia nigricana*) each of which needs accurately timed insecticidal control to avoid fruit damage by the pest (see also **pheremone traps**), because insecticidal control inside the fruit is not possible.

Figure 14.14 **Leopard moth larva** emerging from an apple stem

Recently reported moth pests are the Holm oak leaf-mining moth (*Phyllonorycter messaniella*), the horse chestnut leaf miner (*Cameraria obridella*) and the Leek moth (*Acrolepiosis assectella*).

Flies

This group of insects, of the order Diptera, are characterized by having only a single pair of functioning wings. The hind wings are modified into little stubs which act as balancing organs. The larvae are legless, elongated, and their mouthparts, where present, are simple hooks. The larvae are the only stage causing crop damage.

Figure 14.15 Codling moth damage

Carrot fly (Psila rosae)

Damage. This is a widespread and serious pest on umbelliferous crops (carrots, celery and parsnips). The grubs emerging from the eggs eat fine roots and then enter the mature root using fine hooks in their mouths. Damage is similar in all crops. In carrots, seedlings may be killed, while in older plants the foliage may become red, and wilt in dry weather. Stunting is often seen, and affected roots, when lifted, are riddled with **small tunnels** (see Figure 14.16) that make the carrots unsaleable. Damage should not be confused in carrots with **cavity spot**, a condition associated with a *Pythium* species of fungi which produces elongated sunken spots partly circling the root.

Life cycle. The adult fly is 8 mm long, shiny black and with a red head. It emerges from the rice-grain-sized overwintering pupa in the soil from late May to early June. The small eggs laid on the soil near the host plant soon hatch to give white larvae which damage the plant (see Figure 14.16). The fully grown larva leaves the host to turn into a cylindrical pale yellow pupa when a month old. A second generation of adults emerges in late July, while in October a third emergence is seen in some areas.

Figure 14.16 **Carrot fly damage**

Spread. The adult is the stage which spreads the pest.

Control. The ***amateur*** gardener can use a variety of controls. Planting carrots after the May emergence has occurred reduces infestation. Covering carrot plots with horticultural **fleece** (see Chapter 16, Figure 16.2), prevents the adut from laying eggs next to carrots. Inter-planting carrots with onions is said to prevent carrot fly from homing in on the carrot crop.

For the ***professional*** grower, high levels of carrot fly can be prevented by keeping hedges and nettle beds trimmed, thus reducing sheltering sites for the flies. A seed treatment containing **tefluthrin** reduces early larval infestation. A ground-directed spray at a high volume rate of **lambda-cyhalothrin** reaches the larva in the soil.

Chrysanthemum leaf miner (Phytomyza syngenesiae)

Damage. The leaf miners are a group of small flies, the larvae of which can do serious damage to horticultural crops by tunnelling through the leaf. This species is found on members of the plant family Asteraceae. Plants attacked include chrysanthemum, cineraria and lettuce.

Life cycle. The flies emerge at any time of the year in greenhouses, but normally only between July and October outdoors. These adults, which measure about 2 mm in length and are grey-black with yellow underparts, fly around with short hopping movements. The female lays about 75 minute eggs singly inside the leaves, causing white spot symptoms to appear on the upper leaf surface. The **larva** stage is greenish white in colour, and tunnels into the pal-lisade mesophyll of the leaf, leaving behind the characteristic mines seen in Figure 14.17. On reaching its final instar, the 3.5 mm long larva develops within the mine into a brown pupa, from which the adult emerges. The total life cycle period takes about three weeks during the summer months.

Figure 14.17 **Chrysanthemum leaf** miner damage

Spread. This pest is spread by the adult stage.

Control. Weed hosts such as groundsel and sowthistle should be controlled. Yellow sticky traps remove many of the adult flies. Certain chrysanthemum cultivars show some resistance.

Amateur gardeners have no effective insecticide product to control the larva inside the leaf.

Professional growers use tiny wasps such as *Diglyphus isaea* and *Dacnusa sibirica* to parasitize the tunnelling leaf-miner larvae. Products containing **abamectin** may be used outdoors and in greenhouses. (The occurrence of South American leaf miner (*Liriomyza huidobrensis*) and American serpentine leaf miner (*Liriomyza trifolii*) which are able to damage a wide variety of greenhouse plants has, in recent years, created many problems for horticulture).

Leatherjacket (Tipula paludosa)

Damage. This is an underground pest which is a natural inhabitant of grassland and causes most problems on golf greens. After ploughing up of grassland, leatherjackets may also cause damage to the crops such as potatoes, cabbages, lettuce and strawberries. This pest is particularly damaging in prolonged wet periods when the roots of young or succulent crops may be killed off. Occasionally lower leaves may be eaten.

Life cycle. The adult of this species is the crane fly, or 'daddy-long-legs', commonly seen in late August. The females lay up to 300 small eggs on the surface of the soil at this period, and the emerging larvae feed on plant roots during the autumn, winter and spring months, reaching a length of 4 cm by June. They are cylindrical, grey-brown in colour, **legless** and possess hooks in their mouths for feeding. During the summer months, they survive as a thick-walled pupa.

Spread is achieved by the adults.

Control. ***Amateur*** gardeners remove this pest as they dig in autumn and spring. Crops sown in autumn are rarely affected, as the larvae are very small at this time. There are no pesticide products recommended to control this pest.

Professional growers and groundsmen use products containing the residual **chlorpyrifos**, which is drenched into soil to reduce the larval numbers.

Sciarid fly (Bradysia spp.)

Damage. The larvae of this pest (sometimes called **fungus gnat)** feed on fine roots of greenhouse pot plants such as cyclamen, orchid and freesia, causing the plants to wilt. Fungal strands of mushrooms in commercial houses may be attacked in the compost.

Life cycle. The slender black females, which are about 3 mm long, fly to suitable sites (freshly steamed compost, moss on sand benches and well-fertilized compost containing growing plants), where about 100 minute eggs are laid. The emerging legless larvae are translucent-white with a black head, and during the next month grow to a length of 3 mm before briefly pupating and starting the next life cycle.

Spread is achieved by the adults.

Control. ***Amateur*** gardeners and ***professional*** horticulturists use yellow sticky traps to catch the flying adults in greenhouses. The pest can be reduced by avoiding overwatering of plants. Biological control by the tiny nematode *Steinernema feltiae* is now available. ***Professional*** growers in mushroom houses attempt to exclude the flies from mushroom houses by means of fine mesh screens placed next to ventilator fans. A predatory mite (*Hypoaspis miles)* is used to control the larvae. The larvae also may be controlled by the insecticide, **diflubenzuron**, incorporated into composts.

Beetles

This group of insects in the order Coleoptera is characterized in the adult by hard, horny forewings (elytrae) which, when folded, cover the delicate hind wings used for flight. The meeting point of these hard wing cases produces the characteristic straight line down the beetles back over its abdomen. Most beetles are beneficial, helping in the breakdown of humus, e.g. dung beetles, or feeding on pest species (see **ground beetle**). A few beetles, e.g. wireworm, raspberry beetle and vine weevil, causes crop damage.

Vine weevil (Otiorhyncus sulcatus)

This species belongs to the beetle group but, as with all weevils, possesses a longer snout on their heads than other beetles.

Damage. The larva stage is the most damaging, eating away roots of crops such as cyclamen and begonias in greenhouses, primulas, strawberries, young conifers and vines outdoors, causing above-ground symptoms similar to root diseases such as vascular wilt. Close inspection of the plant's root zone will, however, quickly show the unmistakable white grubs (see Figure 14.18). The adults may eat out neat holes or leaf edges of the foliage of hosts such as rhododendron, raspberry and grapes, and many herbaceous perennials (see Figure 14.18). Several related species, e.g. the clay-coloured weevil (*Otiorhyncus singularis*) cause similar damage to that of the vine weevil.

(a) (b)

Figure 14.18 (a) **Vine weevil larva** and pupa (b) **Adult Vine Weevil** damage on *Tellima*

Life cycle. The adult is 9 mm long, black in colour, with a rough textured cuticle (see Figure 14.19). The forewings are fused together, the pest being incapable of flight. No males are known. The female lays eggs (mainly in August and September) in soil or compost, next to the roots of a preferred plant species. Over a period of a few years, she may lay a thousand eggs as she visits many plants. The emerging larvae are white, legless and with a characteristic chestnut-brown head. They reach 1 cm in length in December when they pupate in the soil before developing into the adult.

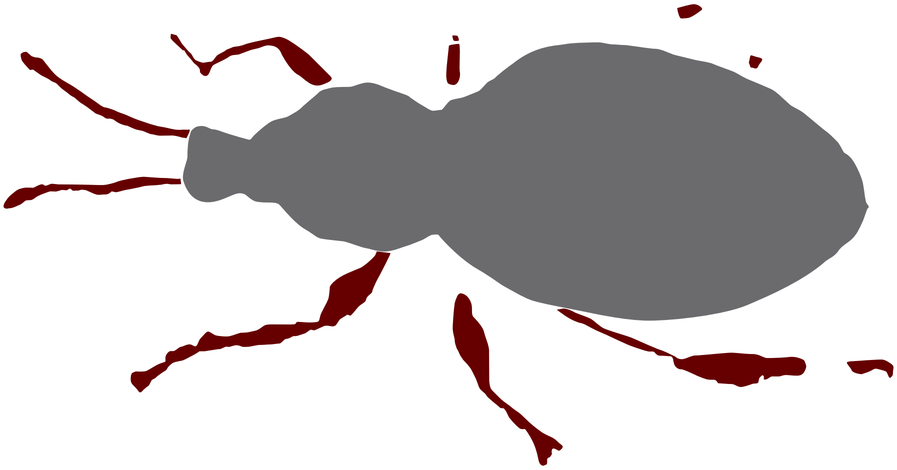


Figure 14.19 **Vine weevil adult**-9 mm in length

Spread is achieved by the female adult crawling around at night, or by the movement of pots containing grubs.

Control. ***Amateur*** gardeners sometimes use traps of corrugated paper placed near infested crops. Inspection of plants at night by torchlight may reveal the feeding adult.

Amateurs and professionals can use the nematode (*Steinemena carpocapsae*) by incorporating it into compost or soil.

Professional growers have residual chemicals, **imidacloprid** or **chlorpyrifos** incorporated or drenched into compost or soil.

Wireworm (Agriotes lineatus)

Damage. This beetle species is commonly found in grassland, but will attack most crops. Turf grass may be eaten away by the larvae (**wireworms)** resulting in dry areas of grass. The pest also bores through potatoes to produce characteristic narrow tunnels, while in onions, brassicas and strawberries the roots are eaten. In tomatoes, the larvae bore into the hollow stem.

Life cycle. The 1 cm long adult (click beetle) is brown-black and has the unusual ability of flicking itself in the air when placed on its back. The female lays eggs in weedy ground in May and June and the larvae, after hatching, develop over a four year period. Fully grown wireworms are about 2.5 cm long, shiny golden-brown in colour, and possess short legs (see Figure 14.7). After a three week pupation period in the soil, usually in summer, the adult emerges and in this stage survives the winter.

Spread is by means of the flighted adults.

Control. Some ***amateur*** gardeners dig in green manure crops to lure wireworms away from underground roots and tubers. ***Professional*** growers may reduce serious damage to young crops by using a seed dressing containing **tefluthrin**.

Garden Chafer (Phyllopertha horticola)

Damage. This pest is increasingly proving a problem on turf where the large white grubs eat the roots. Small yellow patches appear in the lawn or sports area, notably in summer when the grubs are becoming fully grown. Further damage can occur when starlings, crows, moles, foxes and even badgers dig up parts of the lawn to reach the succulent prey.

Life cycle. The adult is a broad, 1 cm long, light-brown beetle with a bottle-green upper thorax and head. Adults emerge from soil-borne pupae in May and June. They feed on leaves of a variety of plants, sometimes badly damaging fruit tree foliage. Eggs are laid near grasses in early summer and emerging larvae develop during the next 10 months into the characteristic stout white grub with a light-brown head. Their body, which may reach nearly 2 cm in length, is curved and bears well-developed legs (see Figure 14.20). The larvae are the winter- survival stage. Pupation occurs in early spring.

Figure 14.20 **Chafer grub**-2 cm in length

Spread is by means of the flighted adults.

Control. For the ***amateur*** gardener, maintenance of a healthy, well-fertilized lawn will lessen chafer attack.

Groundsmen may use a biological control, involving a nematode, *Heterorhabditis bacteriophora* available for application during the summer. The nematode enters the chafer grub through its spiracles, and proceeds to release bacteria which digest the grub's body. A soil-applied insecticide containing **imadocloprid** is used against this pest.

Raspberry beetle (Byturus tomentosus)

The developing fruit of raspberry, loganberry and blackberry may be eaten away by the 8 mm long, golden-brown larvae of this pest. Only one life cycle per year occurs, the larva descending to the soil in July and August, pupating in a cell from which the golden-brown adult emerges to spend the winter in the soil. The adult female lays eggs in the host flower the following June. **Spread** is by means of the flighted adult.

Control. Since the destructive larval stage may enter the host fruit and thus escape insecticidal control, the timing of the spray is vital. In raspberries, a contact chemical such as **bifenthrin**, applied when the fruit is pink, achieves good control.

Other beetle pests

Springtime attack of flea beetle (*Phyllotreta* species) on leaves of young cruciferous plants (e.g. cabbages and stocks) is a serious problem to amateur and professional horticulturist alike (see Figure 14.21). In recent years, four other increasingly common beetle problems have been reported. These are viburnum beetle on *Viburnum opulus*, *V. tinus* and *V. lantana*, rosemary leaf beetle (*Chrysolina americana)* on lavender, rosemary and thyme, red lily beetle (*Lilioceris lilii)* on lilies, and asparagus beetle (*Crioceris asparagi*).

Sawflies

This group, together with bees (see Chapter 10), wasps and ants, are classified in the order Hymenoptera, characterized by adults with two pairs of translucent wings and with the fore- and hind-wings being locked together by fine hooks. The slender waist-like first segments of the abdomen give these insects a characteristic appearance. A sawfly larva is shown in Figure 14.22.

Gooseberry sawfly (Nematus ribesii)

Damage. This is an important pest on gooseberries, redcurrants and whitecurrants, but not on blackcurrants. Extensive damage to foliage may be caused by the caterpillars. In some cases, the leaves of the whole bush may be skeletonized.

Life cycle. The adults emerge from their overwintering soil-borne cocoons in late April. Adults measure about 1 cm in length and resemble flying ants. The male has a black abdomen, the female a yellow abdomen. The female, in early May, lays elongate 1 mm long, light-green eggs in rows along the veins of the leaves situated low down in the host bush. Emerging young caterpillars eat small holes in these leaves. Maturing caterpillars (reaching up to 2 cm in length and identifiable by their **green appearance with numerous black spots** and with a black head) consume whole leaves and move outwards and upwards from their original positions. After 3–4 weeks of feeding, the mature caterpillars drop to the soil and pupate. There are 2–3 more lifecycle generations of the sawfly from the second emergence in early June to last soil pupation in late September.

Figure 14.21 **Flea beetle** damage

Spread is by the flighted adults.

Figure 14.22 **Viburnum sawfly** damage

Control. ***Private*** gardeners often pick off the first few young caterpillars found on the base leaves of the bush at egg-germination times (in late April, early June, early July and late August). In autumn and winter periods, the removal of any mulch from around the bushes and disturbance of soil in the area encourage birds to seek out overwintering pupae. Insecticide products containing **pyrethrins** control this pest.

Professional growers use two ingredients derived from plants. The insecticides, **derris** or **nicotine**, are effective against the young caterpillars if directed on the under-leaf surface, and with special attention being paid to the lower, central leaves.

No biological control is currently available for gooseberry sawfly, and the insecticide formulated from the bacterium, *Bacillus thuringiensis*, whilst effective on many caterpillars of moths, is ineffective against this sawfly species.

Rose leaf-rolling sawfly (Blennocampa pusilla)

The black shiny adults, resembling winged queen ants, emerge from the soil-borne pupa in May and early June. Eggs are inserted into the leaf lamina of roses, which, in responding to the pest, rolls up tightly. The emerging larva, which is pale green with a white or brown head, feeds on the rolled foliage. It reaches a length of 1 cm by August, when it descends to the ground and forms an underground cocoon to survive the winter until it pupates in March. All types of roses are affected, although climbing roses are preferred. Damage caused by leaf-rolling tortrix caterpillars, e.g. *Cacoecia oparana*, may be confused with the sawfly, although the leaves are less curled.

Spread of the sawfly is achieved by means of the flighted adults.

Amateur gardeners may need to control this pest with an insecticide containing **pyrethrins**. Nursery stock ***growers*** may use products containing **pirimiphos-methyl**.

Springtails (order Collembola)

This group of primitive wingless insects, about 2 mm in length (Figure 14.23) has a spring-like appendage at the base of the abdomen. They are very common in soils, and normally aid in the breakdown of soil **organic matter**. Two genera, *Bourletiella* and *Collembola*, however, may do serious damage to conifer seedlings and cucumber roots respectively.

Spread is slow since all stages are wingless.

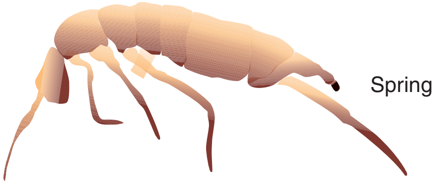
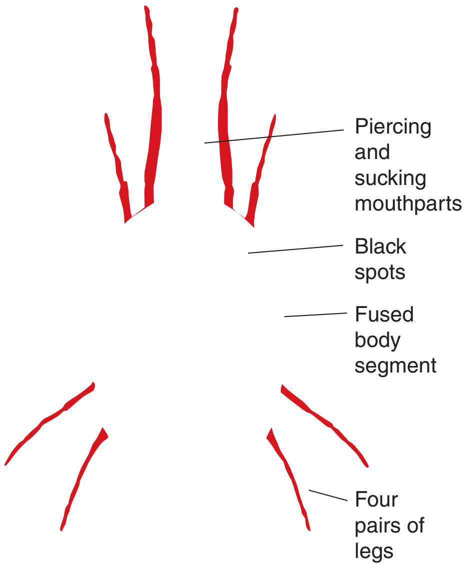


Figure 14.23 **Springtail** – about 2 mm in size – can jump by means of spring at the end of its body

Mite pests

The mites (Acarina) are classified with spiders and scorpions in the Arachnida. Although similar to insects in many respects they are distinguished from them by the **possession of four pairs of legs, a fused body structure and by the absence of wings** (see Figure 14.24). Many of the tiny soil-inhabiting mites serve a useful purpose in breaking down plant debris. Several above-ground species are serious pests on plants. The life cycle is composed of egg, larva, nymph and adult stages.



Glasshouse red spider mite (×100)

Figure 14.24 Glasshouse **red spider mite**. Note that the red spider mite may be light green or red in colour. Its extremely small size (0.8 mm) enables it to escape attention

Glasshouse red spider mite (Tetranychus urticae and T. cinnabarinus)

Damage. The piercing mouthparts of the mites inject poisonous secretions which cause localized death of leaf mesophyll cells. This results in a fine mottling symptom on the leaf (see Figure 14.1), not to be confused with the larger spots caused by **thrips**. In large numbers the mites can kill off leaves and eventually whole plants. Fine silk strands are produced in severe infestations, appearing as 'ropes' (see Figure 14.25) on which the mites move down the plant. On flowering crops such as chrysanthemums, these ropes make the plant unsaleable.

Life cycle. This pest is of tropical origin and thrives best in high greenhouse temperatures. Both species are 1 mm in length. The **first** species (*T. urticae*) is yellowish in colour, with two black spots (see Figure 14.25). The female lays about 100 tiny spherical eggs on the underside of the leaf, and after a period of three days the tiny six-legged larva moults to produce the nymph stage that resembles the adult. The life cycle length varies markedly from 62 days at 10°C, to 6 days at 35°C when the pest's multiplication potential is extremely high. In autumn, when the daylight period decreases to 14 h and temperatures fall, egg production ceases and the fertilized females, which are now red in colour, move into the greenhouse structures to hibernate (diapause), representing foci for the next spring's infestation.

(a) (b)

Figure 14.25 (a) Glasshouse **red spider** in the centre (b) webbing

Spread occurs when adults and nymphs crawl from plant to plant when leaves are touching. Wind currents can move mites attached to their silk strands. The small size and under-leaf habitat of the pest combine to keep its existence on introduced plants away from the gaze of growers, especially older growers.

The **second** species (*T. cinnabarinus*), which is dark reddish-brown, has a similar life cycle to *T. urticae*, but does not hibernate. The hibernation habit of *T. urticae* leads to it being a common pest on annual crops such as tomatoes, cucumbers and chrysanthemums, while *T. cinnabarinus* is found more commonly on the perennial crops such as carnations, arums and hothouse pot plants. The two species often occur together on summer hosts.

Control may be achieved in several ways. ***Amateur*** gardeners and ***professional*** growers should carefully check incoming plants for the presence of the mite, using a hand lens if necessary. A predatory mite, *Phytoseiulus persimilis* is commonly introduced into cucumber, chrysanthemum and tomato crops in spring. For the ***amateur*** there are products containing **fatty acids** that control the mite. For the professional, winter fumigation of greenhouse structures with chemicals such as **formalin** or burning **sulphur** kills off many of the hibernating females. A pesticide containing **abamectin** is commonly used.

Gall mite of blackcurrant (Cecidophyopsis ribis)

Damage. Mites living inside the blackcurrant bud damage the meristem and induce the bud to produce many scale leaves, which gives the bud its unusual swollen appearance (see Figure 14.26). These buds either fail to open or produce distorted leaves. In addition to the mechanical damage, the mite carries the virus responsible for **reversion disease** (see Chapter 15), which stunts the plant and reduces fruit production.

(a) (b)

Figure 14.26 (a) Big bud symptoms on **blackcurrant** (b) Erineum mite damage on **grape leaf**

Life cycle. Unlike red spider mite, this species, sometimes called **big-bud mite**, is elongated in shape and is minute (0.25 mm) in size. It spends most of the year living inside the buds of blackcurrants and, to a lesser extent, other *Ribes* species. Breeding takes place inside the buds from June to September, and January to April.

Spread. In May the mites emerge and are spread on silk threads and on the bodies of aphids to infest newly emerging buds and plants.

Control. The mite is controlled in three ways. **Clean planting material** is essential for the establishment of a healthy crop. **Pruning** out of stems with big bud and destruction of reversion-infected plants slows down the progress of the pest. ***Amateur*** gardeners and ***professional*** growers can spray a fine formulation of **sulphur** during the May–June period when the mites are migrating. There are no chemical ways to control the mite in the bud. Recently there has been a reported problem on hazel in UK caused by the hazel big bud mite (*Phytopus avellanae*).

Tarsonemid mite (Tarsonemus pallidus)

Damage. Distortion of developing leaves and flowers resulting from small feeding holes and injected toxins are the main symptom of this pest. This may happen to such an extent that leaves and petals are stunted and misshapen, and flowers may not open properly. Plant species affected are *Amaranthus*, *Fuchsia*, pelargonium and cyclamen (the pest is sometimes referred to as 'cyclamen mite') A closely related but distinct strain is found on strawberries.

Life cycle. This spherical mite, only 0.25 mm in length, lives in the unex-panded buds of a wide variety of pot plants. In greenhouses, the adults may lay eggs all the year round, and the **2 weeks life cycle** period can cause a rapid increase in its numbers.

Spread occurs mainly on transported bulbs, corms and plants.

Control. Care should be taken to prevent introduction of infested plants and propagation material into greenhouses. For the ***amateur***, there is no recommended chemical product. For the professional grower, the contact acaricide, **abamectin**, is effective against the mite. Addition of a **wetter/spreader** may help the spray penetrate the tight-knit scale leaves of buds.

Other mites

Four other horticulturally important mites require a mention. The fruit tree red spider mite (*Panonychus ulmi*) causes serious leaf mottling of ornamental Malus and apple. Conifer spinning mite (*Oligonychus ununguis*) causes spruce leaves to yellow, and the mite spins a web of silk threads. Bulb-scale mite (*Steneotarsonemus laticeps*) causes internal discoloration of forced narcissus bulbs. Bryobia mite (e.g. *Bryobia rubrioculus*) attacks fruit trees, and may cause damage to greenhouse crops, e.g. cucumbers, if blown in from neighbouring trees.

Other arthropods

In addition to insects and mites, the phylum Arthropoda contains three other horticulturally relevant classes, the Crustacea (woodlice), Symphyla (symphilids) and Diplopoda (millipedes). The Chilopoda (centipedes) superficially resemble millipedes, but are unrelated and are useful general predators.

Woodlouse (Armadillidium nasutum)

The damage is confined mainly to stems and lower leaves of succulent glasshouse crops such as cucumbers, but occasionally young transplants may be nipped. A relative of marine crabs and lobsters, the woodlouse has adapted for terrestrial life, but still requires damp conditions to survive. In damp soils it may number over a million per hectare, and greatly helps the breakdown of plant debris, as do earthworms. In greenhouses, where plants are grown in hot, humid conditions, this species may multiply rapidly, producing two batches of 50 eggs per year. The adults roll into a ball when disturbed. Partial soil sterilization by steam effectively controls woodlice.

Symphilid (Scutigerella immaculata)

In greenhouse crops, **root hairs** are removed and may cause lettuce to mature without a heart. Infectious fungi, e.g. *Botrytis*, may enter the roots after symphilid damage. These delicate white creatures, with 12 pairs of legs, resemble small millipedes. The adult female, 6 mm long, lays eggs in the soil all the year round, and the development through larvae to the adult takes about 3 months. Symphilids may migrate 2 m down into soil during hot, dry weather. The recognition of this pest is made easier by dipping a suspect root and its surrounding soil into a bucket of water and searching for symphilids which float on the water surface.

Millipedes

These elongated, slow-moving creatures are characterized by a thick cuticle and the possession of many legs, two pairs to each body segment. Many species are useful in breaking down soil organic matter, but two pest species, the flat millipede (*Brachydesmus superus*) and a tropical species (*Oxidus gracilus*), can cause damage to roots of strawberries and cucumbers respectively.

Centipedes

These animals resemble millipedes, but are much more active. They help control soil pests by searching for insects, mites and nematodes in the soil.

Nematode pests

This group of organisms, also called **eelworms**, is found in almost every part of the terrestrial environment, and range in size from the large animal parasites, e.g. *Ascaris* (about 20 cm long) in livestock, to the tiny soil-inhabiting species (about 0.5 mm long). Non-parasitic species may be beneficial, feeding on plant remains and soil bacteria, and helping in the formation of **humus** (see p321). The general structure of the nematode body is shown in Figure 14.28. A feature of the plant parasitic species is the **spear** in the mouth region, which is thrust into plant cells. Salivary enzymes are then injected into the plant and the plant juices sucked into the nematode (see Figure 14.27). Nematodes are very active animals, moving in a wriggling fashion in soil moisture films, most actively when the soil is at **field capacity**, and more slowly as the soil either waterlogs or dries out. Five horticulturally important types are described below.

Potato cyst nematode (*Globodera rostochiensis* and *G. pallida*)

Damage. This serious pest is found in most soils that have grown potatoes. Leaves become yellow and plants become stunted (see Figure 14.29) and occasionally die. The distribution of damage in the field is characteristically in patches. Tomatoes grown in greenhouses and outdoors may be similarly affected. The pest may be diagnosed in the field by the tiny, mature white or yellow females seen on the potato roots (a hand-lens is useful for this observation).

Life cycle. A proportion of the eggs in the soil hatch in spring, stimulated by chemicals produced in potato roots. The larvae invade the roots, disturbing **translocation** in xylem and phloem tissues, and sucking up plant cell contents. When the adult male and female nematodes are fully developed, they migrate to the outside of the root, and the now swollen female leaves only her head inserted in the plant tissues (see Figure 14.28). After fertilization, the white female

Figure 14.27 **Nematode feeding**: note the spear inside the mouth, used to penetrate plant tissues

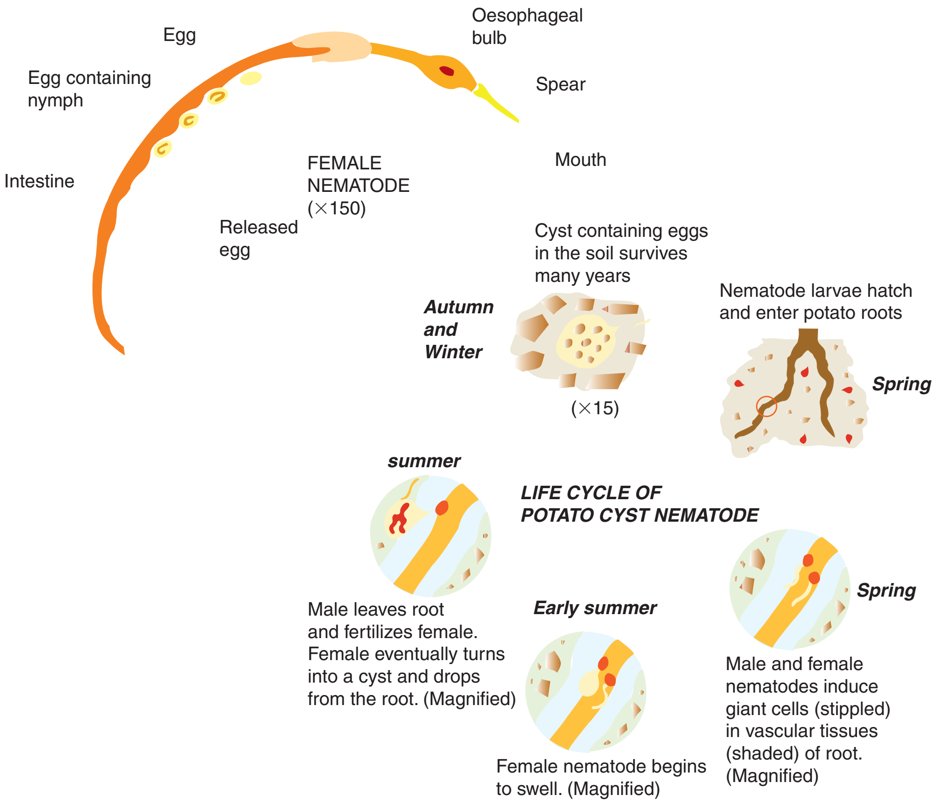


Figure 14.28 The generalized structure of a **nematode** and life cycle of **potato cyst nematode**

swells and becomes almost spherical, about 0.5 mm in size, and contains 200–600 eggs. As the potato crop reaches harvest, the female changes colour. In *G. rostochiensis* (the golden nematode), the change is from white to **yellow** and then to dark brown, while in the other species, *G. pallida*, no yellow phase is seen. The significance of the species difference is seen in its control. Eventually the dark-brown female dies and falls into the soil. This stage, which looks like a minute brown onion, is called the **cyst**, and the eggs inside this protective shell may survive for 10 years or more.

Spread. This nematode spreads with the movement of infested soil. In peat-soil areas, it often travels along with the wind-blown soil.

Control. Several forms of control are available against this pest. Since it attacks only potatoes and tomatoes, **rotation** is a reliable way of overcoming the problem. It has been found that an average soil population of 10 cysts per 100 gm of soil results in about 3 t/ha decline in yield. Thus a soil count for cysts can indicate to a grower (or gardener) whether a field or plot should be used for a potato crop.

Figure 14.29 **Potatoes** stunted by **potato cyst nematode**

Early cultivars of potatoes are lifted before most nematodes have reached the cyst stage, and thus escape serious damage. Some potato cultivars, such as ‘Pentland Javelin’ and ‘Maris Piper’, are **resistant** to golden nematode strains found in Great Britain, but not to *G. pallida*. Since the golden nematode is dominant in the south of England, use of resistant cultivars has proved effective in this region.

There is no chemical control for the ***amateur*** gardener, but the ***professional*** grower may use a residual chemical such as **oxamyl**, incorporated as granules into the soil at planting time. This provides economical control when the nematode levels are moderate to fairly high, but is not recommended at low levels because it is uneconomic, or at high levels because the chemical kills insufficient nematodes.

Stem and bulb eelworm (*Ditylenchus dipsaci*)

Damage. The damage caused by this species varies with the crop attacked. Onions show a loose puffy appearance (called bloat); carrots have a dry mealy rot; the stems of beans are swollen and distorted. Narcissus bulbs show brown rings when cut across and their leaves show raised yellow streaks.

Life cycle. This species attacks many plants, e.g. narcissus, onions, beans and strawberries. Several strains are known, but their host ranges are not fully defined. The 1 mm long nematodes enter plant material and breed continuously, often with thousands of individuals in one plant. When an infected plant matures, the nematodes dry out in large numbers, appearing as white fluffy **eelworm wool** that may survive for several years in the soil. Weeds, such as bindweed, chickweed and speedwells, act as alternate hosts to the pest.

Spread. This pest spreads mainly in infested planting material.

Control is achieved in several ways. Control of **weeds** (see chickweed); **rotation** with resistant crops, e.g. lettuce, brassicas (and cereals in commercial bulb growing areas); use of clean, nematode-free **seed** in onions; **warm-water treatment** (see Chapter 16) onions and narcissus at precisely controlled temperatures. All these methods help reduce this serious pest.

Chrysanthemum eelworm (*Aphelenchoides ritzemabosi*)

Damage. The first symptom is blotching and purpling of the leaves, which spreads and becomes a dead brown, **V-shaped** area between the veins. The lower leaves are worst affected. When buds are infested, the resulting leaves may be misshapen. In addition to chrysanthemum, this nematode also attacks *Saintpaulia* and strawberries.

Life cycle. Most species of nematode live in the soil. This 1 mm long nematode spends most of its life cycle inside young leaves of the species mentioned above. The adults move along films of water on the surface of the plant, and enter the leaf through the stomata. They breed rapidly, the females laying about 30 eggs, which complete a life cycle in 14 days. During the winter they live as adults in stem tissues, but a few overwinter in the soil.

Spread. This pest spreads mainly in infested stools.

Control. Greenhouse-grown chrysanthemums are rarely affected, as they are raised from pest-free cuttings. Warm-water treatment of dormant chrysanthemum stools, e.g. at 46°C for 5 min, is very effective for outdoor grown plants. Dispose of all plant debris.

Root knot eelworm (*Meloidogyne spp.*)

Damage. This nematode, a very serious pest in tropical areas of the world, can be important in UK glasshouse production. It causes large root galls, up to 4 cm in size on the roots of plants such as chrysanthemum, *Begonia*, cucumber and tomato, resulting in wilting and poor plant growth.

Life cycle. The swollen female lays 300–1000 eggs inside the root and on the root surface. These eggs can survive in root debris for over a year, and are an important source of subsequent infestations. The larvae hatch from the eggs and search for roots, reaching soil depths of 40 cm and surviving in damp soil for several months. On entering the plant, the nematode larvae stimulate the adjoining root cells to enlarge. These cells block movement of water to the root stele (see **root structure)**, which results in wilting symptom so commonly seen with this pest.

Spread is mainly caused by the movement of infested soil.

Control. For the ***amateur,*** **resistant** tomato rootstocks, e.g. KVNF, may be used on grafted plants. For the ***professional***, nutrient film and soilless methods of growing reduce the pest's likely importance in a crop. **Partial steam sterilization** effectively controls the nematode only if the soil temperature reaches 99°C to a depth of 45 cm. Less stringent sterilization often results in a severe infestation in the next crop. Chemical sterilization of soil with the chemical fumigant **metam-sodium** is effective if a damp seedbed tilth is first prepared. A 2.5 cm layer of clean soil or compost placed around roots of infested plants allows some new root growth. Care should be taken not to transfer infested soil (together with transplants) from one greenhouse to another.

Figure 14.30 **Root knot nematode** damage on **cucumber**

Migratory plant nematodes

The species of nematodes described above spend most of their life cycle inside plant tissues (**endoparasites**). Some species, however, feed only from the outside of the root (**ectoparasites**). The dagger nematodes (e.g. *Xiphinema diversicaudatum*) and needle nematodes (e.g. *Longidorus elongatus*), which reach lengths of 0.4 and 1.0 cm respectively, attack the young roots of crops such as rose, raspberry and strawberry, and cause stunted growth. In addition, these species transmit the important **viruses**, arabis mosaic on strawberry and tomato black ring on ornamental cherries. The nematodes may survive on the roots of a wide variety of weeds.

Control is achieved by professional growers by the injection of a fumigant chemical, e.g. **dichloropropene** or incorporation of **dazomet** in fallow soils.

Check your learning

1. Define the term 'pest'.
2. Describe the damage caused by a chosen mammal pest.
3. Describe the life cycle of this pest.
4. Describe how the life cycle of this pest is related to its control.
5. Describe the available control measures for this pest.
6. Describe the damage caused by a chosen invertebrate (slug, insect, mite, or nematode) pest.
7. Describe the life cycle of this pest.
8. Describe how the life cycle of this pest is related to its control.
9. Describe the available control measures for this pest.

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Chapter 15 Horticultural diseases and disorders

Summary

This chapter includes the following items:

- **Definition of term 'disease'**
- **Damage caused by fungal diseases**
- **Life cycles of fungal diseases**
- **Relationship between life cycle and control**
- **Control measures for disease**
- **Damage caused by bacteria**
- **Minimizing bacterial problems**
- **Damage caused by viruses**
- **Minimizing virus spread**
- **Definition of term 'physiological disorder'**
- **Symptoms of physiological disorders**
- **Methods of avoiding physiological disorders**

Figure 15.1 Powdery mildew on courgette

A disease is an unhealthy condition in a plant caused by a fungus, bacterium or virus.

Below are described some of the most important horticultural diseases caused by fungi, bacteria and viruses.

Structure and biology of fungi, bacteria and virus

Fungi, commonly called moulds, cause serious losses in all areas of horticulture. They are thought to have common ancestors with the filamentous algae, a group including the present-day green slime in ponds. Some details of their classification are given in Chapter 4.

A fungus is composed, in most species, of microscopic strands (**hyphae**) which may occur together in a loose structure (**mycelium**), form dense resting bodies (**sclerotia**, see Figure 15.2) or produce complex underground rootlike strands (see **rhizomorphs**). The club root group of fungi is quite different, producing a jelly-like structure (**plasmodium**) inside the cells of the host plant.

The hyphae in most fungal species are capable of producing spores. Wind-borne spores are generally very small (about 0.01 mm), not sticky and often borne by hyphae protruding above the leaf surface, e.g. grey mould, so that they catch turbulent wind currents. Water or rain-borne spores are often sticky, e.g. damping off. Minute asexual spores produced without fusion of two hyphae commonly occur in seasons favourable for disease increase, e.g. humid weather for downy mildews and dry, hot weather for powdery mildews. Sexual spores, produced after hyphal fusion, commonly develop in unfavourable conditions, e.g. a cold, damp autumn. They may be produced singly, as in the downy mildews, or in groups within a protective hyphal spore case, often observable to the naked eye, as in the powdery mildews. Different genera and species are identified by microscopic measurement of the shape and size of the spores or of the spore-bearing spore cases.

Horticulturists without microscopes must use symptoms as a guide to the cause of the disease. While disease-causing or parasitic fungi are the main concern of this chapter, in many parts of the environment there are useful saprophytic fungi that break down organic material such as dead roots, leaves, stems and sometimes decaying tree stumps (see Chapter 3) and useful **symbiotic** fungi that may live in close association with the plant, e.g. **mycorrhizal** fungi in fine roots of conifers (see Chapter 18).

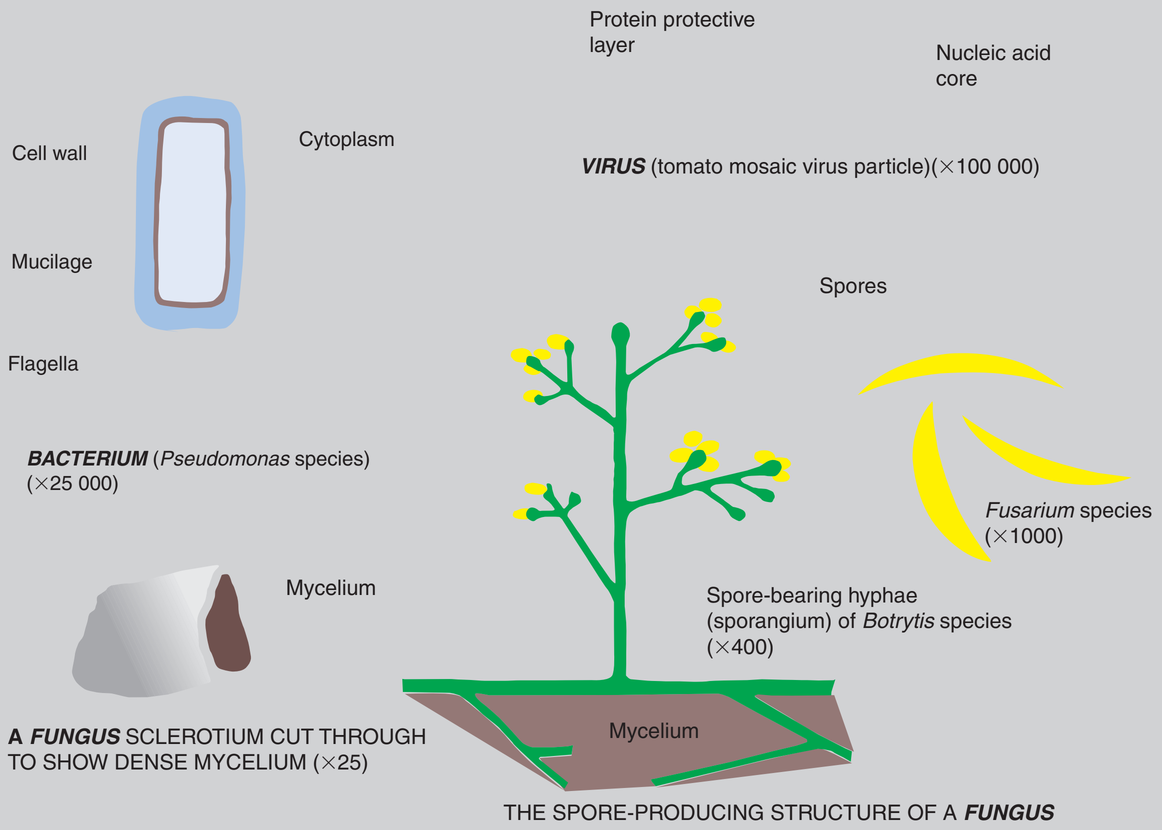

Figure 15.2 Microscopic details of a **virus**, **bacterium** and **three fungi**. Note the relative sizes of the organisms.

The spore of a leaf-infecting fungal parasite, after landing on the leaf in damp conditions, produces a germination tube which, being delicate and easily dried out, must enter through the **cuticle** or **stomata** within a few hours before dry, unfavourable conditions recur. Within the leaf, the hyphae grow, absorbing food until, within a period of a few weeks they produce a further crop of spores (see Figure 15.4). Leaf diseases such as potato blight often increase very rapidly when conditions are favourable. Roots may be infected by spores, e.g. in damping off; hyphae, e.g. wilt diseases; sclerotia, e.g. Sclerotinia rot; or rhizomorphs, e.g. honey fungus. Root diseases are generally less affected by short periods of unfavourable conditions and often increase at a slower, more constant rate.

Phyllosphere

On the surface of leaves and stems a population of micro-organisms (mainly bacteria) lives which occupy a microhabitat commonly called the **phyllosphere** (see also **rhizosphere** p322). These bacteria may be 'casual' or 'resident'. Casual organisms such as *Bacillus* spp. mainly arrive from soil, roots and water, and are more common on leaves closer to the ground. These species are capable of rapid increase under favourable conditions, but then may decline. Resident organisms such as *Pseudomonas* spp. may be weakly parasitic on plants, but more commonly persist (often for considerable periods) without causing damage on a wide variety of plants.

There is increasing evidence that phyllosphere bacteria may reduce the infection of diseases such as powdery mildews, *Botrytis* diseases on lettuce and onion, and turf grass diseases. Practical disease control strategies by phyllosphere organisms have not been developed, but there remains the general principle that a healthy, well-nourished plant will be more likely to have organisms on the leaf surface available to reduce fungal infection.

Figure 15.3 **White rot on onion**. Note the black sclerotia which enable this disease to survive long periods in the soil

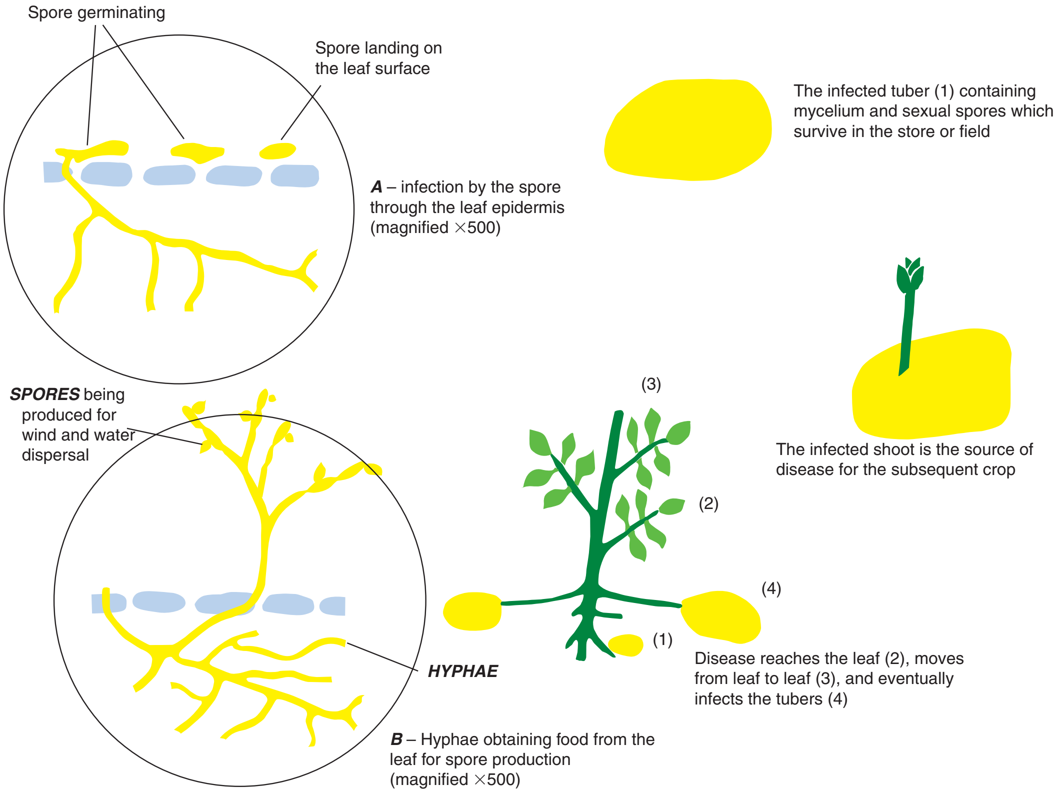

Figure 15.4 **Infection and life cycle of potato blight fungus**. The left side illustrates microscopic infection of the leaf. The right side shows how the disease survives and spreads

Fungi

The **classification** of fungi referred to in Chapter 4 has practical implications in understanding fungal disease life cycles and control. Species within a fungal division often have similar methods of spread, and of survival. Their similarity of spore and hypha structure and of biochemistry also means that they are often controlled by a common fungicide active ingredient. For this reason, the appropriate fungal division is given for each disease as it appears (e.g. Zygomycota is mentioned against potato blight).

Leaf and flower diseases

Potato blight (*Phytophthora infestans*)

This fungus is a member of the Zygomycota division of fungi (see p74).

Damage. This important disease is a constant threat to potato production; it caused the Irish potato famine in the nineteenth century. The first symptoms seen in the field are yellowing of the foliage, which quickly goes **black** and then produces a white bloom on the under surface of the leaf in damp weather. The stems may then go black, killing off the whole plant. The tubers may show dark surface spots that, internally, appear as a **deep dry red-brown rot**. This fungus may attack tomatoes, the most notable symptom being the **dark-brown blisters** on the fruit (Figure 15.5).

(a)

(b)

Figure 15.5 **Potato blight**: (a) Leaf symptoms of potato blight on potato, (b) Fruit symptoms of blight on tomato

Life cycle. The fungus survives the winter as mycelium and sexual spores in the tubers (see Figure 15.4, p235). The spring emergence of infected shoots results in the production of asexual spores.

Spread. The spores are spread by wind and land on potato leaves or stems. They can, after infection, result in a further crop of spores within a few days under warm, wet weather conditions. The disease can spread very quickly. Later in the crop, badly infected plants may have tuber infection as rainfall washes spores down into the soil.

Control. ***The amateur*** gardener should use clean seed, choose resistant varieties, and apply a protective fungicide such as copper sulphate (Bordeaux mixture) before damp conditions appear. ***The professional*** grower similarly needs to use clean seed. Removal and herbicidal destruction, (e.g. using **dichlobenil**), of diseased tubers from stores or 'clamps' prevents disease spread. Knowledge of the disease's moisture requirement leads to better control. DEFRA are able to measure both the duration of atmospheric relative humidity greater than 92 per cent, and mean daily temperatures greater than 10°C (together known as **critical periods**), and to issue forecasts of potato blight outbreaks. In this way, protectant sprays of chemicals such as **mancozeb** can be applied before infection can take place.

Resistant potato cultivars prevent rapid build-up of disease, although resistance may be overcome by newly occurring fungal strains. Early potato cultivars usually complete tuber production before serious blight attacks, while main-crop top growth may deliberately be killed off with foliage-acting herbicides, such as **diquat**, to prevent disease spread to tubers.

A curative, systemic fungicide such as **benalaxyl** penetrates the leaf and kills the infecting mycelium. This ingredient has within its formulation a protectant ingredient (in this case **mancozeb)** to kill off most germinating spores and thus reduce the development of fungus resistance to the systemic fungicide.

Downy mildew of cabbage and related plants (*Perenospora brassicae*)

This fungus is a member of the Zygomycota group of fungi.

Damage. This serious disease causes a white bloom mainly on the under surface of leaves (see Figure 15.6) which present a more favourable humid microclimate for infection and spore production than the upper leaf surface. Ornamental cruciferous plants such as stocks and wallflowers, brassicas such as cabbage and occasionally weeds such as shepherd's purse are attacked by this fungus. The disease is most damaging when seedlings are germinating, particularly in spring when the young infectable tissues of the host plant and favourable damp conditions may combine to kill off a large proportion of the developing plants.

Life cycle and spread. Asexual spores (zoospores) are produced on microscopic structures on the lower leaf surface, mainly in spring and summer, and are spread by wind currents. Thick-walled sexual spores (**oospores)** produced within the leaf tissues fall to the ground with the death of the leaf and survive the winter to initiate the spring infections, when rain splash carries the spores up to the lower leaf surface of seedlings and young plants.

Figure 15.6 **Leaf symptoms of cabbage downy mildew** on stock. Lower leaf symptoms (top), upper leaf symptoms (bottom)

Control. It is not advisable to grow successive brassicas in the same field, and particularly not to sow in spring next to overwintered crops.

The ***amateur*** grower can use a product containing the protectant fungicide, **mancozeb**. The ***professional*** horticulturist uses a protective chemical such as chlorothalinal at the seedling stage to kill off spores on the leaf. A combination of a systemic fungicide **metalaxyl** plus chlorothalinal gives better control, while reducing the development of fungus strains resistant to the systemic ingredient.

Other crops such as lettuce and onions are attacked by different downy mildews (*Bremia lactucae* and *Perenospora destructor* respectively) and no cross-infection is seen between crops belonging to different plant families.

Powdery mildew of ornamental Malus and apple (*Podosphaera leucotricha*)

This fungus belongs to the Ascomycota group of fungi.

Damage. Powdery mildews should not be confused with downy mildews. Powdery mildew is distinguished by its dry powdery appearance, most commonly found on the **upper** surface of the leaf, and by its preference for **hot**, **dry weather** conditions (see examples of powdery mildew in Figure 15.7).

Life cycle and spread. The disease survives the winter as mycelium within the buds which often appear small and shrivelled on twigs which often have a dried, **silvery** appearance. The emergence of the mycelium with the germinating buds in spring results in a white bloom over the young leaves (**primary mildew**). As the spring progresses, asexual spores produced in chains on the upper surface of the leaf are spread as individual spores by wind and cause the destructive **secondary** mildew. This stage of the fungal life cycle involves an **external** mycelium covering the leaf surface, but not entering into the internal leaf tissues other than to sink small peg-like structures (which suck out the leaf's moisture and may cause premature leaf drop). Flowering normally occurs before the secondary infection stage, but infection in young apple fruit may produce a rough skin (**russeting**). This organism may affect other species of fruit such as pears, quinces, medlars and ornamental *Malus.*

Powdery mildews in autumn may produce sexual, dark-coloured spore cases (**cleistothecia**) on the leaf, about 1 mm in size. (Although not important in most horticultural crops as an overwintering stage, they may assume a vital role in powdery mildew of cereals, the sexual spores having the potential to form new strains resistant to fungicides, and new strains capable of overcoming the plant's genetic resistance.)

Control is achieved by two main 'methods'. Pruning of silvered shoots can eliminate a good proportion of the primary mildew. The amateur and professional horticulturist can use a systemic fungicide ingredient such as **myclobutanil** for spring and summer sprays, whilst the professional also has a protective fungicide option such as **dinocap**.

(a)

(c)

(b)

Figure 15.7 **Powdery mildew diseases**: (a) Primary apple powdery mildew on apple shoot. Affected shoot (left), healthy shoot (right), (b) Rose powdery mildew, (c) Gooseberry powdery mildew on fruit.

Other species of powdery mildew commonly occur in horticulture, e.g. *Sphaerotheca pannosa* on rose (Figure 15.7) and *S. fuliginea* on cucumber. Cross-infection between these crops does not occur.

Black spot of roses (*Diplocarpon rosae*)

This fungus belongs to the Ascomycota group of fungi.

Damage. This common disease in garden and greenhouse roses is first seen as dark-brown leaf spots which may be followed by general leaf yellowing and then leaf drop (see Figure 15.8). The infection of young shoots has a slow weakening effect on the whole plant.

Life cycle and spread. Asexual spores (produced within spore cases embedded in the leaves) are released in wet and mainly warm weather conditions, and are then spread a few metres by rain drops or irrigation water before beginning the cycle of infection again. No overwintering sexual stage is seen in Britain, and it is probable that asexual spores surviving in autumn-produced wood or in fallen leaves begin the infection process again the following spring.

Control. Removal of fallen leaves is a very important aspect of control. Resistance is not common in rose cultivars. Both ***amateur*** and ***professional*** horticulturists can use a systemic fungicide ingredient such as **myclobutanil**.

The ***professional*** has also a protectant ingredient, **captan** which, while very effective against this disease, is limited in its action by the vigorous leaf expansion in late spring and summer which leaves unprotected areas of foliage. The addition of a **wetter/spreader** may improve control by spreading the active ingredient more effectively over the leaf surface. In industrial areas the sulphur dioxide in the air may be at a sufficient concentration to help reduce black spot.

Figure 15.8 **Black spot of rose**. Note the leaf-yellowing symptom that accompanies the black spot

Carnation rust (*Uromyces dianthi*)

Rust fungus belongs to the Basidiomycota group of fungi. (The rusts are a distinctive group of fungi which may have very complex life cycles involving five spore-forms within the same fungal species. When these different spore-forms occur on more than one host, e.g. blackcurrant rust (*Cronartium ribicola*), which attacks both blackcurrants and five-needle pines, the close planting of the two crops may give rise to high rust levels. For this reason, in some North American forested regions, blackcurrants may not be planted. Most horticultural rust species are found on only one host species.)

Damage. Carnation rust first appears as an indistinct yellowing of the leaf and stem, soon turning into an elongated raised brown spot which yields brown dust (spores) when rubbed (see Figure 15.9).

Life cycle and spread. The more common thin-walled spores (uredospores) are spread by wind currents and infect the leaf by way of the stomata in damp conditions. The less common thick-walled black spores (teleutospores) may survive and overwinter in the soil. The resistance of carnation cultivars varies, while related species, e.g. pinks or sweet williams, are rarely affected.

Control. Preventative control includes the use of rust-free cuttings, sterilization of border soils and careful maintenance of greenhouse ventilators to prevent damp patches occurring in the crop. ***Amateur*** and ***professional*** horticulturist are able to spray products containing a systemic ingredient, **myclobutanil**, and products containing the protectant **mancozeb**.

(a) (b)

(c) (d)

Figure 15.9 **Rust diseases**: (a) Rose rust, (b) Bean rust, (c) Leek rust, (d) Groundsel rust which affects cinerarias

The occurrence of white rust (*Puccinia horiana*) on chrysanthemums has created serious problems for the horticultural industry and for gardeners, because of the ease with which the disease is carried in cuttings and its speed of increase and spread. Other common rusts are found on antirrhinum, hollyhock, rose and leek, and more recently European pear rust, with an alternate host of juniper, has become more common in the UK.

Stem diseases

Grey mould (*Botrytis cinerea*)

This fungus is classified in the Deuteromycota group of fungi.

Damage. This disease is most commonly recognized by the fluffy, light-grey fungal mass which follows its infection. In lettuce, the whole plant rots off at the base. The plant turns yellow and dies. In tomatoes, infection in damaged side shoots, and yellow spots (**ghost spots)** on the unripe and ripe fruit are found. In many flower crops, e.g. chrysanthemums, infected petals show purple spots which, in very damp conditions, lead to mummified flower heads. This disease may affect many crops.

Life cycle and spread. Grey mould normally requires wounded tissue for infection, which explains its importance in crops which are de-leafed, e.g. tomatoes, or disbudded, e.g. chrysanthemums. Damp conditions are essential for infection and spore production. The millions of spores are carried by wind to the next wounded surface. Black sclerotia, about 2 mm across, produced in badly infected plants, often act as the overwintering stage of the disease after falling to the ground, and are particularly infective in unsterilized soils on young seedlings and delicate plants, e.g. lettuce.

Control. Preventative control may involve soil sterilization. Strict attention to greenhouse humidity control (particularly overnight) reduces the dew formation which is so important in the organism's infection. Cutting out of infected tissue is possible in sturdy stems, e.g. in tomatoes. ***Amateur*** gardeners at present have no effective chemical control against this disease. The ***professional*** grower has two protectant fungicide ingredients, **iprodione** and **chlorothalinal**. As well as being sprayed, **iprodione** can also be applied as a paste to cut plant surfaces.

Apple canker (*Nectria galligena*)

This fungus belongs to the Ascomycota group of fungi.

Damage. This fungus causes sunken areas in bark of both young and old branches of ornamental Malus, apples or pears (see Figure 15.10). Poor shoot growth is seen, and the wood may fracture in high winds.

Life cycle and spread. The fungus enters through leaf scars in autumn or through pruning wounds during winter. Care is therefore necessary to prevent infection, particularly in susceptible apple cultivars, e.g. 'Cox's Orange Pippin', by avoiding pruning in damp conditions. Spread is by rain splash.

Figure 15.10 Apple canker

Control. Removal of cankered shoots may be necessary to prevent further infection, while in cankers of large branches cutting out of brown infected tissue may allow continued use of the branch. Removed tissue should be burnt. ***Amateur*** and ***professional*** horticulturists may apply a spray of **copper** (Bordeaux solution) at bud burst (spring) and leaf fall (autumn) to prevent entry of germinating spores.

Dutch elm disease (*Ophiostoma novo-ulmi*)

This fungus belongs to the Ascomycota group of fungi.

Damage. The first symptom of this disease is a yellowing of foliage in one part of the tree in early summer. The foliage then dies off progressively from this area of the tree, often resulting in death within three months. Trees that survive 1 year's infection may fully recover in the following year. All common species and hybrids of elm growing in Great Britain are susceptible to the disease (see Figure 15.11).

Life cycle and spread. The causative fungus lives in the xylem tissues of the stem, and produces a poison that results in a blockage of xylem

(a) (b)

Figure 15.11 (a) **Dutch Elm Disease**. A young elm tree showing typical yellowing and wilting of leaves, (b) Tunnelling inside elm bark caused by Scolytus beetle larvae

vessels, causing the wilt that is observed. Associated with this disease are two black and red wood-boring species of beetle, *Scolytus scolytus* (5 mm long) and *Scolytus multistriatus* (3 mm long). These beetles bore into elm stems leaving characteristic 'shot holes'. Eggs are then laid, and a fan-shaped pattern of galleries is produced under the bark by the larvae. Later, as adults, they emerge from the wood, carrying sticky asexual and sexual spores of Dutch elm disease to continue its spread to other uninfected elms. Graft transmission of the disease from tree to tree by roots commonly occurs in hedge-grown elms.

Control. For the professional horticulturist, the cost of preventative control on a large number of uninfected trees is uneconomical. However, high pressure injection of a systemic fungicide such as **thiabendazole** which travels upwards through the xylem tissues has proved successful in some cases. Selections of hybrid elms have proved to have high levels of resistance. Examples are the Dutch/French cultivar 'Lutéce' with a complex parentage; the Italian cultivar 'Planio' with resistant Siberian Elm male parentage; and the American 'Princeton Elm' which has shown resistance since the 1920s. The European White Elm (*Ulmus laevis*) exhibits a resistance to the vector beetles, not the fungus itself.

After an estimated 80 per cent removal of the elm population in the UK since the 1970s by Dutch Elm Disease there has been an understandable lack of confidence in planting elms of any species or cultivar around the countryside, especially the English elm. However, there is a growing realization that the native elm contributes considerably to plant and animal biodiversity in the UK. For example, the elm maintains one lichen species (Orange-fruited Elm lichen) and one butterfly (the White letter Hairstreak butterfly) which are both wholly dependant on the elm.

Bleeding Cankers (*Phytophthora species*)

In recent years the following species have been reported on a range of trees: horse chestnut and sweet chestnut affected by *P. cambivora*, and Oak, beech and tulip tree affected by *P. ramorum and P. kernovii*. Symptoms of the problem involve a **dark ooze** coming from the bark. After peeling away the outer bark, deep red, dead patches of inner bark are seen, often with a sharp distinction between dead and living bark. Oaks may be suddenly killed by *P. ramorum*. Control is at the moment limited to scraping away the outer bark in hot weather to allow drying and healing of tissues.

Root diseases

Club root (*Plasmodiophora brassicae*)

This fungus is classified into a quite separate group of fungi, the Plasmodiophorales.

Damage. It causes serious damage to most members of the Cruciferae family, which includes cabbage, cauliflowers, Brussels sprouts, stocks and Alyssum. Infected plants show signs of wilting and yellowing of older leaves, and often severe stunting. On examination, the roots appear stubby and swollen (see Figure 15.12), and may show a wet rot.

Figure 15.12 Club root on cabbage

Life cycle and spread. The club root organism survives in the soil for more than five years as minute spores which germinate to infect the root hairs of susceptible plants. The fungus is unusual in forming a jelly-like mass (**plasmodium**), not hyphae, within the plant's root tissues. The plasmodium stimulates root cell division and causes cell enlargement, which produces swollen roots. The flow of food and nutrients in phloem and xylem is disturbed, with consequent poor growth of the plant. With plant maturity the spores produced by the plasmodium within the root are released as the root rots.

The disease is favoured by high soil moisture, high soil temperatures and acid soils. Although this fungus does not spread much in undisturbed soils it can be easily carried on infected plants, or on tools and wheels of machinery. In peat soil-growing areas, high winds may carry the disease a considerable distance.

Control. Several preventative control measures may be used by the ***amateur*** gardener and ***professional*** grower. Rotation greatly helps by keeping cruciferous crops away from high spore levels in the soil. Liming of soil greatly inhibits spore activity (see **soil fertility**). Recently released cultivars of late-summer cabbage are claimed to have strong resistance to club root. Autumn-sown plants establish in soil temperatures unfavourable to the disease and are normally less infected. Compost made from infected brassica plants should be avoided. The ***professional*** grower using transplants can prepare a seedbed previously sterilized with a granular product containing **dazomet**, which would ensure healthy transplants.

Damping off (*Pythium* and *Phytophthora species*)

These two fungi belong to the Zygomycota.

Damage. These two similar genera of fungi cause considerable losses to the delicate **seedling** stage. The infection may occur below the soil surface, but most commonly the emerging seedling plumule is infected at the soil surface, causing it to topple (see Figure 15.13). Occasionally the roots of mature plants, e.g. cucumbers, are infected, turn brown and soggy, and the plants die. Rose plants often have high levels of *Pythium* around their roots as they age. Although the mature plant is not seriously affected, it is a common experience that on removal of the plant and replacement with a young rose plant, there is a quite rapid decline in its vigour, called **rose-sickness**.

Life cycle and spread. Both *Pythium* and *Phytophthora* occur naturally in soils as saprophytes, but under damp conditions they produce the asexual spores that cause infection. These spores are spread by water. Sexual spores (oospores) are produced in infected roots (mostly in autumn) and may survive several months of dry or cold soil conditions.

Control. Prevention control is best achieved (both for the ***amateur*** gardener and the ***professional*** grower) against

Figure 15.13 **Damping off on seedlings**. Note the shrivelled, papery appearance of the leaves on the infected plants these diseases by providing a disease-free growing medium. This may be produced by using fresh compost, by partial sterilization of soil with heat, or (for the ***professional*** grower) by a sterilant such as **dazomet**. Seed producers often coat crop seed with a protective seed dressing (see also p284) such as **thiram** to prevent early infection.

Water tanks with open tops, harbouring rotting leaves, are a common source of infected water and should be cleaned out regularly. Sand and capillary matting on benches in greenhouses should be regularly washed with hot water. The use of door mats soaked in a sterilant such as dilute **formalin** may prevent foot spread of the organisms from one greenhouse to another. Waterlogged soils should be avoided, as these fungi increase most rapidly under these conditions. The ***amateur*** gardener may use a **copper** formulation (known as Cheshunt mixture) as a drench to slow down the increase of damping off. ***Professional*** growers use a product containing **etridiazole**, which may be mixed in with composts, or drenched on to seed trays, pots or border soil growing young plants.

Conifer root rot (*Phytophthora cinnamomi*)

This fungus belongs to the Zygomycota group of fungi.

Damage. This soil-inhabiting fungus is most commonly a problem in nursery stock production nurseries. It causes the foliage of plants to turn grey-green, then brown and eventually to die off completely (see Figure 15.14). Sliced roots show a chestnut brown rot, with a clear line between infected and non-infected tissues. Two hundred plant species, including *Chaemaecyparis*, *Erica* and *Rhododendron* species may be badly attacked.

Figure 15.14 **Conifer root rot**. Note the different shades of colour in individual trees, representing different stages of infection

Life cycle and spread. The disease is commonly introduced on infected stock plants or contaminated footwear. It multiplies most rapidly under wet conditions, within a temperature range of 20°C and 30°C, infecting the root tissues and producing numerous asexual spores, which may be spread by water currents to adjacent plants. Sexual oospores produced further inside the root are released on decay and allow the fungus to survive in the soil for several months without a host.

Control. Preventative control (see **hygienic growing**, p269) is important. Reliable stock plants should be used. Water supply should be checked to avoid contamination. The stock plant area should be elevated slightly higher than the production area to prevent infection by drainage water. Rooting trays, compost and equipment, e.g. knives and spades, should be sterilized (e.g. with formalin) before use. Placing container plants on gravel reduces infection through the base of the pot. The chemical, **etridiazole**, incorporated in compost protects the roots, but does not kill the fungus. Some species, such as *Juniperus horizontalis*, have some tolerance to this disease.

Honey fungus (*Armillaria mellea*)

This fungus belongs to the Basidiomycota group of fungi.

Damage. This fungus primarily attacks trees and shrubs, e.g. apple, lilac and privet. In spring the foliage wilts and turns yellow. Death of the plant may take a few weeks or several years in large trees. Confirming symptoms are the white mycelium, rhizomorphs and toadstools mentioned below (see Figure 15.15).

Figure 15.15 **Honey fungus**. Note the dense clump of honey-coloured toadstools, and also the fungal strands (rhizomorphs) spreading out from the clump.

Life cycle and spread. The infection process involves **rhizomorphs** (sometimes referred to as 'bootlaces'), which radiate out underground from infected trees or stumps for a distance of 7 m, to a depth of 0.7 m. The infected stump may remain a serious source of infection for twenty years or more. The rhizomorphs are the only means of spread for this disease. The nutrients they are able to conduct provide the considerable energy required for the infection of the tough, woody roots. **Mycelium**, moves up the stem **beneath** the bark to a height of several metres and is visible (when the bark is pulled away) as white sheets, smelling of mushrooms. In autumn, clumps of light-brown **toadstools** may be produced, often at the base of the stem. The millions of spores produced by the toadstools are not considered to be important in the infection process. Honey fungus often establishes itself in newly planted trees and shrubs that have been planted too deeply. Deep planting produces less vigorous plants that are more vulnerable to infection. Vigour is reduced because feeding roots which ideally should be growing near the surface of the soil have been located in the subsoil.

Control is difficult. Some genera of plants are less likely to be infected (see Table 15.1). Removal of the disease source, the infected stump, is strongly recommended. In large stumps which are hard to remove a surrounding trench is sometimes dug to a depth of 0.7 m to prevent the

Table 15.1 Levels of resistance to Honey fungus in garden shrubs and trees

Plant species	Latin name	Resistance level
Maple	*Acer spp.*	susceptible
Box elder	*Acer negundo*	very resistant
Birch	*Betula spp.*	susceptible
Box	*Buxus sempervivans*	resistant
Cedar	*Cedrus spp.*	susceptible
Cypress	*Chamaecyparis lawsoniana*	susceptible
	X Cupressocyparis leylandii	susceptible
Eleagnus	*Eleagnus spp.*	resistant
Holly	*Ilex aquifolium*	resistant
Privet	*Ligustrum spp.*	susceptible
Lonicera	*Lonicera nitida*	resistant
Mahonia	*Mahonia spp.*	resistant
Apple	*Malus spp.*	susceptible
Pine	*Pinus*	susceptible
Cherry and plum	*Prunus spp.*	susceptible
Laurel	*Prunus laurocerasus*	resistant
Rhododendron	*Rhododendron*	susceptible
Sumach	*Rhus typhina*	resistant
Lilac	*Syringa spp.*	susceptible
Tamarisk	*Tamarix spp.*	resistant
Yew	*Taxus baccata*	very resistant

progress of rhizomorphs. Loosening soil with a fork and then applying a sterilant, e.g. **formalin** in a diluted state, may be applied in situations where there are no crops.

Fusarium patch on turf (now called *Microdochium nivale*)

This belongs to the Deuteromycota group of fungi.

Damage. This disease appears as irregular circular patches of yellow then dead brown grass up to 30 cm in diameter on fine turf. These patches eventually merge (see Figure 15.16). Under extreme damp conditions, dead leaves become slimy and then are covered with a light pink bloom, most evident between May and September.

Life cycle and spread. Infection of the leaves by spores and hyphae occurs most seriously between 0°C and 8°C, conditions that are found under a layer of snow (hence its other name, **snow mould**). However, conditions of high humidity at temperatures up to 18°C may result in typical patch symptoms. Spread is by means of water-borne asexual spores under conditions such as autumn dew with no wind. The fungus can survive in frosty or dry summer conditions as dormant mycelium in dead leaf matter or newly infected leaves.

Figure 15.16 **Fusarium patch on turf**. Note the area of dying turf. In the earlier stages of the disease, distinct circular patches about 30 cm across are seen.

Control. Preventative control measures are important. Avoid high soil nitrogen levels in autumn, as this promotes lush, susceptible growth in autumn and winter. Avoid thatchy growth of the turf, as this encourages high humidity and thus favours the disease organism. The groundsman can drench preventative fungicide such as **iprodione** in autumn to slow down infection of the fungus. Summer-applied systemic fungicide such as **thiophanate methyl** is able during the actively growing period of the year to move within the plants and achieve curative control.

Vascular wilt diseases (*Fusarium oxysporum* and *Verticillium dahliae*)

These fungi belong to the Deuteromycota group of fungi.

Damage. These two organisms infect the **xylem** tissues of horticultural plants, causing the leaves to wilt in hot conditions, a symptom which can also be caused by other factors, e.g. lack of soil moisture (see wilt) and nematode infestation (see root knot nematode p230). The wilt diseases can be recognized by yellowing and eventual browning of the **lower** leaves (see Figure 15.17) and by brown staining of the xylem tissue when it is exposed with a knife. *Verticillium* may attack a wide range of plants, e.g. dahlia, strawberry, lilac, tomato and potato, so that rotation is not a feasible control measure. *Fusarium oxysporum*, however, exists in many distinct forms, each specializing in crops in different plant families, e.g. tomato, cucumber, bean or carnation.

Life cycle and spread. Both organisms may live as **saprophytes** in the soil. *Fusarium* survives unfavourable conditions as thick-walled asexual spores, while *Verticillium* forms small sclerotia. Infection by both genera occurs through young roots or after nematode attack in older roots. The fungal hyphae enter the root xylem tissue and then move up the stem, sometimes reaching the flowers and seeds. The diseases are spread by water-borne asexual spores. The two fungi have different temperature preferences. *Verticillium* more commonly attacks in springtime, having an optimum infection temperature of 20°C, while *Fusarium* is more common in summer, with an optimum temperature of 28°C.

Control. Control is often necessary in greenhouse crops. Infected crop residues should be carefully removed from the soil at the end of the growing season. The ***amateur*** gardener or ***professional*** grower may choose to use peat bags instead of soil. The professional may use partial soil sterilization by steam, or a chemical sterilant such as **metam-sodium**.

Figure 15.17 **Fusarium wilt on beans**. Note the leaf yellowing

In unsterilized soils, ***professional*** growers may use resistant rootstocks, e.g. in tomatoes, which are grafted onto scions of commercial cultivars. Rotation may be employed against a *Fusarium oxysporum* attack, as different forms attack different crops. Careful removal of infected and surrounding plants, e.g. in carnations, may slow down the progress of the diseases, especially if the soil area is drenched with a systemic chemical such as **carbendazin**, which reduces the infection in adjacent plants.

Bacteria

These minute organisms (see Figure 15.2) measure about 0.001 mm and occur as single cells that divide rapidly. They are important in the conversion of soil organic matter (see Chapter 18), but may, in a few parasitic species, cause serious damage or losses to horticultural plants. Some details of their classification are given in Chapter 4.

Fireblight (*Erwinia amylovora*)

Damage. This disease, which first appeared in the British Isles in 1957, can cause serious damage on members of the Rosaceae family. Individual branches wilt and the leaves rapidly turn a ‘burnt’ chestnut brown. When the disease reaches the main trunk, it spreads to other branches and may cause death of the tree within six weeks of first infection, the general appearance resembles a burnt tree, hence the name of the disease. Badly infected plants produce a bacterial slime on the outside of the branches in humid weather. On slicing through an infected stem, a brown stain will often be seen. Pears, hawthorn and *Cotoneaster* are commonly attacked, while apples and *Pyracantha* suffer less commonly.

Life cycle and spread. The bacterium is spread by bees as they pollinate, by harmful insects such as aphids and by small droplets of rain. Humid conditions and temperatures in excess of 18°C, which occur from June to September, favour the spread. Natural plant openings such as stomata and lenticels are common sites for infection. Flowers are the main entry point of entry in pears. The bacterial slime mentioned above is an important source of further infections. Fireblight, once notifiable nationally (see p293), must now be reported only in fruit-growing areas.

Control. The compulsory removal of the susceptible 'Laxton's Superb' pear cultivar in the 1960s eliminated a serious source of infection. Preventative measures such as removal of badly infected plants to prevent further infection, and removal of hawthorn hedges close to pear orchards, help in control. Careful pruning, 60 cm below the stained wood of early infection, may save a tree from the disease. Wounds should be sealed with protective paint, and pruning implements should be sterilized with 3 per cent **lysol**.

Bacterial canker (*Pseudomonas mors-prunorum*)

Damage. This disease affects the plant genus *Prunus* that includes ornamental species, plum, cherry, peach and apricot. Symptoms typically appear on the stem as a swollen area exuding a light brown gum (see Figure 15.18). The angle between branches is the most common site for the disease. Severe infections girdling the stems cause death of tissues above the infection, and the resulting brown foliage can resemble the damage caused by fireblight. In May and June, leaves may become

Figure 15.18 **Bacterial canker on Prunus**. Note the swollen trunk and gum oozing from the infected area infected; dark brown leaf spots 2 mm across develop and the infected area may be blown out by heavy winds to give a ‘shot-hole’ effect.

Life cycle and spread. The bacteria present in the cankers are mainly carried by wind-blown rain droplets, infecting leaf scars and pruning wounds in autumn and young developing leaves in summer.

Control. Preventative control involves the use of resistant rootstocks and scions, e.g. in plums. The careful cutting out of infected tissue followed by an application of paint and the use of autumn sprays of a copper compound (Bordeaux mixture), help reduce this disease.

Soft rot (*Erwinia carotovora*)

This bacterium affects stored potatoes, carrots, bulbs and iris, where the bacterium’s ability to dissolve the cell walls of the plant results in a mushy soft rot. High temperatures and humidity caused by poor ventilation promote infection through lenticels, and major losses may occur. A related strain of this bacterium causes **black leg** on potatoes in the field. Preventative control measures are important. Crops should be damaged as little as possible when harvesting, and diseased or damaged specimens should be removed before storage. Hot, humid conditions should be avoided in store. No curative measures are available.

Crown gall (*Agrobacterium tumifasciens*)

This bacterium affects apples, grapes, peaches, roses, *Euonymus* and many herbaceous plants. The disease is first seen just **above** ground level as a swollen, cancer-like structure (often about 5 cm in size) growing out of the stem. It may occasionally cause serious damage, but usually is not a very important problem. The bacterium is able to survive well in soils, and infects the plant through small wounds in the roots.

It is of special scientific interest in the area of **plant breeding**, having the ability to add its genetic information to that of the plant cell. It does this by means of a small unit of DNA called a ‘plasmid’. This plasmid ability of *A. tumifasciens* has been harnessed by plant breeders to transfer genetic information between unrelated plant species. It is the properties of this bacterium that have led to the new term ‘genetically modified crop’ or more simply ‘GM’ (see Chapter 10).

Control of crown gall depends on cultural control methods, such as disease-free propagating material, avoiding wounds at planting time and budding scions to rootstocks (rather than grafting) to avoid injuries near the soil level.

Viruses

Structure and biology

Viruses are extremely small, much smaller even than bacteria (see Figure 15.2). The light microscope is unable to focus in on them, but they appear as rods or spheres when seen under an electron microscope. The virus particle is composed of a DNA or RNA core surrounded by a protective protein coat. On entering a plant cell, the virus takes over the organization of the cell nucleus in order to produce many more virus particles. Since the virus itself lacks any cytoplasm cell contents, it is often considered to be a non-living unit. Some details of its classification are given in Chapter 4.

The virus's close **association with the plant cell nucleus** presents difficulties in the production of a curative virus control chemical that does not also kill the plant. No established commercial 'viricide' has yet been produced against plant viruses.

In recent years the broad area called 'virus diseases' has been closely investigated. Virus particles have, in most cases, been isolated as the cause of disease, e.g. cucumber mosaic. Other agents of disease to be discovered are **viroids** (e.g. in chrysanthemum stunt disease) and these are smaller than viruses. *Mycoplasmas* (the cause of diseases such as aster yellows) are a group of bacteria that induce symptoms similar to those produced by viruses.

Spread. A number of organisms (**vectors)** spread viruses from plant to plant and then transmit the viruses into the plant. **Peach-potato aphid** is capable of transmitting over 200 types of virus (e.g. cucumber mosaic) to different plant species. The aphid stylet injects salivary juices containing virus into the parenchyma and phloem tissues, enabling the virus to then travel to other parts of the plant. '**Persistent virus transmission**' is seen in some vector/virus combinations such as peach-potato aphid/potato virus X, and *Xiphinema* dagger nematode/arabis mosaic where the virus is able to survive and increase within the vector's body for several weeks. In many vector/virus combinations such as plum pox, the virus survives only briefly as a contaminant on the insect's stylet. Other vector/virus combinations include bean weevils/broad bean stain virus; and *Olpidium* soil fungus/big vein agent on lettuce.

Other important methods of spread involve vegetative material (e.g. chrysanthemum stunt viroid and plum pox), infected seed (e.g. bean common mosaic virus), seed testa (e.g. tomato mosaic virus) and mechanical transmission by hand (e.g. tomato mosaic virus).

Symptoms. The presence of a damaging virus in a plant is recognizable to horticulturists only by means of its symptoms. For confirmation, they may need to consult a virologist, whose identification techniques include electron microscopy, transmission tests on sensitive plants such as *Chenopodium* species, and serological reactions using specific antiserum samples.

Leaf **mosaic**, a yellow mottling, is the most common symptom (e.g. cucumber mosaic virus). Other symptoms include leaf **distortion** into feathery shapes (cucumber mosaic virus), flower **colour streaks** (e.g. tulip break virus), fruit **blemishing** (tomato mosaic and plum pox), **internal discolouration** of tubers (tobacco rattle virus causing 'spraing' in potatoes) and **stunting** of plants (chrysanthemum stunt viroid).

Symptoms similar to those described above may be caused by misused herbicide sprays, genetic ‘sports’, poor soil fertility and structure (see **deficiency symptoms**) and mite damage.

In the following descriptions of major viruses, Latin names of genus and species are not included, since no consistent classification is yet accepted.

Tomato mosaic

Damage. This disease may cause serious losses in tomatoes. Infected seedlings have a stunted, spiky appearance. On more mature plants leaves have a pale green mottled appearance, or sometimes a bright yellow (aucuba) symptom. The stem may show brown streaks in summer when growing conditions are poor, a condition often resulting in death of the plant. Fruit yield and quality may be lowered, the green fruit appearing bronze, and the ripe fruit hard, making the crop unsaleable (see Figure 15.19).

Life cycle and spread. The virus is a rod shaped virus. The period from plant infection to symptom expression is about 15 days. The virus may survive within the seed coat (testa) or endosperm of the tomato seed. It is very easily spread by human contact as it is present in large numbers in the leaf hairs of infected plants.

Figure 15.19 **Tomato mosaic virus**. Note the orange-yellow patches on the fruit

Control. Heat treatment of dry seed at 70°C for 4 days by seed merchants helps remove initial infection. Infected debris, particularly roots, in the soil enables the virus to survive from crop to crop, and soil temperatures of 90°C for 10 min are normally required to kill the organism. Peat-growing bag and nutrient-film methods enable the grower to avoid this source of infection. Hands and tools should be washed in soapy water after working with infected plants. Clothing may harbour the virus.

Cultivars and rootstocks containing several factors for resistance are commonly grown, but newly arriving virus strains may overcome this resistance. A mild strain spray inoculation method has been used at the seedling stage to protect non-resistant cultivars from infection with severe strains. Great care is required to avoid mosaic-contaminated equipment when using this method.

Cucumber mosaic

Damage. Several strains of virus cause this disease. In addition to cucumber, the following may also be affected: spinach, celery, tomato, *Pelargonium* and *Petunia*. On cucumbers, a mottling of young leaves occurs (see Figure 15.20) followed by a twisting and curling of the whole foliage, and fruit may show yellow sunken areas. On the shrub *Daphne oderata*, a yellowing and slight mottle is commonly seen on infected foliage, while *Euonymus* leaves produce bright yellow leaf spots. Infected tomato leaves are reduced in size (fern-leaf symptom).

Figure 15.20 **Cucumber mosaic virus**. Note the leaf mottling

Life cycle. The virus may be spread by infected hands, but more commonly an aphid (e.g. peach-potato aphid) is involved. Many crops (e.g. lettuce, maize, *Pelargonium* and privet) and weeds (e.g. fat hen and teasel) may act as a reservoir for the virus.

Control. Since there are no curative methods for control, care must be taken to carry out preventative methods. Choice of uninfected stock is vital in vegetatively propagated plants, e.g. *Pelargonium*. Careful control of aphid vectors may be important where susceptible crops (e.g. lettuce and cucumbers) are grown in succession or next to other susceptible species. Removal of infected weeds, particularly from greenhouses, may prevent widespread infection.

Tulip break

The petals of infected tulips produce irregular coloured streaks and may appear distorted. Leaves may become light green, and plants become stunted after several years' infection. The virus is spread mechanically by knives, while three aphid vectors are known: the bulb aphid in stores, the melon aphid in greenhouses, and the peach-potato aphid outdoors and in greenhouses.

Preventative control must be used against this disease. Removal of infected plants in the field prevents a source of virus for aphid transmission. Aphid control in field, store and greenhouse further reduces the virus's spread.

Plum pox

Damage. This disease, also called 'Sharka', has increased in importance in the British Isles since 1970 after its introduction from mainland

Europe. Plums, damsons, peaches, blackthorn and ornamental plum are affected, while cherries and flowering cherries are immune. Leaf symptoms of faint interveinal yellow blotches can best be seen on leaves from the centre of the infected tree.

The most reliable symptoms, however, are found on fruit, where sunken dark blotches are seen. Ripening of infected fruit may be several weeks premature, yield losses may reach 25 per cent, and the fruit is often sour.

Life cycle. The virus is spread by several species of aphids. The speed of spread is quite slow because the virus is not able to live and multiply in the aphid. Movement of infected young plants is an important method of spread.

Control. Preventative control is the only option open to growers. Clean Ministry-certified stock should be used. Routine aphid-controlling insecticides should be applied in late spring, summer and autumn. Suspected infected trees should be reported and infected trees removed and burnt.

Chrysanthemum stunt viroid

Damage. This disease, found only on plants of the Asteraceae family and mainly on the chrysanthemum, produces a stunted plant, often only half the normal size but without any distortion. Flowers often open one week earlier than normal, and may be small and lacking in colour.

Life cycle. The virus enters gardens and nurseries through infected cuttings, and is readily transmitted by leaf contact and by handling.

Control. Symptoms may take several months to appear, thus seriously reducing the chance of early removal of the disease source. The grower must use preventative control. **Certified planting material** derived from heat-treated meristem stock (see tissue culture) reduces the risk of this disease.

Arabis mosaic

Damage. This virus infects a wide range of horticultural crops. On strawberries, yellow spots or mottling are produced on the leaves, and certain cultivars become severely stunted. On ornamental plants, e.g. *Daphne odorata*, yellow rings and lines are seen on infected leaves, and the plants may slowly die back, particularly when this virus is associated with cucumber mosaic inside the plant.

Life cycle. Several weeds, e.g. chickweed and grass spp., may harbour this disease, and in strawberries severe attacks of the disease may occur when planted into ploughed-up grassland. The virus is spread by a common soil-inhabiting nematode, *Xiphinema diversicaudatum*, which may retain the virus in its body for several months.

Control. Control of this disease can be achieved by preventative methods. Certified virus-free soft fruit planting material is available. Fumigation of soil with chemicals such as **dichloropropene**, applied well before planting time, eliminates many of the eelworm vectors. No curative chemical is available to eliminate the virus inside the plant.

Reversion disease on blackcurrants

Damage. This virus disease, caused by blackcurrant reversion virus can seriously reduce blackcurrant yields. Flower buds on infected bushes are almost hairless and appear brighter in colour than healthy buds. Infected leaves often have fewer main veins than healthy ones (see Figure 15.21). After several years of infection, the bush may cease to produce fruit.

Life cycle and spread. The virus is spread by the blackcurrant gall mite, and reversion infected plants are particularly susceptible to attack by this pest.

Control. Removal and burning of infected plants is an important form of control. Use of certified plant material, raised in areas away from infection and vectors, is strongly recommended. Control of the mite vector in spring and early summer has already been described on p225.

Figure 15.21 **Reversion disease of blackcurrant**. Note that the infected leaf (bottom) has fewer main veins and leaf lobes than the healthy leaf (top)

Physiological disorders

A **physiological disorder** is a condition in the plant resulting from a non-living (abiotic) factor such as nutrient or water being present at the incorrect level.

There are several symptoms that show on plant leaves, stems and flowers that are **not** caused by pests or diseases. The main causes are: nutrient deficiencies, excess fertilizer, frost, high temperature, lack of light, overwatering and underwatering.

Nutrient deficiencies

Each nutrient (the commonest being nitrogen, phosphorus, potassium, calcium and magnesium) is required in the correct amounts to enable the plant to carry out its chemical processes. When amounts present are too low, deficiencies begin to show, usually by means of leaf symptoms (see Chapter 21, p369).

Care should be taken to provide regular applications of a suitable fertilizer, especially during the summer months and in situations where the roots are restricted (as in pots).

Two common horticultural problems should be noted. In tomatoes and peppers, **blossom end rot** (see Figure 15.22) produces a symptom of a black, concave lesion which looks at first sight like a fungal disease. It is caused by an imbalance between potassium and calcium in the soil or compost. It occurs most often when the soil or compost is allowed to dry out while the fruits are swelling. It is seen more often in greenhouse container-grown plants than with plants growing in the open garden or greenhouse borders. It is most common when plants are raised in grow bags, where they have a small, shallow root run that dries out easily. Although there is no cure for blossom end rot once the symptoms begin to appear, the obvious recommendation is that fruiting crops should never be allowed to have dry roots.

A second problem is **bitter pit** in apples. Here the fruit develop many small, dark-brown, sunken pits. The tissues below are stained to depth of about 2 mm. Cultivars such as 'Bramley's Seedling' and 'Egremont Russet' are most susceptible. Young over-bearing trees show the worst effects. The disorder is caused by low calcium levels in the fruit, influenced by irregular water supply in the tree. Four recommendations are given for this problem.

Figure 15.22 **Blossom end rot in tomato**. The fruit at the opposite end from the stalk has a typical black sunken appearance

- Ensure a steady water supply to the tree during dry spells.
- Mulch around the tree to help moisture retention.
- Summer prune young, vigorous trees especially when they are holding too many fruit.
- Occasionally use foliar sprays of calcium nitrate plus detergent in the evening during summer to help prevent this problem.

Excess fertilizer

When fertilizers are present at too high levels, roots are scorched and are unable to provide nutrients for the other parts of the plant, often resulting in the plant's death. This condition is described on p380 in Chapter 21. Careful consideration of the appropriate frequency and amounts of fertilizer will prevent this embarrassing situation.

Low temperatures

Plants differ in their tolerance to low temperatures. Low temperatures slow down the plant's growth. Frost often causes the above-ground parts of sensitive plants to collapse into a mess of green tissue after ice has formed inside the plant and fractured all the cells.

High temperatures

Plants may become exposed to very high temperatures in greenhouses, where growth may be weak and 'leggy'. Their leaves also may become dry and brittle, especially if they are touching the glass sides or roof of the greenhouse. Regular attention to ventilators or the use of the automatic ventilators available to amateur growers avoids this problem.

Lack of light

House plant species are sometimes placed in parts of the house unsuitable for their ideal growth. For example, a poinsettia needs high light levels. Plants outdoors may be subjected to the same oversight. *Pelargoniums* used as bedding plants should be given full sunlight and will develop a pale foliage colour if placed in a shady place. *Impatiens*, on the other hand, is able to withstand considerable shade and maintain its rich dark-green foliage.

Overwatering

Overwatering replaces the air spaces in soil and growing composts with water, thus preventing root respiration which is needed to supply energy for root growth and nutrient uptake. Overwatering symptoms may include the following.

- The whole plant may wilt, the lower leaves turn yellow and drop.
- New foliage may have brown spots.
- The whole plant may become stunted, and stems and roots become brown and decayed.

Underwatering

The plant needs sufficient water to carry nutrients around, to be present as an ingredient for making sugar, to transpire from the leaf in order to keep a desirable leaf temperature and to maintain turgidity in some plant tissues. In some plant species, leaves change from shiny to dull as a first signal of water stress and also may change from bright green to a grey green. New leaves wilt, but in species such as holly and conifers only the very youngest leaves wilt. Flowers may fade quickly and fall prematurely. Older leaves often turn brown, dry and fall off. Digging a few centimetres into the soil may indicate the need for watering with shallow rooted perennials and annual border plants. Shrubs with deep roots rarely need watering, although transplanted older shrubs may show summer water-stress for a number of years (see also Chapters 9 and 19).

Oedema

Oedema is seen as raised corky spots on the undersurface of leaves. Species such as pelargonium (see Figure 15.23), rhododendrons, begonias, pansies, violets and some fleshy-leaved plants such as *Peperomia* are affected. Orchids can show oedema on their petals. Oedema occurs when the roots' ability to supply water exceeds the leaves' ability to release the water by transpiration. Conditions favouring oedema occur most commonly in late winter and early spring especially during extended periods of cool, cloudy weather. Warm, moist soil occurring alongside cool, moist air brings on the condition most severely. The symptoms are commonly seen in unheated greenhouses. The problem can be greatly reduced by glasshouse heating and automatic venting.

Figure 15.23 **Raised oedema spots** on lower leaf surface of pelargonium. This symptom superficially resembles rust pustules

Symptoms of disease and physiological disorders

Below in Table 15.2 is a summary of the most important symptoms to help the reader 'home-in' on disease problems and physiological disorders.

Table 15.2 Some symptoms of diseases and physiological disorders

Symptom	Cause	Other cause
Leaf spot	fungus e.g. apple scab	bacterial canker (*Prunus*)
Raised leaf spots	rusts	oedema (corky spots)
White covering on leaf	powdery mildew – upper	spraying hard water
	downy mildew – lower	
Leaf yellowing	low nitrogen levels	root disease
Brown edge to the leaf	low potassium	
Leaves curl and go brown	underwatering	
Dry, crumbling leaves	plants overheated	too much fertilizer
Yellow leaf veins	low magnesium/iron	
Dark coloured leaves	low phosphorus	
Lower leaves yellow	wilt fungus	overwatering
Yellow/ green leaf mottle	virus mosaic	mutation/chimaera
Fruit spots	fungus	bitter pit (apple)
Sunken fruit lesions	blossom end rot (tomatoes)	
Bud or leaf drop	sudden change of temperature	
Stems elongated	too little light	
Whole plant wilts	severe underwatering	wilt disease, vine weevil grubs
Fluffy mould	*Botrytis* (grey)	*Penicillium* (blue)
Brown stem lesions	tomato mosaic virus	
Swollen woody stems	fungal/bacterial canker	
Oozing from woody stems	bacterial canker/fireblight	
Brown roots	root rot	overfertilizing

Check your learning

1. Define the term ‘disease’.
2. State the damage caused by three named fungal diseases.
3. Describe the life cycle of one named fungal disease.
4. Describe how the life cycle in the above fungal example is related to its control.
5. Describe the available control measures for the disease in question 3.
6. State the damage caused by one named bacterial disease.
7. Describe one method of reducing the damage caused by the above-named bacterium.
8. Explain how fungal resistance to fungicides can be reduced.
9. Explain the difference in the symptoms caused by downy mildews and powdery mildews.
10. Explain what disease danger the roots of a dead tree represent to plants in its vicinity.

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Chapter 16 Plant protection

Summary

In the three preceding chapters important weeds, pests and diseases were described with an emphasis on symptoms and damage, life cycles and with brief comments on control relevant to the particular causative organism.

This chapter includes the following topics:

- **Physical control**
- **Cultural control**
- **Biological control**
- **Chemical control**
- **Plant selection for resistance**
- **Integrated control**
- **Supervised control**
- **Legislative control**

with additional information on environmentally sustainable practices:

- **Benefits or problems and hazards associated with controls**
- **Minimization of risks to humans and the environment**
- **Natural balances and their disturbance**
- **Maintenance and restoration of balances**
- **Selection of plants to avoid plant health problems**

Figure 16.1 Biological control in a **greenhouse**

A good general principle for the gardener or grower is that they use as many different kinds of control as possible within a plant or crop cycle to bring about precise and efficient control for a pest or disease. And so a parasitic wasp may be encouraged or applied against an aphid attack, whilst also considering a cultural control such as the removal of alternate host weeds or a carefully considered pesticide if this is needed.

A second principle highlights a distinction between pests and diseases. For pests, **biological control** is a major form of control in the natural environmental habitat (and to a similar extent in the garden/commercial holding when predators and parasites are encouraged). For diseases, however, in the natural environment, **plant resistance** (rather than biological control) is the important control method. In gardens and horticultural units, plants which have not been highly bred often exhibit a high level of resistance similar to their wild relatives. But intensively bred cultivars of annual flowers, annual vegetables and fruits may largely lack this important form of control.

A third principle suggests that a programme of control against a pest or disease should consider non-pesticide controls first before relying on the alternative route. It has to be admitted that few people would disagree with the principle, but many growers will be able to cite instances when this idealistic attitude has left them with serious pest or disease problems on their hands (such as slugs in wet summers). In the 'supervised control' section of this chapter, there is a brief discussion of 'economic damage'. At relevant points in this chapter, distinction is drawn between those measures available to the amateur gardener and those used by the professional grower.

Physical control

Physical control is a material, mechanical or hand control where the **pest** is directly blocked, or destroyed.

Benefits. Physical controls are long-lasting and need little maintenance.

Limitations. Some physical methods are expensive to set up.

Warm water treatment

This method is used for pests such as stem and bulb nematodes in narcissus bulbs. Immersion of bulbs for 2 hours at 44°C controls the pest without seriously affecting bulb tissues. Chrysanthemum stools and strawberry runners may be similarly treated, using temperature and time combinations favourable to each crop. Viruses (such as aspermy virus on chrysanthemum) are more difficult to control, since viruses are more intimately associated with the plant nuclei. Virus concentrations may be greatly reduced in meristems of stock plants grown at temperatures of 40°C for about a month. This has enabled the production of tissue-cultured disease-free stock material of both edible and non-edible crops (see **tissue culture**, p177).

Flame throwers are used for the control of weeds when other methods, such as cultivation, hand-weeding or herbicidal control are not considered suitable.

Partial soil sterilization

Commercial greenhouse soils are commonly sterilized by high-pressure steam released to penetrate downwards into the soil, which is covered by heat resistant plastic sheeting (sheet steaming). The steam condenses on contact with soil particles, and moves deeper only when that layer of soil has reached steam temperature. Some active soil pests, such as symphilids, may move downwards ahead of the steam 'front'.

The temperatures required to kill most nematodes, insects, weed seeds and fungi are 45°C, 55°C, 55°C and 60°C respectively. Beneficial bacterial spores are not killed below 82°C, and therefore growers attempt to reach, but not exceed, this soil temperature. Most mycorrhizal fungi are unfortunately killed by this process.

In this way, organisms difficult to sterilize, such as fungal sclerotia, Meloidogyne and Verticillium in root debris, may be killed. Sheet steaming is effective only to depths of about 15 cm, and its effect is reduced when soil aggregates (see p311) are large and hard to penetrate, or when soils are wet and hard to heat up. When soil pests and diseases occur deep in the soil, heating **pipes** may be placed below the soil surface, as grids or spikes, to achieve a more thorough effect. The 'steam-plough' achieves a similar result, as it is winched along the greenhouse. If soil is to be used in growing composts it should be sterilized (see sterilizing equipment). The clear advantage of soil sterilization may occasionally be lost if a serious soil fungus (such as *Pythium*) is accidentally introduced into a crop where it may quickly spread in the absence of fungal competition.

Barriers

A physical **barrier** such as a fence sunk into the ground deters rabbits and deer. Fine screens placed over ventilation fans help prevent the entry of pests, such as fungus gnats, from outside a greenhouse or mushroom house. Pots placed on small stands in water-filled trays are freed from the visitations of red spider mite and adult vine weevils. Peach leaf curl is a difficult disease to control. A plastic sheet placed over the peach or almond over winter will greatly reduce both arrival of spores and the moisture needed for infection of the buds.

Traps

Pheremone traps containing a specific synthetic chemical similar to the attractant odour of a female moth are used in apple orchards to lure male codling and tortrix moths onto a sticky surface, thus enabling an accurate assessment of their numbers and therefore more effective control. Comparable traps are available against plum moth and pea moth.

A rodent trap is available that entices the rat or mouse into a container with suitable bait and then the pest is killed humanely with a high voltage charge.

Allotment owners sometimes use containers such as plastic milk bottles or jam jars sunk into the ground that when part-filled with beer, attract slugs. Between two rows of tomatoes, a ‘sacrificial’ row of lettuce can be grown to attract slugs (see Figure 16.2), which can then be controlled in a trap (see Figure 16.2).

(a) (b)

(c) (d)

Figure 16.2 (a) **Horticultural fleece** used to protect from pests (b) **Plastic guard** used against rabbits and deer (c) **Lettuce** planted to attract slugs away from tomatoes (d) **Slug trap** that avoids bird-poisoning

Deterrents

Measures here warn off the pest in a chemical or physical way. **Ultrasonic** devices create high frequency sounds, unheard by humans, but offensive to animals such as rats and mice. The odour from onions inter-planted with carrots may deter the carrot fly from attacking its host crop. Marigolds planted in amongst crops deter whitefly and aphids. A spray repellent using an extract from a *Yucca* species is used to deter slug attack.

Cultural control

Cultural control is a procedure, or manipulation of the growing environment that results in pest, disease or weed control.

Horticulturists, in their everyday activities, may remove or reduce damaging organisms in many different ways and thus protect the crop. Below are described some of the more important methods used.

Benefits. Fit in with daily routines. Have a long-lasting effect.

Limitations. May be time-consuming.

Cultivation

Ploughing and **rotavating** of soils enables a physical improvement in soil structure as a preparation for the growing of crops. The improved drainage and tilth may reduce damping-off diseases, disturb annual and perennial weeds, such as chickweed and couch-grass, and expose soil pests, such as leatherjackets and cutworms, to the eager beaks of birds. Repeated **rotavation** may be necessary to deplete the underground rhizomes or tap roots of perennial weeds, such as couch-grass. **Hoeing** annual weeds is an effective method, provided the roots are fully exposed, and the soil dry enough to prevent root re-establishment.

Soil fertility

While the correct content and balance of major and minor nutrients (see Chapter 21) in the soil are recognized as vitally important for optimum crop yield and quality, it should be remembered that plant resistance to pests and diseases is also affected by nutrient levels in the plant. Excessive nitrogen levels, causing soft tissue growth, encourage the increase of insects such as peach-potato aphid, fungi such as grey mould, and bacteria such as fireblight. Adequate levels of potassium, on the other hand, help control fungal diseases, such as Fusarium wilt on plants such as peas, tomatoes and carnation, and tomato mosaic virus. Fertility provided by composted material usually provides nutrients to the plant at the correct concentrations.

Club root disease of brassicas is less damaging in soil with a pH greater than 6, and lime may be incorporated before planting these crops to achieve this aim. Amenity horticulturists apply mulches, such as composted bark, grass cuttings or straw, to bare soil in order to control annual weeds by excluding the source of light. Black polythene sheeting is used in soft fruit production to achieve a similar objective.

Crop rotation

Some important soil-borne pests and diseases attack specific crops, such as potato cyst nematode on potato and club root on cruciferous plants. As they are soil-borne, they are slow in their dispersal, but are difficult to control. By the simple method of planting a given crop in a different plot each season, such pests or diseases are excluded from their preferred host crop for a number of years, during which their numbers will slowly decline. A gardener often creates five or six plots (sometimes bounded by wooden planking) to achieve successful rotation. Plants belonging to the same plant families fit into the rotation system. They have the same sensitivity to particular pests and diseases. Potatoes, tomatoes, peppers and aubergines are all members of the Solanaceae. Melons, marrows, courgettes and cucumbers all belong to the Cucurbitaceae. When considering a rotation plan, it is advisable to confine members of the same family to the same plot in the same growing season. Rotation does not work well against unspecific problems, such as grey mould, which may attack a wide range of plant families. Rotation is also not likely to be effective against rapidly spreading organisms such as aphids.

Figure 16.3 **Rotation plots** used to reduce pest and disease problems

The **sclerotium** stage of white rot disease (*Sclerotum cepivorum*) on onion and related crops, such as leeks, garlic, chives and shallots, is able to survive in the soil for 15 years or more. It can be seen that a very long rotation period would be necessary to remove this serious disease. A six year rotation is not normally sufficient.

Planting and harvesting times

Some pests emerge from their overwintering stage at about the same time each year, such as cabbage root fly in late April. By planting early to establish tolerant brassica plants before the pest emerges a useful supplement to chemical control is achieved. The deliberate planting of early potato cultivars enables harvesting before the maturation of potato cyst nematode cysts, so that damage to the crop and the release of the nematode eggs is avoided. Annual weeds may be induced to germinate in a prepared seedbed by irrigation. After they have been controlled with a contact herbicide, such as paraquat, a crop may then be sown into the undisturbed bed or stale seedbed, with less chance of further weed germination.

Clean seed and planting material

Seed producers take stringent precautions to exclude weed seed contaminants and pests and diseases from their seed stocks. While weed seeds are, in the main, removed by mechanical separators, and insects can be killed by seed dressings, systemic fungal seed infections, such as celery leaf spot disease in celery seed, are best controlled by immersion of dry seed in a 0.2 per cent thiram solution at 30°C for 24 hours (**thiram soak treatment**). The seed is then re-dried. A similar treatment is often given for carrot and parsley seed.

Equal care is taken to monitor seed crops likely to carry virus disease (such as tomato mosaic). Curative control by dry heat at 70°C for four days is usually effective, although it may reduce subsequent seed germination rates.

Vegetative propagation material

Vegetative propagation material is used in all areas of horticulture, such as bulbs (tulips and onions), tubers (dahlias and potatoes), runners (strawberries), cuttings (chrysanthemums and many trees and shrubs) and graft scions in trees. The increase of nematodes, viruses, fungi and bacteria by vegetative propagation is a particular problem, since the organisms are inside the plant tissues, and since the plant tissues are sensitive to any drastic control measures.

Inspection of introduced material may greatly reduce the risk of this problem. Soft, puffy narcissus bulbs, chrysanthemum cuttings with an internal rot, whitefly or red spider mite on stock plants, virus on nursery stock, are all symptoms that would suggest either careful sorting, or rejection of the stocks.

Accurate and rapid methods of virus testing (using test plants, electron microscopy and staining by ELISA techniques) now enable growers to learn quickly the quality of their planting stocks. Fungal levels in cuttings (such as *Fusarium* wilt of carnations) can be routinely checked by placing plant segments in sterile nutrient culture.

The quality of vegetative material is monitored in the UK by the **Plant Health Propagation Scheme**. In particular, it supervises the provision of six quality levels of plant material (Foundation, Super Elite, Elite, A, Approved and Healthy grades) for the soft fruit, top fruit and bulb industries.

Hygienic growing

During the crop, the grower should aim to provide optimum conditions for growth. Water content of soil should be adequate for growth (see **field capacity**), but not so excessive that root diseases (such as damping off in pot plants, club root of cabbage and brown root rot of conifers) are actively encouraged.

Water sources can be analyzed for *Pythium* and *Phytophthora* species if damping off diseases are a constant problem. Covering and regular cleaning of water tanks to prevent the breeding of these fungi in rotting organic matter may be important in their control. Seed trays and pots should be washed to remove all traces of compost that might harbour damping off disease.

Conifer nursery stock grown on raised gravel beds is less likely to suffer the water-borne spread of conifer brown rot. Many protected crops are grown in isolated beds or peat modules to reduce spread of wilt-inducing organisms (such as *Fusarium* spp.). Gooseberry sawfly caterpillars can be removed in spring from leaves found on the lower centre stems of the gooseberry. This action helps prevent subsequent invasions by the pest in the summer months.

High humidity encourages many diseases. In greenhouses, the careful timing of daily overhead irrigation and of ventilation (to reduce overnight condensation on leaves or flowers) may greatly reduce levels of diseases, such as grey mould on pot plants or downy mildew on lettuce. The slow drawing-back of motorized **thermal screens** high above commercial glasshouse crops (so as to prevent condensation problems) has contributed greatly to the reduction of disease.

Reducing spread of pests and diseases

The spread of pests and diseases from plant to plant or field to field can be slowed down. Tomato mosaic virus spread may be reduced by leaving suspect plants till the end of de-leafing or harvesting. Washing knives and hands regularly in warm, soapy water will reduce subsequent viral spread. Soil-borne problems, such as club root, eelworms and damping off diseases, are easily carried by boots and tractor wheels. Foot and wheel dips, containing a general chemical sterilant, such as formaldehyde, have been successfully used, especially in preventing damping off problems in greenhouses.

Alternate hosts

Alternate hosts harbouring pests and diseases should be removed where possible. A few examples of many alternate hosts are given here. Soil-borne problems, such as club root of cabbage and free-living eelworms on strawberries are harboured by shepherd's purse (*Capsella bursa-pastoris*) and chickweed (*Stellaria media*) respectively. Groundsel (*Senecio vulgaris*) is an alternate host of rust on cinerarias, while docks (*Rumex spp.*) act as a reservoir of dock sawfly, which damages young apple trees.

Figure 16.4 A **sowthistle** acting as alternate host to glasshouse whitefly

Removal of infected plant material

With rapid-increase problems, such as peach-potato aphid and white rust of chrysanthemum fungus in greenhouses, removal of affected leaves is practicable in the early stages of the problem, but becomes progressively unmanageable after the pest or disease has increased and dispersed throughout the plants. Slow-increase problems, such as Fusarium wilt disease on tomatoes or carnations and vine weevil larvae found damaging roots of plants such as primulas and begonias, may be removed throughout the crop cycle, but the infected roots and soil must be carefully placed in a bag to prevent dispersal of the problem. In commercial outdoor production, labour costs usually prevent such removal during the growing season. However, removal is achieved chemically in some situations. The destruction of blight-infected potato foliage with herbicide such as diquat prior to harvest reduces infection of the tubers. Burning of post-harvest leaf material and lifting of root debris after harvest (against grey mould on strawberries and club root on brassicas respectively) may help prevent problems in the next crop.

In fruit tree species such as apple, routine pruning operations may remove serious pests such as fruit tree red spider mite, and diseases such as canker and powdery mildew. Pruning should also aim to reduce the density of shoots in the centre of the tree. The reduction in humidity provides a microenvironment less favourable to disease increase.

Tree stumps harbouring serious underground diseases such as honey fungus should be removed manually or using a mechanical stump grinder. Making a feature of an infected stump by placing a bird table on it is one of the least recommended activities in gardening.

Safe practice

In physical/cultural control, some **hazards** are:

- Unsafe use of cultivation equipment, such as ploughs, rotavators, flame throwers and steam sterilization equipment, used to control weeds, pests and diseases.
- Unsafe removal of infected trees.
- Unsafe burning of infected plant material.

When using cultural control, risks can be **minimized** by:

- following guidelines for the safe use of ploughs and rotavators to avoid damage to humans and adjoining crops or plantings;
- following guidelines for the safe use of flame throwers and steam sterilization equipment;
- taking safety precautions when removing infected shrubs and trees;
- carefully transferring infected plants to dumps or compost sites, thus avoiding the spread of infections.

Biological control

Biological control is the use of natural enemies to reduce the damage caused by a pest (or disease).

Benefits. Non-toxic, no build-up of resistant pests and diseases.

Limitations. Needs careful introduction and knowledge of life cycles. Can easily be affected by pesticides.

There are two sources of ‘natural enemies’ to pests, the local species and the exotic ones. Many pests of outdoor horticultural crops such as peach-potato aphid are **indigenous** (i.e. they are present in wild plant communities in the UK). Such pests are often reduced in nature by other organisms which, as predators, eat the pest, or, as parasites, lay eggs within the pest. These beneficial organisms, found also on horticultural crops, are to be encouraged and in some cases are deliberately introduced. A range of important organisms useful in horticulture is now described in some detail.

Indigenous predators and parasites

Wild birds

It has been shown that a pair of blue tits can consume 10 000 caterpillars and one million aphids in a 12 month period. The installation of tit boxes is a worthwhile activity. Wrens, thrushes and blackbirds similarly contribute to the control of garden insects.

Hedgehogs

Hedgehogs belong to the insectivore group of mammals, but are omnivorous. Although their preferred diet is insects (up to 200 g per day) they will eat slugs. Care must be taken that they are not exposed to dead slugs which have consumed slug bait containing methiocarb or methaldehyde, as these would be toxic to the hedgehog. Hedgehogs are encouraged to enter gardens by means of small holes cut into the base of a fence panel. Within gardens, heaps of logs and piles of leaf litter in a quiet location are suitable for their daytime and overwintering retreat. Wooden hedgehog shelters are commercially available.

The black-kneed capsid

The **black-kneed capsid** (*Blapharidopterus angulatus*) is an insect found on fruit trees alongside its pestilent relative, the common green capsid. It eats more than 1000 fruit tree red spider mites per year. Its eggs are laid in August and survive the winter. Winter washes used by professional horticulturalists against apple pests and diseases often kill off this useful insect. The closely related **anthocorid bugs**, such as *Anthocoris nemorum*, are predators on a wide range of pests, such as aphids, thrips, caterpillars and mites, and have recently been used for biological control in greenhouses.

Lacewings

Lacewings, such as *Chrysopa carnea*, lay several hundred eggs per year on the end of fine stalks, located on leaves. Several are useful horticultural predators, their hairy larvae eating aphids and mite pests, often reaching the prey in leaf folds where ladybirds cannot reach.

Ladybird beetle

The 40 species of **ladybird** beetle are a welcome sight to the professional horticulturist and lay person alike. Almost all are predatory. The red two-spot ladybird (*Adalia bipunctata*) emerges from the soil in spring, mates and lays about 1000 elongated yellow eggs on the leaves of a range of weeds, such as nettles, and crops such as beans, throughout the growing season. Both the emerging slate-grey and yellow larvae and the adults feed on a range of aphid species. Wooden ladybird shelters and towers are now available to encourage the overwintering of these useful predators.

A worrying development in the last few years has been the rapid spread and increase of the **harlequin ladybird** from South-East Asia. This species is larger (6–8 mm long) and rounder than the two-spot species (4–5 mm). It has a wider food range than other ladybird species, consuming other ladybird's eggs and larvae, and eggs and caterpillars of moths. Furthermore, it is able to bite humans and be a nuisance in houses when it comes out of hibernation.

Carabid beetles

The **ground beetle** (such as *Bembidion lampros*), a 2 cm long black species (see Figure 16.5), is one of many active carabid beetles that actively predates on soil pests such as root fly eggs, greatly reducing their numbers.

Hoverflies

Superficially resembling wasps, these are commonly seen darting or hovering above flowers in summer. Several of the 250 British species, such as *Syrphus ribesii*, lay eggs in the midst of aphid colonies, and the legless light-green coloured grubs consume large numbers of aphids.

(a) (b)

Figure 16.5 (a) Predatory **ground beetle** (b) **Ichneumon wasp** parasitic on caterpillars

The flowers of some garden plants are especially useful in providing pollen for the adults and therefore encouraging aphid control in the garden. Summer flowering examples are poached-egg plant (*Limnanthes douglasii*), baby-blue-eyes (*Nemophila menziesii*) and Californian poppy (*Romneya coulteri*). Later summer and autumn examples are *Phacelia tanacetifolium* and ice plant (*Sedum spectabile*).

Mites and spiders

Predatory **mites** such as *Typhlodromus pyri* eat fruit tree red spider mite and contribute importantly to its control. The numerous species of web-forming and hunting **spiders** help in a very important but unspecific way in the reduction of all forms of insects.

Wasps

The much maligned **common wasp** (*Vespula vulgaris*) is a voracious spring and summer predator on caterpillars, which are fed in a paralyzed state to the developing wasp grubs. **Digger wasps** also help control caterpillar numbers and benefit from dead hollow stems of garden plant which they use as nests all year round.

There are about 3000 **parasitic wasp** species of the families Ichneumonidae, Braconidae and Chalcidae found on other insects in Britain. Ichneumons (*Opion spp*. see Figure 16.5) lay eggs in many moth caterpillars. The braconid wasp (*Apanteles glomeratus*) lays about 150 eggs inside a cabbage white caterpillar and the parasites pupate outside the pest's dead body as yellow cocoon masses. The chalcid (*Aphelinus mali*) parasitizes woolly aphid on apples.

The spiracles of insects provide access to specialized **parasitic fungi**, particularly under damp conditions. In some years, aphid numbers are quickly reduced by the infection of the fungus *Entomophthora aphidis*, while codling moth caterpillars on apple may be enveloped

Figure 16.6 Swollen **aphid** parasitized by tiny wasp by *Beauveria bassiana*. Cabbage white caterpillar populations are occasionally much reduced by a **virus**, which causes them to burst.

Increased attention is being given by horticulturalists to the careful selection of pesticides (if they are needed) to avoid unnecessary destruction of indigenous predator and parasite numbers (see also p271).

In recent years, commercial firms have begun to make available **ready-to-use products** containing indigenous predators or parasites to outdoor growers. Examples are two-spot ladybird, lacewing larvae and three nematode parasites (against slugs, vine weevil larvae and flea beetles (see also Table 16.1).

Table 16.1 Biological control organisms reared commercially for use in horticulture

Pest or disease	Crop	Control	Type
Aphids	G	*Aphidoletes aphidimyza*	Midge
	G	*Aphidius spp.*	Wasp
	Ch	*Verticillium lecani*	Fungus
Caterpillars	B	*Trichogramma brassicae*	Wasp
	G	*Bacillus thuringiensis*	Bacterium extract
Flea beetle	B	*Howardula phyllotreta*	Nematode
Glasshouse whitefly	T	*Macrolophus caliginosus*	Anthocorid bug
	G	*Encarsia formosa*	Wasp
Leaf miner	T, C, F	*Dacnusa sibirica*	Wasp
	T, C, F	*Diglyphus isaea*	Wasp
Leaf hopper	T	*Anagrus atomus*	Wasp
Mealy bug	G	*Cryptolaemus montrouzieri*	Ladybird
	G	*Leptomastix dactylopii*	Wasp
Red spider mite	G	*Phytoseiulus persimilis*	Mite
	G	*Amblyseius calfornicus*	Mite
	G	*Feltiella acarisuga*	Midge
	T, C, F	*Therodiplosis persicae*	Midge
Sciarid fly	G	*Steinernema feltiae*	Nematode
	G	*Hypoaspis miles*	Mite
	G	*Bacillus thuringiensis strain*	Bacterial extract
Silver leaf fungus	Tf	*Trichoderma viride*	Fungus
Slugs	G	*Phasmarhabditis hermaphrodita*	Nematode
Thrips	C, F, P	*Neoseiulus cucumeris*	Mite
	C, F	*Orius laevigatus*	Anthocorid bug
Tomato mosaic virus	T	mild strain of virus	
Vine weevil	G	*Steinernema capsicarpae*	Nematode

Key; B: brassicas; T: tomato; C: cucumber; P: sweet peppers; F: flowers; Tf: top fruit; Ch: chrysanthemum; G: general use.

Exotic predators and parasites

In greenhouses and polythene tunnels, high temperatures often all year round and sub-tropical species of plants bring with them exotic pests and diseases. Further, the increase of both pests and diseases is much quicker than comparable pests or diseases growing outdoors. Also, these greenhouse inhabiting organisms have, over the last half-century, developed resistance to almost all available pesticides.

Biological control of exotic pests requires exotic predators and parasites. And so the health of the major greenhouse crops is in large measure due to two organisms: a South American mite which eats all stages of the glasshouse red spider mite, and a tiny South-East Asian wasp that parasitizes the glasshouse whitefly.

The conditions in a greenhouse have two **advantages** for biological control. Firstly, the environment is relatively isolated so that the controlling organisms are not likely to disappear. Secondly, the glasshouse environment is relatively stable and allows biological control to be more measured (than in the outdoor situation) with interactions between pests and their predator or parasite being more predictable.

Almost all commercial production of glasshouse crops in the UK now uses biological control. The two commonest biological control organisms are described below in some detail. Much more information is available from commercial companies or from the Internet. A more extensive listing of commercially available biological control species is given in Table 16.1.

Phytoseiulus persimilis (see Figure 16.7)

This is a 1 mm globular, deep orange, predatory tropical mite used in greenhouse production to control glasshouse red spider mite (see p224). It is raised on spider mite-infected beans and then evenly distributed throughout the crop, such as cucumbers, at the rate of about one predator per plant. Some growers who have suffered repeatedly from the pest first introduce the red spider mite throughout the crop at the rate of about five mites per plant a week before predator application, thus maintaining even levels of pest–predator interaction. The predator's short egg–adult development period (7 days), laying potential (50 eggs per life cycle) and appetite (five pest adults eaten per day), explain its extremely efficient action.

(a)

(b)

(c)

Figure 16.7 Glasshouse **red spider mite predator.** (a) Phytoseiulus predator eating glasshouse red spider mite (b) Eggs and young of Phytoseiulus (c) Application of Phytoseiulus to crop

(a)

(b)

(c)

Figure 16.8 Glasshouse **whitefly parasite**. (a) Encarsia wasp laying an egg into a whitefly scale (b) Parasitized whitefly scale has turned black in colour (c) Application of Encarsia to a crop (as blackened whitefly scales)

Encarsia formosa (see Figure 16.8)

This is a small (2 mm) wasp which lays an egg into the glasshouse whitefly **scale** (see p210), causing it to turn black and eventually to release another wasp. This parasite is raised commercially on whitefly-infested tobacco plants. It is introduced to the crop, such as tomato, at a rate of about 100 blackened scales per 100 plants. The parasite's introduction to the crop is most successful when the whitefly levels are low (recommended less than one whitefly per 10 plants). Its mobility (about 5 m) and successful parasitism are most effective at temperatures greater than 22°C when its egg-laying ability exceeds that of the whitefly.

The wasp lays most of its 60 or more eggs within a few days of emergence from the black scale. Thus, a series of weekly applications from late February onwards ensures that viable eggs are laid whenever the susceptible whitefly scale stage is present. The appearance of newly infected **black scales** on leaves is often taken as an indication that parasite introductions can be stopped.

An understanding of each pest's and each biological control organism's life cycle is vital to ensure success in control. A combination of biological methods may be used on some crops, such as chrysanthemums, tomatoes, peppers, aubergines and cucumbers in order to simultaneously control a range of organisms occurring on the crop at the same time (see Table 16.1, and **integrated control**, p292). Several specialist firms now have contracts to apply biological control organisms to greenhouse units. There are several practical points that confront growers in both the outdoor and the glasshouse situation.

Safe practice

The main problems with biological control are:

- Unsuccessful application of biological control organisms that lead to a severe pest problem.
- Introduction of a biological control organism that subsequently kills desirable or beneficial organisms in the environment.

These can be **minimized** by:

- understanding both the pest's and predator/parasites' life cycles in order to achieve reliable control;
- carefully choosing the best predator or parasite for the problem pest or disease concerned;
- taking care that environmentally useful species are not subject to the attacks of the predators and parasites.

In most horticultural situations, there are important examples of **natural balance** between species.

- With pests, their naturally occurring predators and parasites are an important form of crop protection (see page 271).
- With diseases, naturally occurring predators and parasites are less common, but the nutritional condition of the plant and the resulting naturally occurring bacterial and fungal populations on leaf, stem and root surfaces (see phyllosphere p235and rhizosphere p322) often help slow a disease's progress.
- The garden represents a complex situation. There may be plant species present from every continent (see p73), and any of these plant species may be accompanied by a specific pest from its country of origin. Plant species that have been present in the UK for many years (such as apple) often have beneficial predators and parasites introduced accidentally or deliberately, from their country of origin, that limit pest numbers. It is quite likely, however, that for more recently imported plant species, there may not be appropriate predators or parasites to control an introduced pest occurring on the plant species in the British Isles.

Some horticultural practices can **disturb natural balances**.

- In a natural habitat such as woodland, a **climax population** of plants and animals develops (see p52). Here, a complex balance exists between indigenous pests and their predators/parasites. The food webs (see p53) include several types of predator/parasite found on each plant species that limit (but do not eliminate) the pests. This development of food webs is **not** achieved to such an extent in most gardens since the natural succession of wild plant species mentioned above is not desirable to gardeners as they aim for optimum production of edible crops or for an aesthetic layout of decorative plants free from weeds (see also Chapter 3).
- Regular movement or removal of cultivated plants and weeds without particular thought to the natural balance between predator/parasites and pests will make pest attacks more likely in the garden/nursery situation.
- The removal of the rotting hollow stems of herbaceous perennials and branches of decaying wood which are common sheltering sites for predatory beetles and centipedes reduces their control potential.
- In a similar way, removal of old plants such as brassicas or bedding plants in autumn may take away the parasitized aphids or caterpillars that would normally serve as the next year's control measures.
- The absence in gardens of plant species acting as a pollen food source to adults such as hoverflies may delay the emergence of their predatory larvae amongst aphid populations.
- The lack of good soil structure (see p310) resulting from poor cultivation or inadequate incorporation of organic matter in a garden may hinder the movement of predatory animals in their search for soil pests.
- A poor physical preparation of soil, and lack of attention to pH and nutrient levels in soil may result in poor soil microbial action (see p321).

- The repeated planting of crops or annual bedding plants into the same area of soil often leads to serious attacks of persistent soil-borne pests or diseases. Notable examples are club root disease on brassicas (see p228) and potato cyst nematode pest on potatoes (see p244). A comparable situation is found when young trees and shrubs (such as roses) are planted into a soil previously occupied by an old specimen of the same plant species, with the resulting problem called '**replant disease**' caused by high level of *Pythium* fungus (see p246).
- The unconsidered use of **pesticides** may result in a rapid decrease in predators and parasites and may considerably delay their appearance and build-up the following growing season.

The natural balances of organisms can be **maintained** and **restored** in order to reduce pesticide use. At the private garden level, there are an increasing number of practices being used that encourage natural balances in order to reduce pesticide use. These physical and cultural methods have been described earlier.

Chemical control

Chemical control is the use of a chemical substance intended to prevent or kill a destructive pest, disease or weed.

Benefits. Produce a rapid control. Are easily accessible.

Limitations. Can be dangerous to humans, animals and plants. Can cause resistant strains of pests and diseases to develop.

In past centuries pests, such as apple woolly aphid, were sprayed with natural products, such as turpentine and soap, while weeds were removed by hand. In the nineteenth century, the chance development of Bordeaux mixture from inorganic copper sulphate and slaked lime, and in the early twentieth century the expansion of the organic chemical industry, enabled a change of emphasis in crop protection from cultural to chemical control.

The word '**pesticide**' is used in this book to cover all crop protection chemicals, which include **herbicides** (for weeds), **insecticides** (for insects), **acaricides** (for mites), **nematicides** (for nematodes) and **fungicides** (for fungi). About 2.5 million tonnes of crop protection chemicals are used worldwide each year, about 40 per cent being herbicides, about 40 per cent insecticides and about 20 per cent fungicides. Health and Safety aspects of chemical control are described at the end of the 'chemical control' section.

Chemical sterilization

This involves the use of substances toxic to most living organisms and must be used only by specialist operators and professional horticulturists. The chemical's toxicity to plants also means that they can only be applied to soil or compost that has no crops.

With the recent discontinuation of methyl bromide, two remaining soil applied ingredients are **dazomet** (applied outdoors and in protected crops as a granule against soil-borne insects, fungi, and weed seeds) and **dichloropropene** (applied outdoors as a vapour-releasing liquid by an injection apparatus against nematodes). The fumigant action of these substances is prolonged by rolling the soil after application. Precautions such as rotavating the soil need to be taken several weeks after application, to release any chemical residues before succeeding crops can be planted.

Professional horticulturists sterilize greenhouse structures using toxic compounds, such as **formaldehyde** and burning **sulphur**. Common pests and diseases, such as whitefly, red spider mite and grey mould, may be greatly reduced by this intercrop method of control.

European legislation saw the withdrawal of **methyl bromide** in 2005 on the grounds of human and environmental safety. Whilst being very effective as a sterilant of growing media, methyl bromide had three serious drawbacks. It was very poisonous to man and animals. As a gas, it found its way into the atmosphere. Lastly, its chemical similarity to the chlorinated hydrocarbons used in refrigerator coolants meant that it was held partly responsible for the 'global warming' phenomenon. These three factors combined to rule out its continued use in horticulture.

Active ingredients

Each container of commercial pesticide contains several ingredients. The active ingredient's role is to kill the weed, pest or disease. More detailed lists of the range of active ingredients can be found in government literature. The other constituents of pesticides are described under **formulation** (see page 284).

Herbicides

Herbicides that are applied to the seedbed or growing crop must have a **selective** action, i.e. kill the weed but leave the crop undamaged. This selective action may succeed for one of several reasons. Chemicals often affect different plant families in different ways. The broad-leaved turf weed, daisy (*Bellis perennis*, a member of the Asteraceae) is controlled by **2,4-D**, leaving the turf grasses (Graminae) unaffected.

Sometimes plant species are affected by different concentrations of the chemical to a degree that can be exploited. The correct concentration of selective chemicals may be vital if the crop is to remain unharmed.

It can thus be seen that a concentration of 25 ppm of propyzamide applied to lettuce would leave the crop unaffected, but control all the weeds except groundsel.

The following relative values (parts per million, ppm) for the amount of **propyzamide** herbicide required to kill different plant species illustrate this point:

Crops	
carrot	0.8
cabbage	1.0
lettuce	78.0

Weeds	
knotgrass	0.08
black nightshade	0.2
fat hen	0.2
pennycress	0.6
groundsel	78.0

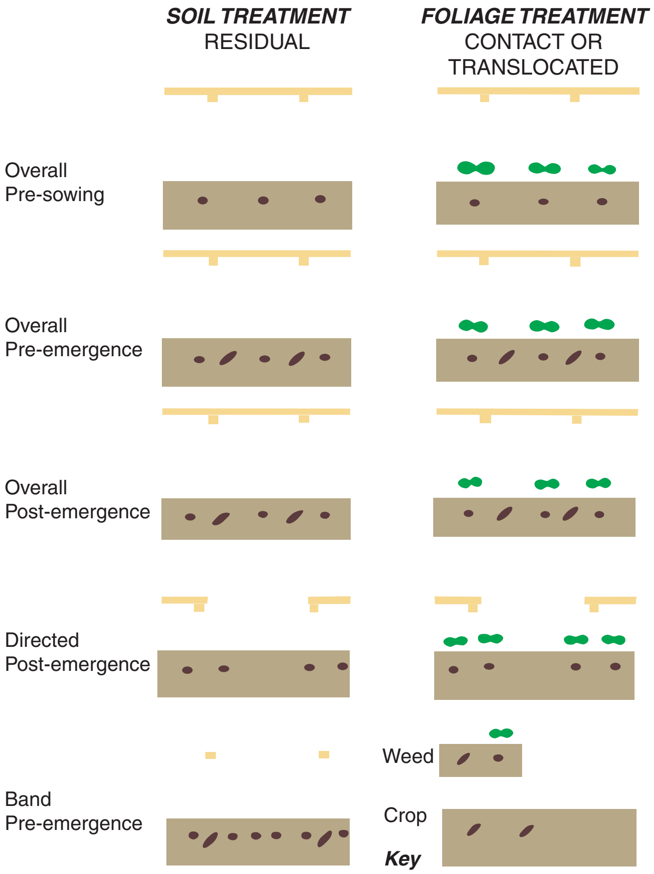

Figure 16.9 **Types of herbicide action**. (Reproduced by permission of Blackwell Scientific Publications)

A third form of selectivity operates by correct timing of herbicide application. A seedbed with crop seeds deep enough below and weed seeds germinating at the surface may receive a contact chemical, such as **paraquat**, which permits germination of the crop without weed competition. A similar effect is achieved when a residual herbicide, such as **propachlor**, is sprayed onto the soil surface to await weed seed germination. The situations for weed control are summarized in Figure 16.9.

Herbicides may conveniently be divided into two main groups: the **foliage-acting**, and the **soil-acting** (residual) chemicals.

Foliage-acting herbicides

These enter the leaf through fine pores in the cuticle or the stomata. The herbicide may move through the vascular system (translocated chemicals) to all parts of the plant before killing plant cells, or it may kill on contact with the leaf. Four active ingredients are described, each belonging to a different chemical group, and each having a different effect on weeds:

- **Glufosinate-ammonium** is a non-selective, non-residual herbicide available to both amateur and professional growers. It is commonly used to kill top growth of a wide spectrum of weeds in stale seedbeds, after harvest, in bush and tree fruit, or in waste land. It is translocated from leaves to the roots. It is quickly absorbed in damp soils, thus allowing planting soon after its application. It should not be used on foliage of vegetables, annual bedding plants or on turf. Similarly, after spraying this chemical, it is crucial that soles of boots contaminated with the chemical do not inadvertently walk across grass.
- **2,4-D** is available to both amateur and professional growers. It is an auxin and causes uncontrolled abnormal growth on leaves, stems and roots of broad-leaved weeds, which eventually die. It is a useful

selective herbicide on turf because the protected meristems of grasses can survive unaffected. It must be kept well away from nearby border plants and from some crops, such as tomatoes, which are extremely sensitive to minute quantities of the chemical. In formulations for the private garden, 2,4-D is mixed with other ingredients, such as **dichlorprop**, to give a broader spectrum of weed control.

- **Amitrole** is available to professional growers. It is used in similar situations to glufosinate-ammonium, but is more residual, surviving in the soil for several weeks. It stops photosynthesis, scorching both grass and broad-leaved weeds (**non-selective**). It is especially useful on uncropped land and, when applied in autumn, it is translocated to underground rhizomes of couch that are then killed. It should not be sprayed onto the foliage of growing plants.
- **Glyphosate** is available to professional and amateur growers. It enters the foliage of actively growing annual and perennial weeds (**unselective**) and is translocated (see p130) to underground organs, subsequently killing them. It is commonly used several weeks before drilling or planting of crops, around perennial plants such as apples or in established nursery stock trees. Glyphosate is inactivated in soils (particularly peats), thus preventing damage to newly sown crops. It may cause damage if spray-drift to adjoining plants or fields occurs.

Soil-acting herbicides

These are either sprayed onto the soil surface or soil incorporated (see Figure 16.9). They must be persistent (**residual**) for several weeks or months to kill the seedling before or after it emerges. Root hairs are the main point of entry. Increased rates may be necessary for peat soils (since they inactivate some herbicides). The chemical may be applied as a spray or granule before the crop is sown (**pre-sowing stage**), before the crop emerges (**pre-emergence**) or, with more selective chemicals, after the crop emerges (**post-emergence**). Three active ingredients are described, each belonging to a different chemical group, and each having a different effect on weeds:

- **Sodium chlorate** is a residual inorganic ingredient available to amateur and professional growers for total weed control in non-crop situations. It enters leaves and roots and has a rapid action. No plantings can be made until six months after the chemical has been applied.
- **Chlorpropham**, available only to professional growers, is a relatively insoluble compound. It is applied as a pre-emergent spray to control many germinating weeds species, such as chickweed, in crops such as bulbs, onions, carrots and lettuce. It usually persists for less than three months in the soil. In light, porous soils with low organic matter, its rapid penetration to underlying seeds make it an unsuitable chemical. Earthworm numbers may be reduced by its presence.
- **Propachlor**, available only to professional growers, is a relatively insoluble compound; it is applied as a pre-sowing or pre-emergent spray to control a wide variety of annual weeds in brassicas, strawberries, onions and leeks. For weeds in established herbaceous borders (such as rose), the granular formulation gives a residual protection against most germinating broad-leaved and grass weeds.

Mixtures

The horticulturist must deal with a wide range of annual and perennial weeds. The somewhat specialized action of some of the herbicide active ingredients previously described may be inadequate for the control of a broad weed spectrum. For example, in the case of chlorpropham, the addition of diuron enables an improved control of charlock and groundsel, while a different formulation containing chlorpropham plus linuron is designed to have greater contact action and thus control both established and germinating weeds in bulb crops. Careful selection of the most suitable mixture of active ingredients is therefore necessary for a particular crop/weed situation.

Insecticides and acaricides

The insects and mites have three main points of weakness for attack by pesticides which are as follows:

- their waxy exoskeletons (see Chapter 14) may be penetrated by wax-dissolving contact chemicals;
- their abdominal spiracles allow fumigant chemicals to enter tracheae;
- their digestive systems, in coping with the large food quantities required for growth, may take in stomach poisons.

Four groups of insecticides are described (details of associated hazards to spraying operators and the general public are discussed later in this chapter):

- An insecticide manufactured from **natural plant extracts** is approved for amateur and professional growers. It contains **alginates/polysaccharides** and acts by blocking the spiracles of pests such as aphids, thrips and mites. It has been given clearance for use by organic growers.
- **Pirimicarb** is available to professional growers. It belongs to the carbamate group. It enters the pest as a stomach poison, acting on the insect's nervous system. It is slightly systemic in plants, and controls many aphid species without affecting beneficial ladybirds. **Aldicarb**, a related chemical, combines a soil action against nematodes with a systemic, broad-spectrum activity against foliar pests, such as aphids, whitefly, leaf miners, mites and nematodes of ornamental plants.
- **Bifenthrin** is available to amateur and professional growers. It belongs to the pyrethroid group. It has both cuticle and stomach action. It is effective against caterpillars, aphids and mites outdoors. It is residual in soils for a period of up to eight months.
- A fourth group of insecticides contains potassium salts of **fatty acids**. It is available to amateur and professional growers. It works by contact action dissolving the cuticle of pests such as aphids, whitefly spider mites, mealy bugs and scale insects.

Nematicides

No active ingredients are, at present, available exclusively for nematode control. Soil-inhabiting stages of cyst nematodes, stem and bulb eelworm, and some ectoparasitic root eelworms are effectively reduced by soil incorporation of granular pesticides, such as **aldicarb**, at planting time of crops such as potatoes and onions. This group of chemicals acts systemically on leaf nematodes of plants such as chrysanthemum and dahlia.

Fungicides

Fungicides must act against the disease, but not seriously interfere with plant activity. **Protectant** chemicals prevent the entry of hyphae into roots and the germination of spores into leaves and other aerial organs (see Figure 15.4). **Systemic** chemicals enter roots, stems and leaves, and are translocated to sites where they may affect hyphal growth and prevent spore production. Although there are many fungicidal chemical groups, four are chosen here as examples:

- **Inorganic chemicals** contain no carbon. Two chemicals are available to amateur and professional growers. Commercially formulated compounds of copper salts mixed with slaked lime (**Bordeaux mixture**) form a protective barrier to fungi such as potato blight when sprayed onto the leaf. Fine-grained (colloidal) **sulphur** controls powdery mildews and apple scab.
- Organic chemicals contain carbon. **Mancozeb** (dithiocarbamate group) and related synthetic compounds act protectively on a wide range of quite different foliar diseases, such as downy mildews, celery leaf spot and rusts, by preventing spore germination. Mancozeb is available to both amateur and professional growers.
- **Carbendazim** (benzimidazole group) is available only to professional growers. It is an example of a systemic ingredient, which moves upwards through the plant’s xylem tissues, slowing hyphal growth and spore production of fungal wilts, powdery mildews and many leaf spot organisms. Damping off, potato blight and downy mildews are **not** controlled by chemicals within this chemical group. Many different systemic groups are now used in horticulture.
- **Myclobutanil** belongs to the conazole group. It is available to both amateur and professional growers. It is protectant and systemic, on powdery mildews, black spot of rose and apple scab.

Resistance to pesticides

The development of resistant individuals from the millions of susceptible weeds, pests and diseases occurs most rapidly when exposure to a particular chemical is continuous or when a pesticide acts against only one body process of the organism. Resistance, e.g. in powdery mildews, to one member, e.g. carbendazin, of a chemical group confers resistance to other chemicals in the same benzimidazole group. Growers should therefore follow the strategy of alternating between different groups and not simply changing active ingredients. Particular care should be taken with systemic chemicals that present to the organism inside the plant a relatively weak concentration against which the organism can develop resistance. Increase in dosage of the chemical will not, in general, provide a better control against resistant strains. Biological control, unlike chemical control, does not create resistant pests.

Formulations

Active ingredients are mixed with other ingredients to increase the efficiency and ease of application, prolong the period of effectiveness or reduce the damaging effects on plants and man. The whole product (formulation) in its bottle or packet is given a trade name, which often differs from the name of the active ingredient. The main formulations are as follows:

- **Liquids** (emulsifiable concentrates) contain a light oil or paraffin base in which the active ingredient is dissolved. Detergent-like substances (emulsifiers) present in the concentrate enable a stable emulsion to be produced when the formulation is diluted with water. In this way, the correct concentration is achieved throughout the spraying operation. Long chain molecular compounds (wetter/spreaders) in the formulation help to stick the active ingredients onto the leaf after spraying, particularly on smooth, waxy leaves such as cabbage.
- **Wettable powders** containing extremely small particles of active ingredient and wetting agents form a stable suspension for only a short period of time when diluted in the spray tank. Continuous stirring or shaking of the diluted formulation is thus required. An inert filler of clay-like material is usually present in the formulation to ease the original grinding of particles, and also to help increase the shelf life of the product. It is suggested that this formulation is mixed to a thin paste before pouring through the filter of the sprayer. This prevents the formation of lumps that may block the nozzles.
- **Dusts** are applied dry to leaves or soil, and thus require less precision in grinding of the constituent particles and less wetting agent.
- **Seed dressings** protect the seed and seedling against pests and diseases. A low percentage of active ingredient, such as **iprodione** applied in an inert clay-like filler or liquid reduces the risk of chemical damage to the delicate germinating seed.
- **Baits** contain attractant ingredients, e.g. bran and sugar, mixed with the active ingredient, e.g. **methiocarb**, both of which are eaten by the pest, such as slugs.
- **Granules** formulated to a size of about 1.0 mm contain inert filler, such as pumice or charcoal, onto which the active ingredient is coated. Granules may act as soil sterilants (e.g. **dazomet**), residual soil herbicide (e.g. **dichlobenil**), residual insecticide (e.g. **chlorpyrifos**), or broad-spectrum soil nematicide and insecticide (e.g. **aldicarb**). Granular formulations normally present fewer hazards to the operator and fewer spray-drift problems.

Labels on commercial formulations give details of the active ingredient contained in the product. Application rates for different crops are included. DEFRA approves pesticide products for effectiveness.

Phytotoxicity (or plant damage) may occur when pesticides are unthinkingly applied to plants. Soil applied insecticides, such as **aldicarb**, can cause pot plants, such as begonias, to go yellow if used at more than the recommended rate. Plants growing in greenhouses are more susceptible because their leaf cuticle is thinner than plants growing at cooler temperatures. Careful examination of the pesticide (particularly herbicide) packet labels often prevents this form of damage.

Application of herbicides and pesticides

This subject is described in detail in machinery texts. However, certain basic principles related to the covering of the leaf and soil by sprays will be mentioned. The application of liquids and wettable powders by means of sprayers may be adjusted in terms of pressure and nozzle type to provide the required spray rate. Cone nozzles produce a turbulent spray pattern suitable for fungicide and insecticide use, while fan nozzles produce a flat spray pattern for herbicide application. In periods of active plant growth fortnightly sprays may be necessary to control pests and diseases on newly expanding foliage.

- **High volume** sprayers apply the diluted chemical at rates of 600–1000 l/ha in order to cover the whole leaf surface with droplets of 0.04–0.10 mm diameter. Cover of the under-leaf surface with pesticides may be poor if nozzles are not directed horizontally or upwards. Soil applied chemicals, such as herbicides or drenches, may be sprayed at a larger droplet size, 0.25–0.5 mm in diameter, through a selected fan nozzle. The correct height of the sprayer boom above the plant is essential for downward-directed nozzles if the spray pattern is to be evenly distributed. Savings can be achieved by band spraying herbicides in narrow strips over the crop to leave the inter-row for mechanical cultivation.

Figure 16.10 **Knapsack sprayer** being used in nursery stock

- **Medium volume** (200–600 l/ha) and low volume (50–200 l/ha) equipment, such as knapsack sprayers, apply herbicides and pesticides onto the leaf at a lower droplet density, and in tree crops, mist blower equipment creates turbulence, and therefore increased spray travel, by means of a power driven fan. **Ultra-low volume** sprays (up to 50 l/ha) are dispersed on leaving the sprayer by a rapidly rotating disc which then throws regular-sized droplets into the air. Larger droplets (about 0.2 mm) are created by herbicide sprayers to prevent spray-drift problems, while smaller droplets (about 0.1 mm) allow good penetration and leaf cover for insecticide and fungicide use.

Fogging machines used in greenhouses and stores produce very fine droplets (about 0.015 mm diameter) by thermal and mechanical methods, and use small volumes of concentrated formulation (less than 1 l in 400 m^3) which act as fumigants in the air, and as contact pesticides when deposited on the leaf surface. **Dust and granule applicators** spread the formulations evenly over the foliage or ground surface. When mounted on seed drills and/or fertilizer applicators, granules may be incorporated into the soil. Care must be taken to ensure good distribution to prevent pesticide damage to germinating seeds or planting material.

Safe practice

In chemical control, the **hazards** are:

- possible acute poisoning of humans, pets, farm animals, bees, and wild animals;
- possible accumulation of pesticides that lead to toxic levels in humans, pets, farm animals, bees and wild animals;
- possible cancer inducing effects in humans;
- possible damage to cultivated and wild plants especially by herbicides;
- possible contamination of streams and dams;
- possible development of strains of rodents, insects, mites, and fungi, resistant to pesticides.

When using chemical control, risks can be **minimized** by:

- restricting chemical applications to only those situations that justify such a control measure. In many instances, other controls measures may be preferable and less hazardous;
- carefully choosing the least hazardous chemical to effectively control the problem organism;
- carefully reading the instructions on the product label;
- carefully choosing the correct clothing, where necessary;
- carefully measuring the correct amount of concentrate water (where relevant);
- calculating (where appropriate) the amount of pesticide and water necessary for application to the crop area in question;
- carefully mixing the two, avoiding spillage on to skin, clothing and the surrounding area;

- carefully applying the product so that the same area is not covered more than once, at any one time;
- carefully applying the product under suitable dry, wind-free weather conditions;
- carefully applying the product so that other humans, beneficial animals, waterways and adjacent plantings are avoided;
- carefully avoiding spray drift, especially with herbicides;
- carefully storing pesticides in a secure, safe, dry place away from children and pets.

Toxicity aspects of pesticides

The basic biochemical similarities between all groups of plants and animals means that any potential chemical chosen for its action against a weed, pest or disease may also be toxic to humans, pets, horticultural species and wildlife animals and plants. Prospective pesticides therefore have to go through a thorough examination over a period of several years to determine whether there are any dangers. This is carried out by the chemical companies and by contracted independent organizations. The evidence is scrutinized by government committees before there can be any possibility of the product's commercial release. This ensures that no damage will occur to non-target species (particularly humans) if safety precautions are followed. During 2005, 360 pesticide commercial products were withdrawn from use in agriculture and horticulture. During the same period, 160 products were approved.

Acute toxicity to humans

An important indicator of the safety of an ingredient is the lethal dose figure (LD50) by ingestion of a chemical. It expresses the amount of active ingredient required to kill 50 per cent of a population of animals and is expressed as mg/kg of animal tissue. This oral LD50 is used as an indicator for establishing the precautions needed for a grower to safely mix and apply a product. The lower the LD50 figure for a chemical, the more toxic it is. To put toxicity levels into some perspective, five everyday substances are presented in Table 16.2 alongside a range of five pesticides/growth regulators available to amateur and professional growers.

Other aspects of toxicity

Acute toxicity is not the only property of a potential pesticide to be assessed. Its chronic (long lasting) aspect must also be tested. For example, its **survival time** on the surface of the leaf may influence its suitability, particularly on leaf crops, such as lettuce, which have a large surface area of pesticide deposit and which are eaten fresh. Pesticides must also be checked against their ability to cause **irritation** and **allergies** in humans and their ability to cause cancer. An active ingredient may be particularly toxic to other mammals, fish, earthworms, bees and predatory animals. When testing active ingredients, research workers remember very well the havoc that chemicals such as DDT caused in killing animals at the top of food chain (see also p52).

Table 16.2 A comparison of LD50s in households, private gardens, and commercial units

Material	Use	Oral LD50 mg/kg
Aldicarb (most toxic)	Insecticide/nematicide (CU)	0.5
Nicotine	Cigarettes (H)	50
	Insecticide (CU)	50
Methiocarb	Slug pellets (G, CU)	100
Caffeine	Beverage (H)	190
Deltamethrin	Insecticide (CU)	50
2,4-D	Herbicide (G, CU)	450
Bifenthrin	Insecticide (G, CU)	630
Metalaxyl	Fungicide (CU)	670
NAA	Plant growth regulator (G, CU)	1000
Common salt	Food additive (H)	1000
Mancozeb	Fungicide (G, CU)	5000
Alcohol	Beverage (H)	5000
Glyphosate	Herbicide (CU)	5000
Fatty acids	Insecticide (G, CU)	5000
Vitamin C (least toxic)	Food ingredient (H)	12000

Key: Household – H; Garden – G; Commercial Unit – CU

Product label

The 'statutory area' on the label present on each packet or bottle of pesticide must provide the following details:

- The 'field' of use, whether agriculture, horticulture, home garden or animal.
- The plant species, crop or situation where treatment is permitted.
- The maximum dose or concentration.
- The maximum number of treatments.
- The latest time of application or harvest interval (days between application and harvest).
- Any specific restrictions, such as clothing required, temperature at which application should be made. (The nature of the protective clothing stated on the label commonly reflects the LD50 status of the ingredient.)
- A reminder to read all other safety precautions on the label and directions for use.

The **amateur gardener** does not need to pass a proficiency test for pesticide usage. Active ingredients have been selected with care to ensure that no danger from toxicity is present. In 2008 there is a choice of 24 active ingredients (4 insecticides/acaricides, 4 fungicides, 1 animal repellent, 5 slug control chemicals, 9 herbicides, and 1 growth regulator for plant propagation). The **professional horticulturist** may need to use pesticides which have special requirements in terms of their storage, mixing and application. Three main items of legislation come into play for them.

The first item of legislation focuses on the skill and understanding of the operator as they approach a chosen pesticide application. This was seen in the **Health and Safety Regulations 1975** which was summarized in the government '**Poisonous Chemicals on the Farm**' leaflet. This document specifies the correct procedures for pesticide use. A detailed register must be kept of spraying operations and any dizziness or illness reported. Correct washing facilities must be provided. A lockable dry store is necessary to keep chemicals safe. Warnings of spraying operations should be prominently displayed. A suitable fabric coverall suit with a hood must be used to protect most of the body from diluted pesticide. Rubberized suits should be used in conditions of greater danger, such as in an enclosed greenhouse environment, when dealing with ultra-low volume spray or when applying upward-directed sprays into orchards. Rubber boots should be worn inside the legs of the suit. Thick gauge gauntlets are worn outside the suit when dealing with concentrates, but inside when spraying. Face shields should be worn when mixing toxic concentrates. A face mask covering the mouth and/or nose, and capable of filtering out less toxic active ingredients may need to be used for spraying, but a respirator with its large filter is required for toxic products, particularly when used in greenhouses where toxic fume levels build up.

With regard to wildlife, pesticides should not be sprayed near ponds and streams unless designed for aquatic weed control. Crops frequented by bees, such as apples and beans, should be sprayed with insecticides only in the evening when most of the insects' foraging has ceased. Beekeepers should be informed of spraying operations.

The second item of legislation was the important, wide ranging, **Food and Environmental Protection Act 1985 (FEPA)** which highlighted public and government concern about pesticide dangers, and the need for a UK-wide improvement in responsible pesticide usage. The Act further required that chemical manufacturers, distributors and professional horticulturists should be able to demonstrate skills in the choice and careful management of pesticides. The Act also sought to make information about pesticides more available to the public.

A very practical aspect of FEPA is the specific requirement that all professional personnel involved with pesticides should demonstrate a high level of competence. To this end, the Act requires anyone intending to apply a pesticide to have passed two tests. The first (PA 1) test assesses knowledge in the following subject areas; legislation, places of special environmental value, safe use of pesticides, keeping records of products used and applications performed, storage of pesticides, cleaning of equipment, protective clothing and appliances, disposal of unwanted pesticide, and dealing with contamination and poisoning incidents. The second test (PA 6) assesses practical ability in pesticide application (normally by means of a knapsack sprayer or tractor mounted field sprayer). This involves proficiency in choosing a product for a specified job, calculating the amount of product and volume of water needed for a given area of land, using the correct clothing and equipment for mixing a concentrate and for the application of diluted product, performing the spraying operation, disposing of excess spray liquid, and the cleaning of spray equipment.

A third item of legislation was the **Control of Substance Hazardous to Health (COSHH) Regulations 2002** which formalized further the responsibility of the pesticide operator to assess whether each pesticide application was necessary. Once a decision to use a pesticide has been made, further investigation should lead to the choice of the most appropriate and safe active ingredients available, and the most appropriate clothing to wear.

A fourth development relating to pesticides has been the **Voluntary Initiative**, set up in 2001 by the farming and crop protection industries in association with the UK government to minimize the impact of pesticides on the environment.

In the **commercial horticultural** sector, the number of active ingredients available for use is much greater than in the private garden area. In 2008 there are about 145 active ingredients (33 insecticides/acaricides, 2 nematicides, 39 fungicides, 6 sterilants/fumigants, 11 animal repellants, 2 slug control chemicals, 46 herbicides and 16 growth regulators). Many active ingredients with low LD50 values which were used in the recent past have been banned as too dangerous. The chemical sodium cyanide, which is used to control rabbits, has an oral LD50 of 5 mg/kg and must now be applied to rabbit burrows only by licensed operators. Once the approval by the UK government Pesticide Safety Directorate has been given, further details for the product are then formalized following the guidelines given in Regulations under the Food and Environmental Protection Act 1985 (**FEPA**), to ensure the pesticide's transport, storage and application do not endanger humans and wildlife.

Selection for plant resistance

Genetic answers to plant health problems

Wild plants show high levels of resistance to most pests and diseases. In the search for high yields and extremes of flower shape and colour, plant breeders have often failed to include this **wild plant resistance**. However, in crops such as antirrhinum, lettuce and tomatoes, one or more resistance genes have been deliberately incorporated to give protection against rust, downy mildew and tomato mosaic virus respectively. However, the disease organisms competing against the resistance may overcome the genetic barriers and the crop thus again becomes infected. Growers may sow a sequence of cultivars (such as in lettuce), each with different resistance genes, in order that the disease organism (such as downy mildew) is constantly exposed to a new resistance barrier, and thus limit the disease.

Examination of the genetics of wild plant resistance usually shows that there are several (often many) genes contributing to the overall resistance effect. The complex nature of the resistance prevents the frequent development of new strains of diseases that could seriously affect the plant. Gardeners and professional horticulturist alike are increasingly looking to choose cultivars with proven long-term resistance as a feature that is as important to them as yield and plant quality, etc.

Recently introduced cultivars of cabbage such as 'Kalaxy' are claimed to have stable resistance to club root, while cultivars of potatoes such as 'Sarpo Axona' have until now shown very good leaf resistance and very good tuber resistance to potato blight. Looking at plant resistance with a slightly wider view, it should be noted that some strains of fungus are specific to particular families of plant. For example, a *Fusarium oxysporum* wilt strain attacking tomatoes (member of the Solanaceae family) will not carry over to a subsequently planted crop of pinks and carnations (members of the Caryophyllaceae).

Vegetatively propagated species, such as potatoes, and tree crops, such as apple, which remain genetically unaltered for many years are now being bred with high levels of 'wild plant' resistance (to blight and powdery mildew respectively on potato and apple) so that the crops may resist these serious problems more permanently.

Crop resistance to insects is now being more seriously considered by plant breeders. Some lettuce cultivars are resistant to lettuce root aphid (*Pemphigus bursarius*). A few carrot cultivars have some resistance to carrot fly (*Psila rosae*). A new apple cultivar has shown resistance to apple aphids. Table 16.3 illustrates some vegetable cultivars showing their resistance to various diseases and pests.

Table 16.3 Some examples of resistance to pests and diseases present in vegetable crops

Crop	Cultivar	Pest or disease
Aubergine	'Bonica'	Cucumber mosaic
Bean, dwarf	'Forum'	Anthracnose
Brussels sprout	'Saxon'	Powdery mildew
		Turnip mosaic virus
		White blister rust
Carrot	'Fly away'	Carrot fly
Chinese cabbage	'Harmony'	Club root
Cucumber	'Burpee Hybrid'	Cucumber mosaic
		Downy mildew
Leek	'Poristo'	Viruses
Lettuce	'Beatrice'	Root aphid
		Downy mildew
Pea	'Onward'	Fusarium wilt
Pepper	'Bell Boy'	Tomato mosaic virus
Potato	'Sarpo Axona'	Blight
Tomato	'Primato'	Tomato mosaic virus
		Fusarium wilt
		Verticillium wilt

Integrated control

Integrated control involves the use of natural pest enemies together with cultural, physical and chemical controls.

In integrated control the main **hazard** is the unintentional killing of biological control organisms by pesticides (which are being used for pests that cannot be controlled biologically). When using integrated control, **risks** can be minimized by choosing the appropriate pesticides that do not harm biological control organisms.

Integrated control, increasingly termed '**Integrated Pest Management**' or IPM, requires the grower to understand all types of control measures, particularly biological and chemical, in order that they complement each other. In greenhouse production of cucumbers, the *Encarsia formosa* parasite and *Phytoseiulus persimilis* predator are used for whitefly and red spider mite control respectively. However, the other harmful pest and disease species must be controlled, often by chemical means, without killing the parasites and predators. Drenches of systemic insecticide, such as **pirimicarb** against aphids, soil insecticides, such as **deltamethrin** against thrips pupae, and systemic fungicide drenches, such as **carbendazim** against wilt diseases and powdery mildew, are all applied away from the sensitive biological control organisms. Similarly, high volume sprays of selective chemicals, such as **iprodione** against grey mould, *Bacillus thuringiensis* extracts against caterpillars, have little or no effect on the parasite and predator. Similar considerations may be given in control of apple pests and diseases. Reduced usage of extremely toxic winter washes and increased use of selective caterpillar and powdery mildew control by chemicals, such as **diflubenzuron** and **fenarimol** respectively, allow the almost unhindered build-up of beneficial organisms, such as predatory capsid and mites.

The methods of **organic growers** emphasize the non-chemical practices in plant protection (as well as in soil fertility). Hedges are developed within 100 m of production areas and are clipped only one year in four to maintain natural predators and parasites. Rotations are closely followed to enable soil-borne pest or disease decline, while encouraging soil fertility. Resistant cultivars of plant are chosen and judicious use of mechanical cultivations and flame weeding enables pests, diseases and weeds to be exposed or buried. A restricted choice of pesticide products such as **pyrethrins**, **derris**, **metaldehyde** (with repellant), **sulphur**, **copper salts** and **soft soap** are allowed to be applied, should the need arise. *Bacillus thuringiensis* extract, and **also pheremone** attractants, are similarly used. Table 16.4 gives a list of permitted substances.

Supervised control

Supervised control involves the careful assessment of pest, disease and weed levels in order to achieve effective control.

Most plants can tolerate low levels of pest and disease damage without yield reduction, unless the damage is to parts of the plant that become unacceptable (such as fruits for the supermarket trade). The term '**economic threshold**' is used to summarize this concept. Cucumbers, for example, require more than 30 per cent leaf area affected by red spider mite before **economic damage** occurs in terms of yield loss. This enables methods of control that depend on some damage being

Table 16.4 Some permitted products for pest and disease control in organic crop production

Preparations on basis of metaldehyde containing a repellent to higher animal species and as far as possible applied within traps. For control of slugs
Preparations of pyrethrins extracted from *Chrysanthemum cinerariaefolium*, containing possibly a synergist for insect control
Preparations from *Derris elliptica* for insect control
Preparations from *Quassia amara* for aphid control
Preparations from *Ryania speciosa* for insect control
Sulphur for fungal diseases
Bordeaux mixture (copper based) for fungal and bacterial diseases
Burgundy mixture (copper based) for fungal diseases
Potassium soap (soft soap) for insect control
Pheremone traps for evaluating insect numbers
Bacillus thuringiensis preparations for caterpillar control

done to ensure continued success, such as the use of predators. Damage assessments are used in apple orchards to decide whether control measures are necessary. Thus, at green-cluster stage (before flowers emerge) chemical sprays are considered only when an average of half the observed buds has five aphids per bud. Similarly, an average of three winter moth larvae per bud-cluster merit control at late blossom time. Pheremone traps enable the precise time of maximum codling moth emergence to be determined in early June. Catches of less than 10 moths per trap per week do not warrant control. DEFRA issue **spray warning** information to growers when serious pests, such as carrot root fly, and diseases, such as potato blight, are likely to occur. Supervised control may greatly reduce pesticide costs.

Legislative control

Before 1877 no legal measures were available in the UK to prevent importation of plants infested with pests such as Colorado beetle. Measures taken at ports from that year onwards were brought together in the 1927 Destructive Insects and Pests Acts, empowering government officials to inspect and, if necessary, refuse plant imports. Within this Act, the ‘Sale of Diseased Plants Order’ placed on the grower the responsibility for recognition and reporting of serious pests and diseases, such as blackcurrant gall mite and silver leaf of plums. Lack of education and enforcement led to the need for specific orders relevant to particular current problems, such as in 1958 the fireblight-susceptible pear cultivar, ‘Laxton’s Superb’, was declared **notifiable** and prohibited under the Fireblight Disease Order.

Recent orders have helped prevent outbreaks of white rust on chrysanthemums, plum pox virus and two American leaf miner species; less success has been achieved with the Western flower thrip organism. Further importation legislation under the ‘1967 Plant Health Act’ prohibits the landing of any non-indigenous pest or disease by aircraft or post, and the ‘Importation of Plants, Produce and Potatoes Order

1971' specifically names prohibited crops, such as plum rootstocks from eastern Europe, crops without a **phytosanitary** certificate, such as potato tubers from Europe, and crops that first need to be examined by inspectors, such as Acacia shrubs and apricot seeds.

The carrying out of these orders is supervised by the Plant Health Branch of the Department for Environment, Food and Rural Affairs (DEFRA). Complete success in preventing the introduction of damaging organisms may be limited by dishonest importations and by the difficulty of detection of some diseases, especially viruses. European Council directives, such as 77/93/EEC and 2000/29/EC, are moving member nations towards a unified approach in reducing the transfer of infected plant material across national boundaries, and the UK Plant Health Order (2005) implements the EC legislation. The Weeds Act 1959 places a legal obligation on each grower to prevent the spread of weeds such as creeping thistle, spear thistle, curled dock, broad-leaved dock and ragwort. In addition, under the UK Wildlife and Countryside Act (1981), it can be an offence to plant Japanese knotweed (*Polygonum japonicum*) and giant hog-weed (*Heracleum mantegazzianum*).

Check your learning

1. Define the terms 'biological control', 'chemical control', 'physical control' and 'cultural control'.
2. State the benefits and limitations of using biological control.
3. Describe one physical method of plant protection.
4. Describe one cultural method of plant protection.
5. Describe one biological method of plant protection.
6. Describe one chemical method of plant protection.
7. Name five types of hazard which may be encountered with pesticide use.
8. Describe an example of the term 'economic threshold' used in plant protection.
9. Describe an example of an 'integrated control' used in plant protection.
10. Describe an example of warm water treatment used in plant protection.

Further reading

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Chapter 17 Physical properties of soil

Summary

This chapter includes the following topics:

- Soil profiles
- Topsoil and subsoil
- Characteristics of sand, silt and clay
- Soil texture
- Soil structure
- Cultivations
- Bed systems

with additional information on the following:

- Plant requirements
- Composition of soils
- Formation of soils
- Natural soil profiles
- Soils of the British Isles
- Management of main soil types

Figure 17.1 Formation of soil begins with the weathering rocks which includes the powerful force of the sea.

Plant requirements

The growing tip of the root wriggles through the growing medium following the line of least resistance. Roots are able to enter cracks that are or can be readily opened up to about 0.2 mm in diameter, which is about the thickness of a pencil line. Compacted soils severely restrict **root exploration**, but once into these narrow channels the root is able to overcome great resistance to increase its diameter. Anything which reduces root exploration and activity can limit plant growth. When this happens action must be taken to remove the obstruction to root growth or to supply adequate **air**, **water** and **nutrients** through the restricted root volume.

The root normally provides the **anchorage** needed to secure the plant in the soil. Plants, notably trees with a full leaf canopy, become vulnerable if their roots are in loose material, in soil made fluid by high water content or are restricted, e.g. shallow roots over rock strata close to the surface. Until their roots have penetrated extensively into the surrounding soil, transplants are very susceptible to **wind rocking**: water uptake remains limited as roots become detached from the soil and delicate root growth is broken off. The plant may be left less upright.

In order to grow and take up water and nutrients the root must have an **energy** supply. A constant supply of energy is only possible so long as oxygen is brought to the site of uptake (see respiration). Consequently the soil spaces around the root must contain air as well as water. There must be good **gaseous exchange** between the atmosphere around the root and the soil surface. This may sometimes be achieved by the selection of plants that have modifications of their structure that enables this to occur throughout the plant tissues (see adaptations), but it is normally a result of maintaining a suitable soil structure. A lack of oxygen or a build-up of carbon dioxide will reduce the root's activity. Furthermore, in these conditions anaerobic bacteria will proliferate, many produce toxins such as ethylene. In warm summer conditions roots can be killed back after one or two days in waterlogged soils.

Composition of soils

Mineral soils form in layers of rock fragments over the Earth's surface. They are made up of mineral matter comprising **sand**, **silt** and **clay** particles. There is also a small quantity of organic matter which is the part derived from living organisms. This framework of solid material retains water and gases in the gaps or **pore space**. The water contains dissolved materials including plant nutrients and oxygen and is known as the **soil solution**. The **soil atmosphere** normally comprises nitrogen, rather less oxygen and rather more carbon dioxide than in normal air, and traces of other gases. Finally, a soil capable of sustaining plants is alive with **micro-organisms** (organisms, such as

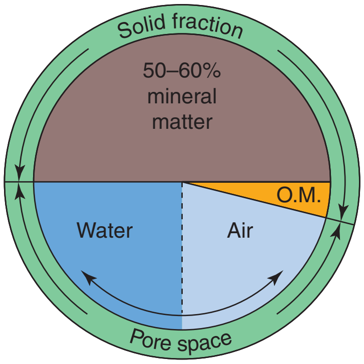


Figure 17.2 **Composition of a typical cultivated soil**. The solid fraction of the soil is made up of mineral (50–60 per cent) and organic (1–5 per cent) matter. This leaves a total pore space of 35–50 per cent that is filled by air and water, the proportions of which vary constantly.

bacteria, fungi and nematodes, too small to be seen with the naked eye). Larger organisms such as earthworms and insects are also normally present (see p321).

The composition of a typical mineral soil is given in Figure 17.2, which also illustrates the variation that can occur. The content of the pore space varies continually as the soil dries out and is rewetted. The spaces can be altered by the compaction or 'opening up' of the soil which in turn has a significant effect on the proportions of air and water being held.

Over a longer period the organic matter level can vary. The composition of the soil can be influenced by many factors and under cultivation these have to be managed to provide a suitable root environment. Organic soils have considerably higher organic matter content and are dealt with in Chapter 18.

Formation of soils

The Earth formed from a ball of molten rock minerals. The least dense rocks floated on the top and as they cooled the surface layer of granite, with basalt just below, solidified to form the Earth's crust. The Earth's surface has had a long and turbulent history during which it has frequently fractured, crumpled, lifted and fallen, with more molten material being pushed up from below through the breaks in the crust and in volcanoes.

Weathering

Weathering is the breakdown of rocks.

From the moment that rocks are exposed to the atmosphere, they are subject to weathering. This breakdown of the rocks is brought about by the effect of chemical, physical and biological factors.

Chemical weathering is mainly brought about by the action of **carbonic acid** that is produced wherever carbon dioxide and water mix, as in rainfall. Some rock minerals dissolve and are washed away. Others are altered by various chemical reactions, most of which occur when the rock surface is exposed to the atmosphere. All but the inert parts of rock are eventually decomposed and the rock crumbles as new minerals are formed and soluble material is released. **Oxidation** is particularly important in the formation of iron oxides, which give soils their red and yellow (when aerobic), or blue and grey colours (in anaerobic conditions).

Physical or mechanical weathering processes break the rock into smaller and smaller particles without any change in the chemical character of the minerals. This occurs on exposed rock surfaces along with chemical weathering but, in contrast, has little effect on rocks protected by layers of soil.

The main agents of physical weathering are frost, heat, water, wind and ice. In temperate zones, frost is a major weathering agent. Water percolates into cracks in the rock and expands on freezing. The pressures created shatter the rock and, as the water melts, a new surface is exposed to weathering. In hot climates the rock surface can become very much hotter than the underlying layers. The strains created by the different amounts of expansion and the alternate expansion and contraction cause fragments of rock to flake off the surface; this is sometimes known as the ‘onion skin’ effect. Moving water or wind carries fragments of rock that rub against other rocks and rock fragments, wearing them down. Where there are glaciers the rock is worn away by the ‘scrubbing brush’ effect of a huge mass of ice loaded with stones and boulders bearing down on the underlying rock.

Biological weathering is attributable to organisms such as mosses, ferns and flowering plants which fragment rock by both chemical and physical means, e.g. they produce carbon dioxide which, in conjunction with water, forms carbonic acid; roots penetrate cracks in the rock and, as they grow thicker, they exert pressure which further opens up the cracks.

Rocks

Erosion is the movement of rock fragments and soil.

Igneous rocks are those formed from the molten material of the Earth’s crust. All other rock types, as well as soil, are ultimately derived from them. When examined closely, most igneous rocks can be seen to be a mixture of crystals. **Granite** is one of the commonest and contains crystals of quartz, white and shiny, felspars that are grey or pink, and micas, which are shiny black (see Figure 17.3). Many of these crystalline materials have a limited use in landscaping as formal structures rather than in the construction of rock gardens; more commonly they are used in monuments and building facades.

As granite is weathered (‘rotted’) the felspars are converted to kaolinite (one of the many forms of clay) and soluble potassium, a plant nutrient. Similarly, the mica present is chemically changed to form clay and yield soluble minerals. Whilst the many types of clay retain much of the potassium, sodium, calcium, etc., the soluble material is carried by water to the sea making the sea ‘salty’. The inert quartz grains are released and form sand grains.

Sedimentary rock is derived from accumulated fragments of rock. Most have been formed in the sea or lakes to which agents of **erosion** carry weathered rock. Organisms in the seas with shells die and accumulate on the bottom of the sea. Layers of sediment build up and, under pressure and slow chemical change,

Figure 17.3 **Rocks**. Granite: pink (left) silver (top) sandstone (right) slate (bottom) eventually become rock strata such as shale, chalk or limestone. In subsequent earth movements much of it has been raised up above sea level and weathered again. Similarly, the sand grains that accumulate to great depths in desert areas eventually become sandstones (Figure 17.3).

Moving water and winds are able to carry rock particles and are thus important agents of erosion. As their velocity increases the '**load**' they are able to carry increases substantially. The fast-moving water in streams is able to carry large particles, but in the slower-moving rivers some of the load is dropped. The particles settle out in order of size (see settling velocities). This leads to the **sorting** of rock fragments, i.e. material is moved and deposited according to particle size. By the time the rivers have reached the sea or lakes only the finest sands, silts and clays are in the water. As the river slows on meeting the sea or lake all but clay is dropped. The clay eventually settles slowly in the quieter waters of the sea or lake. Moving ice is also an agent of erosion, but the load dropped on melting consists of unsorted particles known as **boulder clay** or till.

The type of sedimentary rock formed depends on the nature of its ingredients. Sandstones, siltstones and mudstones are examples of sedimentary rocks derived from sorted particles in which characteristic layers are readily seen. Limestones are formed from the accumulation of shells (see Figure 17.4) or the precipitation of materials from solution mixed with varying amounts of deposited mud. Chalk is a particularly pure form derived from the calcium carbonate remains of minute organisms that lived in seas in former times. Many of these are attractive materials for use in hard landscaping, where care should be taken to align the strata (layers) for a natural effect.

Metamorphic rock is formed from igneous or sedimentary rocks. The extreme pressures and temperatures associated with movements and fracturing in the Earth's crust or the effect of huge depths of rock on underlying strata over very long periods of time has altered them. Slate is formed from shale, quartzite from sandstone, and marble from limestone. Metamorphic rock tends to be more resistant to weathering than the original rock.

Figure 17.4 Limestone

Natural soil profiles

Sedentary soils

Sedentary soils develop in the material gradually weathered from the underlying rock. True sedentary soils are uncommon because most loose rock is eroded, but the same process can be seen where great depths of transported material have formed the parent material, as in the boulder clays left behind after the Ice Ages. A hole dug in such a soil shows the gradual transition from unweathered rock to organicmatter rich topsoil (Figure 17.5). Under cultivation a distinctive topsoil develops in the plough zone.

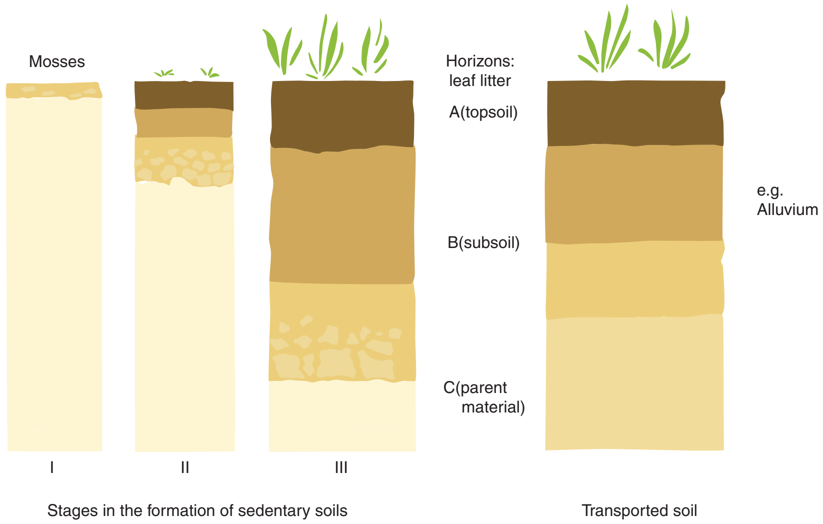


Figure 17.5 **The development from a young soil** consisting of a few fragments of rock particles to a deep sedentary soil is shown alongside a transported soil. A subsoil, topsoil and leaf litter layer can be identified in each soil. Simple plants such as lichens and mosses establish on rocks or fragments to be succeeded by higher plants as soil depth and organic matter levels increase.

Transported soils

Once rock fragments and soil particles are created they become subject to **erosion**. **Transported soils** are those that form in eroded material that has been carried from sites of weathering, sometimes many hundreds of miles away from where deposition has occurred. They can be recognized by the definite boundary between the eroded material and the underlying rock and its associated rock fragments. Where more than one soil material has been transported to the site, as in many river valleys, several distinct layers can be seen. The right-hand part of Figure 17.5 shows an example. How they are moved depends on where the loose material lies:

- **Gravity** affects anything on a slope. On steep sides, e.g. cliffs, particles fall and accumulate at the bottom to form heaps of rock called 'scree'.
- On gentler slopes particles are helped downhill by **rainsplash**. Raindrops striking soil dislodge loose particles that tend to move downhill. As a result, surface soil is slowly removed from higher ground and accumulates at the bottom of slopes. This means that soils on slopes tend to be shallow, whereas at the bottom deep, transported soils develop, known as **colluvial** soils.
- **Glaciers** carry vast quantities of rock downhill and deposit their load at the 'snout' (terminal moraines). Of more significance is the enormous load that was left behind when the glaciers retreated after the last Ice Age (10 000 years ago). This is known as 'till' or 'boulder clay' (it comprises boulders down to clay size particles).
- Material washed away in **running water** eventually settles out according to particle size. The river valley bottoms become covered with material (alluvium) in which **alluvial** soils develop.

- **Wind** removes dry sands and silts that are not 'bound in' to the soil. The soils that develop from wind-blown deposits are known as 'loess' or 'brick-earth'.

Many of these transported soils provide ideal rooting conditions for horticultural crops because they tend to be deep, loose and open. Most are easily cultivated. However, those that have a high silt or fine sand content, notably the brick-earths, may be prone to compaction.

Soil development

The nature of a new soil (regosols) is largely determined by the rock minerals from which it is formed, but it continues to undergo changes under the influence of **climate**, **vegetation**, **topography** and **drainage**. These interact over **time** to give rise to characteristic soil profiles in different parts of the world. The soils that develop can be described in terms of the characteristics of the different horizons (layers) that make up the soil profile.

A **soil horizon** is a specific layer in the soil seen by digging a **soil pit**. The layers revealed make up the **soil profile**.

The 'O' or 'L' horizon is the organic matter found on top of the mineral soil and commonly referred to as the litter layer. The upper layer of the soil, from which components are normally washed downwards, is the 'A' horizon. This is usually recognized by its darker colouring, which is a result of the significant levels of humus present. The lighter layer below it, where finer materials tend to accumulate, is the 'B' or illuvial horizon. Under cultivation, the 'A' horizon broadly aligns with the 'topsoil' and the 'B' with the 'subsoil'. The parent material below these is the 'C' horizon and where there is an underlying unweathered rock layer it is often known as bedrock.

Soils of the British Isles

In the British Isles four main types of mineral soil are found; **brown earths**, **gleys**, **rendzinas** and **podsols** (see Figure 17.6). **Peats** develop in waterlogged conditions (see organic soils p328).

Brown earth soils develop in the well-drained medium to heavy soils in the lowlands of the British Isles. They are associated with a climax vegetation (p52) of broad-leaved woodland especially oak, ash and sycamore, the roots of which have ensured that nutrients moving down the soil profile are captured and returned to the soil via the leaf fall. Surplus water does not accumulate and the soil remains aerobic for most of the year. The plentiful earthworms incorporate the deep litter layers. The resultant dark A horizon ('topsoil') rich in organic matter merges gradually into a bright brown and deep B horizon ('subsoil'). The soil structures that develop in the surface layers are granular and rounded fine blocky in which there is an excellent balance of air and water and into which roots can readily penetrate.

Brown earths are usually mildly acid (pH 5.5 to 6.5), but **acid brown earths** (pH 5.5 to 4.5) can develop on lighter textured soils in wetter areas

(800–1000 mm rain per year) especially under beech or birch woodland. There is less earthworm activity, with a resultant reduced incorporation of organic matter down the profile. The soil structure is usually less satisfactory and clay particles that work their way down can form clay pans (see p313) in the B horizon. These can be productive soils if ameliorated with lime and fertilizer (see Chapter 21).

(a) (b) (c) (d)

Figure 17.6 **Soil types**: (a) Podsol; (b) Gley; (c) Brown earth; (d) Rendzina.

Gleys occur in poorly drained soils (see p343). **Surface water gleys** are found where the percolation of water is restricted by the poor structure in the A or B horizon to produce a **perched water table** (see p340). This is typically where the subsoil is heavy and impervious, especially in wetter regions. Oxygen in the waterlogged soil is depleted and, in these anaerobic conditions below the water table, the iron oxides that colour the soil become dull grey or bluey (in aerobic conditions the iron oxides are rust coloured). The extent of the waterlogging that the soil has been subjected to as the water table fluctuates can be judged from the degree to which it has become completely grey; usually there is a rusty mottle present, indicating that aerobic conditions exist in the soil for part of the year (see Figure 17.7). Plants growing in them are often shallow rooted and suffer from drought in dry periods. These soils are only productive after they have been drained, limed and fertilized.

Ground water gleys develop where there is a permanent water table that is very near the surface of the soil, so that to lower the water table drainage has to be undertaken on a regional basis, e.g. Romney Marsh. Drainage pipes can only be used when the water can be run to a ditch with a water level below that desired in the field (see p344); for some areas this can only be achieved by maintaining an artificially low level by the use of pumps (powered in former times by windmills).

Podsols (from the Russian ‘under-ash’) are strongly leached, very acid soils that develop on freely draining soils, such as coarse sands and gravels, commonly under heather or pine or spruce forest in high rainfall areas. Because of the high acidity levels, earthworms are absent so there is a build-up of the litter layer. Poorly decomposed organic matter that is not incorporated (a ‘mor’ humus) is characteristic of this soil type. Some of the organic matter combines with the iron in the top layers to form soluble compounds which are leached (‘podsolization’) to leave a grey (‘ash-like’) A horizon (all that remains are bleached sand grains). These compounds become insoluble again in the conditions that prevail in the B horizon, where organic matter accumulates to create a dark or black horizon below which is an iron rich red layer. The iron compounds that accumulate can form a strongly cemented ‘iron pan’. As a continuous pan that water (and roots) cannot penetrate is formed, a waterlogged

Figure 17.7 **Soil colours**. Brown (top), Mottled, Gley (bottom).

area develops and peat can form at the surface. Podsols are prone to drought and are 'hungry' soils that require considerable ongoing inputs of lime and manure to make them productive. They are of little use in horticulture except for the growing of acid loving trees and shrubs.

Rendzinas are very thin dark-brown, sometimes black, soils with a strong granular structure sitting directly on chalk or limestone. They are typical of the soils on the steeper slopes of chalk or limestone hills under grass. Shallow soils develop because of the continued erosion on the slopes, which also keeps these soils heavily charged with lime. Where the soils become deeper on the less severe slopes it is common for the A horizons to become acid, as the lime is leached downwards. They are well drained because of the slope and because of the porous nature of the underlying rock. Rendzinas are not suitable for most horticultural purposes because the high lime content causes induced nutrient deficiencies (see p372). Roots are severely restricted by the shallow soils and vulnerable to drought.

Topsoil and subsoil

Topsoil is the uppermost layer of soil normally moved during cultivation. Typically it is 10 to 40 cm deep and darkened by the decomposed organic matter it contains.

Subsoil is the layer below that normally cultivated and lighter in colour because of its low organic matter level.

In natural conditions organic matter is more abundant at the surface and declines in concentration with depth (see p327), whereas under cultivation the organic matter is redistributed to create a distinct topsoil and subsoil with the boundary at 'plough depth'. The dark colour that the decomposed organic matter gives the soil makes the boundary obvious by the colour change.

Soil components

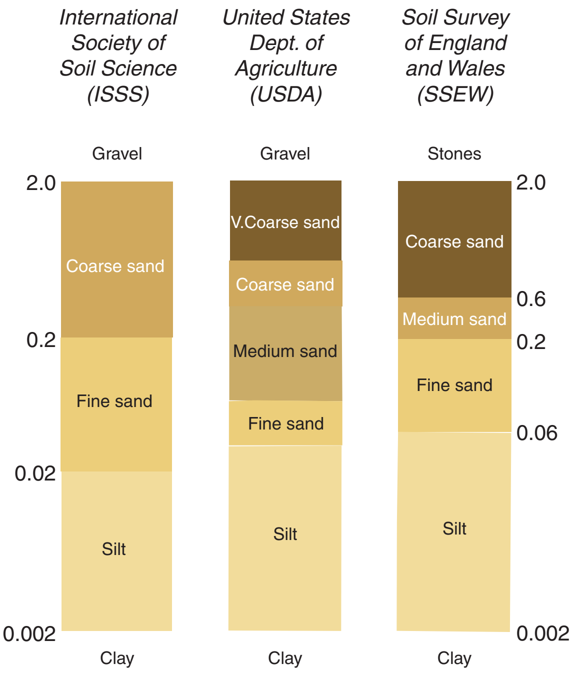


Figure 17.8 **Particle size classes** (diameters in mm)

The solid parts of soils consist of mineral matter derived from rocks and organic matter derived from living organisms. Levels and characteristics of organic matter are dealt with in Chapter 18. Most soils have predominantly mineral particles that vary enormously in size from boulders, stones and gravels down to the smaller soil particles ('fine earth'); sand, silt and clay.

Particle size classes

There is a continuous range of particle sizes, but it is convenient to divide them into classes. Three major classification systems in use today are those of the International Society of Soil Science (ISSS), United States Department of Agriculture (USDA) and the Soil Survey of England and Wales (SSEW). These are illustrated in Figures 17.8 and 17.9. In this text the SSEW scale used by the Agricultural Development and Advisory Service of England and Wales (ADAS) is adopted. In each case, soil is considered to consist of those particles that are less than 2 mm in diameter. The silt and clay particles are sometimes referred to as ‘fines’.

Sand

Sands are gritty to the touch; even fine sand has an abrasive feel. Sand is mainly composed of quartz. (Although any particle of this size is a sand grain, it is most often quartz because, unlike other minerals, it resists weathering.)

The shape of the particles varies from the rough and angular sand to more weathered, rounded grains. They are frequently coated with iron oxides, giving sand colours from very pale yellow to rich, rusty brown. Silver sand has no iron oxide covering. Chemically most of the sand grains are **inert**; they neither release nor hold on to plant nutrients and they are not cohesive.

The influence of sand on the soil is mainly physical, and as such the size of the particles is the important factor. As the particles become smaller and the volume of individual grains decreases, the **surface area** of the same quantity of sand becomes greater (see Figure 17.10). Sand grains are non-porous so their water-holding properties are directly related to their surface areas. It can be readily seen that, since water will not flow through gaps less than about 0.05 mm in diameter, there are very big differences in the drainage characteristics of coarse and fine sands (Figure 17.9). Consequently, soils dominated by coarse sand are usually free draining but have poor water retention, whereas those composed mainly of unaggregated fine

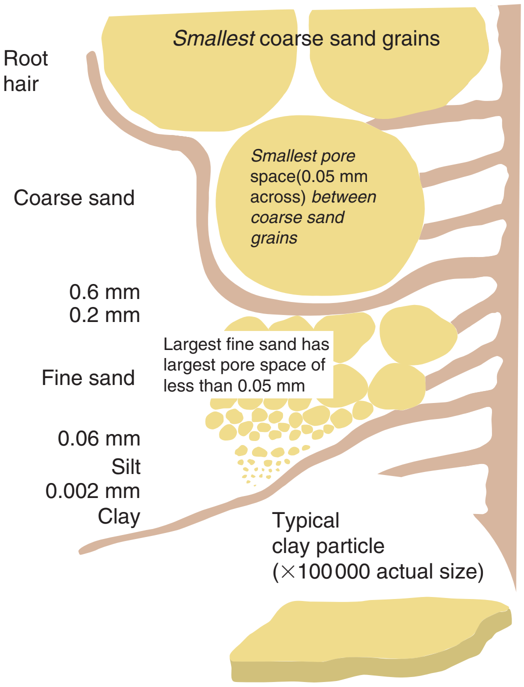
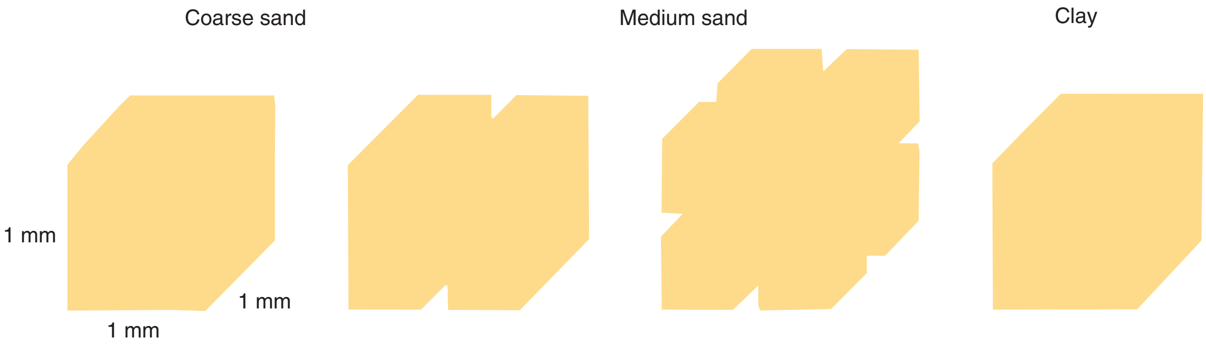


Figure 17.9 The relative sizes of coarse sand, fine sand, silt and clay particles (based on SSEW classification) with root hairs drawn alongside for comparison. Note that even the smallest pore spaces between unaggregated spherical coarse sand grains still allow water to be drawn out by gravity and allow some air in at field capacity, whereas most pores between unaggregated fine sand grains remain water-filled (pores less than 0.05 mm diameter)



Volume	1 mm^3	1 mm^3	1 mm^3	1 mm^3
No of pieces	1	2	8	1000 million
Total surface area	6 mm^2	8 mm^2	12 mm^2	6000 mm^2

Figure 17.10 Surface area of soil particles. The effect of sub-dividing a cube corresponding in size to a grain of coarse sand. The same volume of medium sand is made up of over eight times more pieces that have a total surface area more than double that of coarse sand. It requires over a thousand million of the largest clay particles to make up the volume of one grain of coarse sand and their total surface area is approximately six thousand times greater.

Sand grains are particles between 0.06 mm and 2.0 mm in diameter.

sand hold large quantities of water against gravity. The water held on all sand particles is readily removed by roots (see available water p342).

Clay

There are many different clay minerals, e.g. kaolinite, montmorillinite, vermiculite, and mica, all of which are derived from rock minerals by chemical weathering.

Clay particles are those less than 0.002 mm in diameter.

Most clay minerals have a layered crystalline structure and are plate-like in appearance (Figure 17.9). The clay particles have surface charges that give clay its very important and characteristic property of **cation exchange**. The charges are predominantly negative which means that the clay platelets attract positively charged **cations** in the soil solution. These include the nutrients potassium, as K^+; ammonia, as $NH_4{}^+$; magnesium, as Mg^{++}; and calcium, as Ca^{++}, as well as hydrogen and aluminium ions. These **ions** (p371) are held in an **exchangeable** way so that they remain available to plants, but are prevented from being leached unless displaced by other cations. The greater the **cation exchange capacity**, the greater the reserves of cations held this way.

Hydrogen and aluminium cations make the soil acid. The other cations Ca^{++}, Mg^{++}, K^+ and Na^+ are called **bases** and make soils more alkaline (see soil pH (p356)). The proportion of the cation exchange capacity occupied by bases is known as its **percentage base saturation**. A soil's **buffering capacity**, i.e. its ability to resist changes in soil pH, also depends on these surface reactions. The presence of high levels of exchangeable aluminium and hydrogen means that very large quantities of calcium, in the form of lime, are required to raise the pH of acid clays. In contrast, only small quantities of lime are needed to raise the pH of a sand by the same amount (see liming p361).

The clay particles are so small that the minute electrical forces on the surface become dominant (Figure 17.10); thus clay and water mixtures behave as colloids (see Table 17.1). This gives clay soils properties of cohesion, plasticity, shrinkage and swelling. The small particles can pack and stick together very closely and in a continuous mass they restrict water movement.

The water-holding capacity of clay-dominated soils is very high because of the large surface areas and because many of the particles are porous. However, a high proportion of the water is held too tightly for roots to extract (see p342). Moist balls of clay are plastic, i.e. can be moulded. On drying, they harden and some shrink. In the soil, the cracks that form on shrinking become an important network of drainage channels. The cracks remain open until the soils are re-wetted and the clay swells. Humus and calcium appear to combine with clay in such a way that when the combination dries, extensive cracking occurs and favourable growing conditions result. Some clays are non- shrinking and are consequently more difficult to manage although they present less problems with regard to building foundations.

Characteristics of small particles

Taking a cube and then cutting it up into smaller cubes readily demonstrates the relationship between volume and surface area (see Figure 17.10). While the total volume is the same in all the small cubes compared with the original large cube, the sides of each are smaller, but the total surface area is much greater because new surfaces have been exposed. Many soil particle characteristics are directly related to particle size and in particular to surface area.

Note that as a particle is sub-divided the total surface area increases; the surface area doubles each time the sides of the individual pieces are reduced by half. In particles that are less than 0.001 mm in diameter, which includes most clay, colloidal properties are observed; most notably the properties of their surface dominate their chemical behaviour. **Colloids** are mixtures that are in permanent suspension.

Table 17.1 Colloidal systems

Mixture	Colloidal system	Examples
Solid dispersed in gas	Solid aerosol	Smoke, dusts
Solid dispersed in liquid	Sol or gel	Paste, clay, humus, protoplasm
Liquid dispersed in gas	Liquid aerosol	Mist, fog
Liquid dispersed in liquid	Emulsion	Milk
Gas dispersed in gas		The atmosphere

Water based colloids, such as clay, are ‘runny’ when mixed with plenty of water (a ‘sol’) but with less water they are stiff and jelly-like (a ‘gel’), e.g. paste. As they dry, these mixtures become sticky and eventually hard. Many natural materials such as gelatin, starch, gums and protoplasm (mainly protein and water) are colloidal.

Silt

Most in this size range are inert and non-porous like sands, but many particles, including felspar fragments, have the properties of clay. Soils dominated by silt do have a small cation exchange capacity, but in the main they behave more like a very fine sand. They have very good water-holding capacity and plants can take up a high proportion of this water.

Silt particles are those between 0.002 mm and 0.06 mm in diameter.

When wetted they have a distinctly soapy or silky feel. Silt soils are made up of particles that readily pack closely together, but have little ability to form stable crumbs (see soil aggregates p311). This makes them particularly difficult to manage.

Stones and gravel

Stones are particles larger than 2 mm in diameter.

Particles bigger than sand are commonly known as grit, gravel, pebbles, cobbles and boulders, according to size and shape. The effect of stones on cultivated areas depends on the type of stone, size and the proportion in the soil. The presence of even a few stones larger than 20 cm prevents cultivation. Stones in general have detrimental effects on mechanized work; ploughshares, tines and tyres are worn more quickly, especially if the stones are hard and sharp such as broken flint. Stones interfere with drilling of seeds and the harvesting of roots. Close cutting of grasses is more hazardous where there are protruding stones. Mole draining becomes less effective in stony soils and large stones make it impossible.

Stones can accumulate in layers and become interlocked to form **stone pans**. In very gravelly soils the water-holding capacity is much reduced and the increased leaching leads to acid patches. Nutrient reserves are also reduced by the dilution of the soil with inert material. However, stones can help water infiltration, protect the surface from capping, and check erosion by wind or water.

Soil texture

Soil texture can usefully be defined as the relative proportions of the sand, silt and clay particles in the soil.

Soil texture describes the mineral composition of a soil. In most cultivated soils the mineral content forms the framework and exerts a major influence on its characteristics. Examples of different textures are given in Figure 17.11.

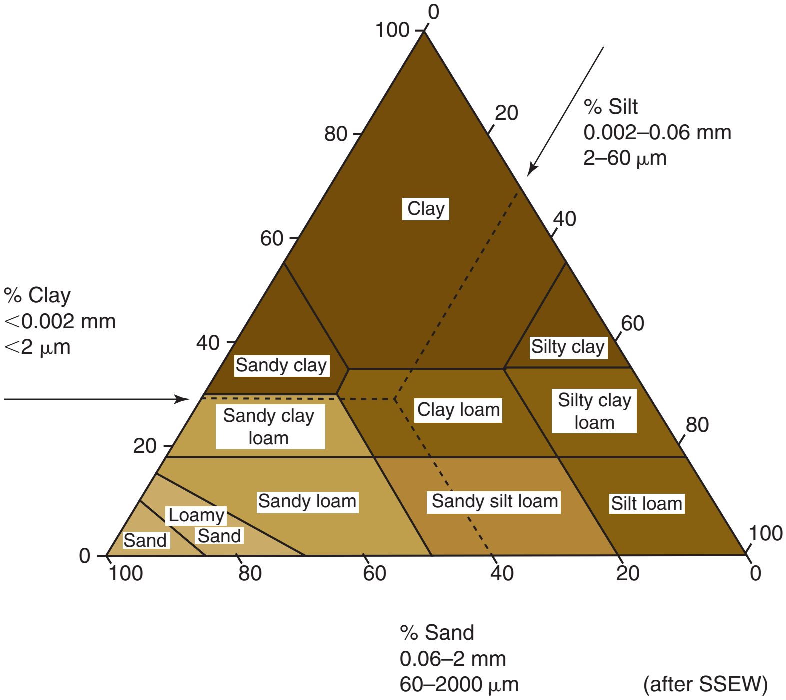


Figure 17.11 **Soil textural triangle**. The soil texture can be identified on this type of chart when at least two of the major size of fractions are known, e.g. 40 per cent sand, 30 per cent silt and 30 per cent clay is a clay loam (SSEW Soil-Particle Size Classification).

Texture can be considered to be a fixed characteristic and provides a useful guide to a soil's potential. Fine-textured soils such as clays, clay loam, silts and fine sands have good water-holding properties, whereas coarse textured soils have low water-holding capacity but good drainage. This also means that **soil temperatures** are closely related to soil texture, because water has a very much higher specific heat value than soil minerals. Consequently freely draining, coarse sand warms up more quickly in the spring but is also more vulnerable to frosts than wetter soils.

Soils with high clay content have good general nutrient retention, whereas nutrients are readily lost from sandy soils, especially those with a high coarse sand fraction. The application rate of pesticides and herbicides is often related to soil texture. The power requirement to cultivate a clay soil is very much greater than that for a sandy soil. The expression 'heavy' for clay and 'light' for sandy soils is derived from this difference in working properties rather than the actual weight of the soil. The texture of a soil also influences the soil structure and soil cultivations.

The addition of a calcareous clay to a sandy topsoil, a practice known as **marling**, can improve its water-holding capacity, as well as reducing wind erosion, but it requires the incorporation of 500 tonnes of dry clay per hectare to convert it to a sandy loam. The practice of adding clay is now largely confined to the building of cricket squares. To 'lighten' a clay loam topsoil to a sandy loam more than 2000 tonnes of dry sand is needed on each hectare (roughly the same volume of sand has to be added as the volume to be changed). The addition of smaller quantities of sand is often an expensive exercise to no effect; at worst it can make the resultant soil more difficult to manage.

Texturing by feel

A more practical method of determining soil texture, especially in the field, is by feel. This can, with experience, be a very accurate means of distinguishing between over thirty categories. A ball of soil about the size of a walnut is moistened and worked between the fingers to remove particles greater than 2 mm and to break down the soil crumbs. It is essential that this preparation is thorough or the effect of the silt and clay particles will be masked. The characteristics of the different mixtures of sand, silt and clay enable the texture to be determined:

- **Sands** are soils that have little cohesion. Sand has little tendency to bind even when wetted and it cannot be rolled out into a 'worm'.
- **Loamy sand** has sufficient cohesiveness to be rolled into a 'worm', but it readily falls apart.

What is generally known as loam moulds readily into a cohesive ball and it has no dominant feel of grittiness, silkiness or stickiness:

- **Sandy loam** – if grittiness is detected and the ball is readily deformed.
- **Silty loam** – if it is readily deformed but has a silky texture.
- **Clay loams** bind together strongly, do not readily deform, and take a polish when rubbed with the finger.

Clays bind together and are very difficult to deform. A clay soil readily takes a very marked polish but it is:

- **Silty clay** if there is also a feeling of silkiness, or
- **Sandy clay** if grittiness is evident.

Wherever grittiness is detected, the designation sand can be further qualified by stating whether it is coarse, medium or fine sand, e.g. coarse sandy loam. Table 17.2 shows the range of textural groupings commonly used.

Determining texture by feel has the limitation that the influence of organic matter and chalk cannot be eliminated. Chalk tends to give a soil a silky or gritty feel depending on fineness, but the fact that a soil is known to be chalky should not influence the texturing. Its textural class may be prefixed '**calcareous**', e.g. calcareous silty clay. **Organic matter**

Table 17.2 Soil texture classification based on hand-texturing

Textural class	Symbol	Textural group
Coarse sand	CS	
Sand	S	
Fine sand	FS	
Very fine sand	VFS	
Loamy coarse sand	LCS	
Loamy sand	LS	Very light soils
Loamy fine sand	LFS	
Coarse sandy loam	CSL	
Loamy very fine sand	LVFS	Light soils
Sandy loam	SL	
Fine sandy loam	FSL	
Very fine sandy loam	VFSL	Medium soils
Silty loam	ZyL	
Loam	L	
Sandy clay loam	SCL	
Clay loam	CL	Heavy soils
Silt loam	ZyCL	
Silty clay loam	ZyCL	
Sandy clay	SC	Very heavy soils
Clay	C	
Silty clay	ZyC	

tends to increase the cohesiveness of light soils, reduce the cohesiveness of heavy soils, and large quantities can impart a silky or greasy feel. The prefix '**organic'** can be used for describing mineral soils with 15–20 per cent organic matter. Soils with 20–35 per cent organic matter are **peaty loams**, 35–50 per cent organic matter **loamy peats** and soils with greater than 50 per cent organic matter are termed **peaty**. **Peats** are almost pure organic matter (see organic soils p320).

Mechanical analysis of soils

Soil texture can be determined by finding the particle size distribution. There are several methods, but all depend on the complete separation of the particles, the destruction of organic matter and the removal of particles greater than 2 mm in diameter. Sieving can separate the stones, coarse sand, medium sand and fine sand fractions.

Finer particles are usually separated by taking advantage of their different **settling velocities** when in suspension. The settling velocity of a particle depends on its density and radius, the viscosity and density of the liquid and the acceleration due to gravity; the method is simplified by assuming that soil particles are spherical and have the same density and the investigations are conducted in water at 20°C.

Particles that are less than 0.001 mm in diameter are kept permanently in suspension by the bombardment of vibrating water molecules and are referred to as **colloids**, e.g. most clay particles. All sand particles will have fallen more than 10 cm after 50 seconds, so a sample taken at that depth can be used to calculate the clay plus silt left in the suspension. Similarly, other fractions can be calculated until the sand, silt and clay are determined. The soil texture can be deduced from this information using a **textural triangle** (Figure 17.11), which is the basis of identifying soil types.

Soil structure

Soil structure is the arrangement of particles in the soil.

In order to provide a suitable root environment for cultivated plants the soil must be constructed in such a way as to allow good gaseous exchange, whilst holding adequate reserves of available water. There should be a high water infiltration rate, free drainage and an interconnected network of spaces allowing roots to find water and nutrients without hindrance. There should be no large cavities that prevent thorough contact between soil and roots and allow roots to dry out in the seedbed. The soil should be managed so that erosion is minimized. Good structural stability should be maintained so that the structure does not deteriorate and limit crop growth.

Porosity

The plant roots and soil organisms live in the pores between the solid components of the growing medium. In the same way that a house is mainly judged by the living accommodation created by the bricks, wood, plaster, cement, etc., so a soil is evaluated by examining the spaces created.

The key to managing most growing media is in maintaining a high proportion of **air-filled pores** without restricting water supply.

Pores greater than about 0.05 mm in diameter, called **macropores**, can drain easily to allow in air within hours of being saturated (i.e. fully wetted), whereas the smaller pores, **micropores** continue to contain only water. The roots remove more water from these micropores allowing more air back into the soil (see soil water p338). Ideally, there should be a mixture of pore sizes allowing good water holding, free drainage, gaseous exchange and thorough root exploration, as shown in Figure 17.12.

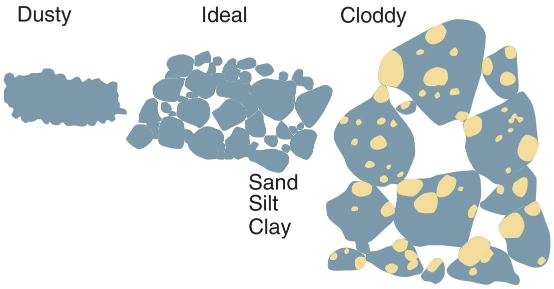


Figure 17.12 **Tilth**. The ideal tilth for most seedbeds is made up of soil aggregates between 0.5 and 5 mm diameter. Within these crumbs are predominantly small pores (less than 0.05 mm) that hold water and between the crumbs are large pores (greater than 0.05 mm) that allow easy water movement and contain air when soil is at field capacity (×5 actual size).

An important indicator of a satisfactory growing medium is its air-filled porosity or air capacity, i.e. the percentage volume filled with air when it has completed draining, having been saturated with water.

Bulk density is the mass of soil per unit volume and it can be measured by taking a core of soil of known volume and weighing it after thorough drying. In normal mineral soils results are usually between 1.0 and 1.6 g/ml. The difference is largely attributable to variation in total pore space. Finer textured soils tend to have more pore space and therefore lower bulk density than sands, but for all soils higher values indicate greater packing or **compaction**.

This information is not only useful to diagnose compaction problems, but can also be used to calculate the weight of soil in a given volume. Assuming a cultivated soil to have a bulk density of 1.0 g/ml, the weight of dry soil in one hectare to a plough depth of 15 cm is 1500 tonnes; when compacted the same volume weighs 2400 tonnes. Similarly, 1 m^3 of a typical topsoil with a bulk density of 1.0 will weigh 1 tonne (1000 kg) when dry and up to half as much again when moist.

Soil structures

The pore space does not depend solely upon the size of the soil particles as shown in Figure 17.8, because they are normally grouped together. These **aggregates**, or peds, are groups of particles held together by the adhesive properties of clay and humus. The ideal arrangement of small and large pores for establishing plants is illustrated in Figure 17.12 alongside a dusty tilth with too few large pores and a cloddy tilth that has too many large pores.

A soil with a **simple structure** is one in which there is no observable aggregation. If this is because none of the soil particles are joined together, as in sands or loamy sands with low organic matter levels, it is described as **single grain** structure. Where all the particles are joined with no natural lines of weakness the structure is said to be **massive**.

A **weakly developed** structure is one in which aggregation is indistinct and the soil, when disturbed, breaks into very few whole aggregates, but a lot of unaggregated material. This tends to occur in loamy sands and sandy loams. Soils with a high clay content form **strongly-developed** structures in which there are obvious lines of weakness and, when disturbed, aggregates fall away undamaged. The prismatic, angular blocky, round blocky, crumbs and platy structures which are found in soils are illustrated in Figure 17.13.

Development of soil structures

Soil structure develops as the result of the action on the soil components of natural **structure-forming agents**, freezing and thawing, wetting and drying, root growth, soil organisms, as well as the influence of cultivation:

- **frost** leads to the shattering of clods by producing a frost mould. It is largely confined to the surface layers and is advantageous in the management of clays;
- **drying** soil can affect the whole rooting depth. Cracks usually open up in heavier soils as the clay shrinks;
- **earthworms** and other soil organisms play an important part in loosening soil, maintaining the network of drainage channels and stabilizing the soil structure;

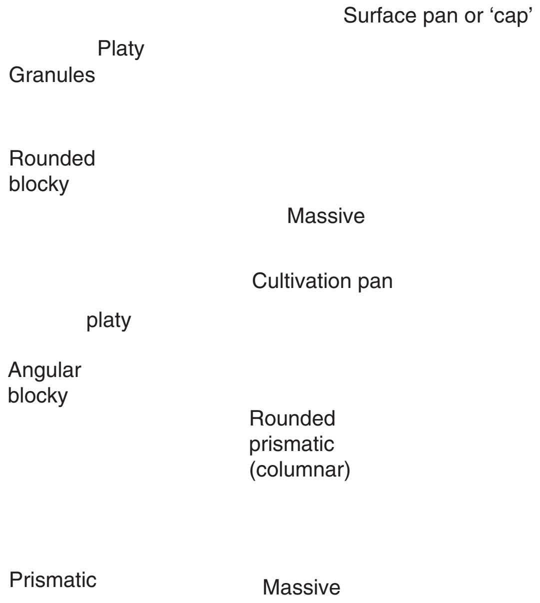


Figure 17.13 **Soil structures**. The soil profile on the left is composed of soil particles aggregated into structures that produce good growing conditions. Examples of structures that create a poor rooting environment are shown in the profile on the right.

- **roots** have a major effect on the drying of deeper soil layers, but they also play an important part in soil structure by growing into the cracks and keeping them open. They help establish the natural fracture lines. In strong structures, a close-fitting arrangement of **prismatic** (see Figure 17.13) or **angular blocky** aggregates is readily seen.

In soils with low clay content the roots are vital in maintaining an open structure. The exploring roots probe the soil, opening up channels where the soil is loose enough and producing sideways pressure as they grow. On death, the root leaves behind channels stabilized by its decomposed tissue for other roots to follow. Fine **granular** structures are developed under pastures by the action of the fibrous rooting over many years. The soil structure is greatly improved by the rootball. Its physical influence is most easily appreciated by shaking out the soil crumbs from around the root of a tuft of well-established grass and comparing them with the structure of soil taken from a nearby bare patch.

Freshly exposed land is often referred to as **raw**; when weathered it becomes mellow. Once **mellow**, a seedbed is more easily prepared. The weathering process and influence of cultivation tend to produce rounded blocky **structures** and **rounded granules** in the cultivated zone.

Cultivation of soil by hand or mechanized implements is undertaken to produce a suitable rooting environment for plants, to destroy pests and weeds and to mix in plant residues, manures and fertilizers (see p374). However, the use of cultivators can lead to the formation of platy layers or **pans**, which are characterized by the lack of vertical cracks and form an obstruction to root and water movement. The surface of soils is also compacted to create surface capping by associated traffic, whether by feet or tyres, if undertaken in the wrong conditions (see soil consistency p342).

Natural pans develop in some soils as a result of fine material cementing a layer of soil together. In some sandy soils rich in iron oxide, these oxides cement together a layer of sand where there has been a fluctuating water table, to produce an **iron pan**.

Structural stability

The **structural stability** of soil refers to its ability to resist deformation when wet.

Soil aggregates with little or no stability collapse spontaneously as they soak up water, i.e. they slake. Those high in fine sand or silt are particularly vulnerable to slaking. Aggregates with better stability maintain their shape when wetted for a short time, but gradually pieces fall off if left immersed in water. Aggregates with **good structural stability** are able to resist damage when wet unless vigorously disturbed. Soils with a high level of clay content have better stability than those with low levels. Stability is also increased by the presence of calcium carbonate (chalk), iron oxides, and, most importantly, **humus** (see p326).

Tilth

Tilth is the structure of the top 50 mm of the soil.

The soil surface or seedbed should be carefully managed to produce the required crumb structure.

Sandy soils are easily broken down to the right size with cultivation equipment. Heavier soils are less easy to cultivate and benefit from weathering to produce a frost ‘mould’.

The fineness of a seedbed should be related to the size of seeds, but ideally consists of granules or crumbs between 0.5 and 5 mm in diameter (see Figure 17.12). Cloddy surfaces lead to poor germination, as well as poor results from soil herbicide treatments. The rain on the soil surface breaks down tilth. As soil crumbs break up, the particles fill in the gaps; this reduces infiltration rates. As the surface dries, a **cap** or **pan** is formed (Figure 17.14). Thus fine ‘dusty’ tilths should be avoided and the soil crumbs should be stable so that they can withstand the effect of rain until plants are established. This is particularly important on fine sandy and silty soils, which tend to have poor structural stability. In general, fine tilths should be avoided outdoors until well into spring when conditions are becoming more favourable and growth through any developing cap is rapid.

Figure 17.14 Soil cap.

Cultivations

In temperate areas, the conventional preparation of land for planting is a thorough disturbance of the top 20–30 cm of soil. Digging or ploughing buries residues of previous plantings and weeds, and with repeated passes of rakes or harrows a suitable **tilth** is created (see p313). This procedure is very demanding on energy, labour and time. Many of the cultivations tend to interfere with the natural structure-forming agents and when undertaken at the wrong time they create pans or leave a bare, loose soil vulnerable to erosion (see soil structure p311).

Some of the compaction problems are overcome by cultivating in **beds** which confines traffic to well-defined paths between the growing areas. The advent of effective herbicides has, in certain cases, enabled the inversion of soil to be eliminated. The use of powered implements has speeded up work and reduced the number of tillage passes. In some areas of horticulture the adoption of **minimum** or **zero tillage** has preserved natural structure while beneficially concentrating organic matter levels in the surface layers and reducing wind and water erosion.

Ploughing and digging

Ploughing and digging are used to loosen and invert the soil. The land is broken up into clods and an increased area is exposed to weathering. As the soil is inverted, weeds, plant residues and bulky manures are incorporated. The depth of ploughing or digging should be related to the depth of topsoil, because bringing up the subsoil reduces fertility in the vital top layers, seriously affecting germination of seeds and establishment of plants. If deeper layers are to be loosened a **subsoiler** should be used. In plastic soil conditions the plough can smear the soils, more so if the wheels of the tractor spin in the furrow bottom. These **plough pans** tend to develop with successive ploughing to the same depth. Ploughing at different depths or attaching a subsoil tine can reduce their incidence. Digging with a spade does not produce a cultivation pan and is still used on small areas. **Spading machines** or **rotary diggers** imitate the digging action without the disadvantages of ploughing, but tend to be very slow.

Rotary cultivators

Rotary cultivators are used to create a tilth on uncultivated or on roughly prepared ground. The type of tilth produced depends on suitable adjustment of forward speed, rotor speed, blade design and layout, shield angle and depth of working. The 'hoe' blade is normally used for seedbed production, but does have the disadvantage of smearing plastic soils at the cultivation depth, producing a **rotovation pan** . 'Pick' tines produce a rougher tilth, but less readily cause a pan. Subsoil tines can be fitted to prevent these pans developing.

Harrowing and raking

Harrowing and raking are methods of levelling soils, incorporating fertilizers and producing a suitable tilth on the roughly prepared ground. The soil must be in a **friable** condition (see p342) for this operation and it is made easier if the top layers have been suitably weathered. The impact of the tines breaks the clods. The number of passes to create a seedbed has been reduced by the use of rotavators and other equipment that completes several of the stages in one pass (see Figure 17.15).

‘Progressive’ type cultivators were introduced essentially to loosen coarse structured clays by drawing through the soil banks of tines, increasing in depth from the front, to cultivate the soil from the top down in one pass. Although this requires powerful tractors to pull, especially if subsoiling tines are attached, it is a time-saving operation and the recompaction inherent in multiple pass methods is reduced. These cultivators should not be used on well-structured soils where full depth loosening is unnecessary.

Figure 17.15 **Seedbed preparation**. Several stages of the process are completed in a single pass

‘Under-loosening’ cultivators have been designed to loosen compact topsoils without disturbing the surface, which ensures a level, clod-free and organic-matter-rich tilth. Used under the right conditions these implements improve water movement and plant growth. However, loosened soils are more susceptible to compaction and consequently the equipment should only be used when compaction is known to be present.

Subsoiling

Subsoiling is used to improve soil structure below plough depth by drawing a heavy cultivation tine through the soil to establish a system of deep cracks in compacted zones. This helps the downward movement of water, circulation of air and penetration of roots (see Figure 17.16). The operation is most effective when the subsoil is friable and the surface

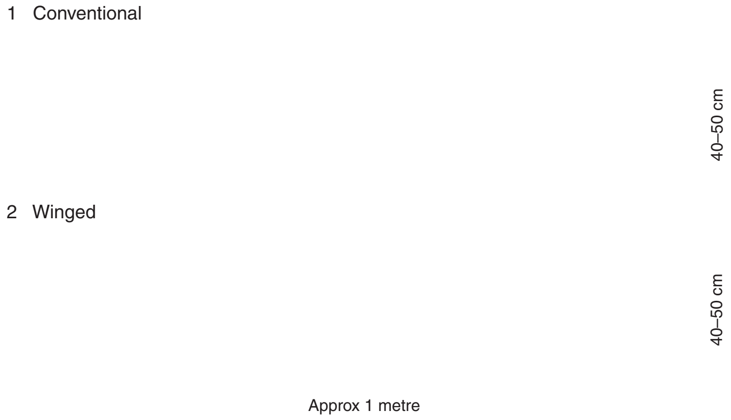


Figure 17.16 **Subsoiling**. The subsoiler is drawn through the soil to burst open compacted zones. It leaves cracks which remain open to improve aeration, drainage, and root penetration. The cracks created should link up with artificial drainage systems unless the lower layers are naturally free draining

dry enough to be able to withstand the heavy tractor that is needed (see loadbearing).

Effective subsoiling is made easier if the top surface is loosened by prior cultivation. Although the draught is higher, subsoil disturbance is increased substantially by attaching inclined blades or wings. Successful subsoiling is accompanied by a lift in the soil surface (soil heave) which usually makes it unsuitable for improving conditions in playing fields.

Subsoiling should only be used when the cause of any waterlogging is related to a soil structure fault (see also drainage). Slow subsoil permeability caused by high clay content is usually rectified with **mole drainage** (see p345). If the soil is too sandy or stony, a subsoiler can be used so long as the cracks created lead the water into a natural or artificial drainage system. Subsoilers used in the right conditions readily burst massive structures and soil pans created by machinery, but some natural pans are too strong for normal equipment. The problem of cultivation pans can be dealt with by using conventional subsoilers or by attaching small subsoil tines to the cultivation equipment. This tends to increase the power requirement but eliminates the pan as it is created.

Management of main soil types

Sandy soils

Sandy soils are usually considered to be easily cultivated, but serious problems can occur because the particles readily pack together, especially when organic matter levels are low. Consequently many sandy soils are difficult to firm adequately without causing over-compaction. Pans near the surface caused by traffic and deeper cultivation pans frequently occur on sandy soils, resulting in reduced rooting and water movement. **Subsoiling** is frequently undertaken on a routine basis every 4–6 years, although the need can be reduced by keeping machinery off land while it has low **load-bearing** strength (see p342) and by encouraging natural structure-forming agents.

Coarse sands have low water-holding capacity, which makes them vulnerable to drought, particularly in drier areas. This is not such a disadvantage if irrigation equipment is installed and water is readily obtainable. In many categories of horticulture there is a demand for soils with **good workability**. Coarse sands, loamy sands and sandy loams have the advantage of good porosity and can be cultivated at field capacity. Sands tend to go acid rapidly and are vulnerable to overliming because of their **low buffering capacity** (see p359).

Silts and fine sands

These can be very productive soils because of their good water-holding capacity and, while organic matter levels are kept above 4 per cent, their ease of working. However silts and fine sands present soil management problems, especially when used for intensive plantings, because they have **weak structure**, are vulnerable to **surface capping**, and are easily compacted to form **massive structures**. To achieve their high potential, efficient drainage is vital to maximize the rooting depth. Fine tilths in the open should be avoided, especially in autumn and early spring, because frosts and heavy rainfall reduce the size of surface crumbs. For the same reason, care should be taken with irrigation droplet size that, if too large, can damage the surface structure. Improving soil structure is not easy after winter root crop harvesting or orchard spraying on wet soils, because low clay content results in very little cracking during subsequent wetting and drying cycles. Improvement therefore depends on other natural structure forming agents or on subsoiling.

Clay soils

Clay soils tend to be **slow draining**, **slow to warm** up in spring, and have **poor working properties** (see soil consistency p342). A serious limitation is that the soil is still plastic at field capacity, which delays soil preparation until it has dried by evaporation. Permanent plantings are established to avoid the need to rework the soil. Playing surfaces created over clays have severe limitations, particularly when required for use in all-weather conditions. Where high standards have to be maintained, as in golf greens, fine turf is established in a suitable growing medium overlying the original soil. However, a high clay content is an advantage for the preparation of cricket squares where a hard, even surface is required but is played on only in drier weather. Increasingly, heavily used areas are replaced by artificial surfaces.

Horticultural cropping of clays is limited to summer cabbage, Brussels sprouts and to some top fruit in areas where the water table does not restrict rooting depth. Under-drainage is normally necessary. In wetter areas most clay soils are put down to grass. Timeliness, encouraging the annual drying cycle of the soil profile and maximizing the effect of weathering to help cultivations are essential for successful management of clay soils.

Peat soils

Peat soils (see p328) have very many advantages over mineral soils for intensive vegetable and outdoor flower production. Fenland soils and Lancashire Moss of England; peatlands of the midland counties of Ireland; the ‘muck’ soils of North America; and similar soils in the Netherlands, Germany, Poland and Russia have proved valuable when their limitations to commercial cropping have been overcome.

Well-drained peat at the correct pH is an **excellent root environment**. It has a very much higher water-holding capacity than the same volume of soil and yet gaseous exchange is good. Root development is uninhibited because friable peat offers hardly any mechanical resistance to root penetration. This leads to high quality root crops that are easily cleaned. These cultivated peat lands **warm up quickly** at the surface because the sun’s energy is efficiently absorbed by their dark colour, with consequent rapid crop growth. These soils have a very **low power requirement** for cultivation, are free of stones, and can be worked over a wide moisture range.

Plant nutrition is complicated by natural **trace element deficiencies** and the effect of pH on plant **nutrient availability**. Peat has **poor load-bearing** characteristics and specialized equipment is often needed to harvest in wet conditions. Whilst peat warms up quickly on sunny days, its dark surface makes it vulnerable to air frost because it acts as an efficient radiator. Firming the surface and keeping it moist combat this. Weeds grow well and their control is made more difficult by the ability of peat to absorb and **neutralize soil-acting herbicides**. The high organic matter levels also make the peats and sandy peats **vulnerable to wind erosion** in spring when the surface dries out and there is no crop canopy to protect it.

Check your learning

1. Describe the profile of a typical mineral soil.
2. Describe the differences between topsoil and subsoil.
3. Summarize the differences between the main soil types.
4. State the differences between soil texture and structure.
5. State how structure in cultivated soils is: a) improved; b) damaged.
6. Explain how soil development occurs on poorly drained soils in a temperate area.

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Chapter 18 Soil organic matter

Summary

This chapter includes the following topics:

- **Organic matter in soil**
- **Decomposition of organic matter**
- **Nutrient cycles**
- **Humus**
- **Benefits of organic matter**
- **Bulky organic matter**
- **Methods of composting**
- **Green manures**

with additional information on the following:

- **The rhizosphere**
- **Carbon to nitrogen ratio**
- **Organic matter levels in the soil**
- **Organic soils**
- **Mulching**

Figure 18.1 **Earthworms**. Casting worms in the foreground eat organic matter and soil and most cast the waste on the surface. In the background are worms that only eat organic matter which we find in compost heaps and wormeries

Organic matter in soil

The main **types of organic matter** in the soil are

- living organisms;
- dead, but recognizable;
- dead but decomposed;
- humus.

A typical mineral soil contains between 2 and 5 per cent organic matter. This is made up of **living organisms** such as plant roots, earthworms, insects, fungi and bacteria. On death these then decompose along with any other organic matter that is incorporated, either naturally such as leaves or by the addition of organic matter from elsewhere such as compost, farmyard manure, spent mushroom compost, coir and bark. Many of the living organisms are responsible for the decomposition of the **dead organic matter**. This is eventually broken down into its component parts becoming carbon dioxide, water, and minerals; all of which is recycled. There also persists for a very long time a group of organic compounds collectively known as **humus**.

Living organisms in the soil

As in any other plant and animal community the organisms that live in the soil form part of the **food webs** (see p53). The main types present in any soil are the **primary producers** which are those capable of utilizing the sun's energy directly, synthesizing their own food by photosynthesis, such as green plants (see photosynthesis), the **primary consumers** which are those organisms which feed directly on plant material, and **secondary consumers** which feed only on animal material. In practice, there are some organisms that feed on both plants and animals and also parasites living on organisms in all categories many of which are pests or diseases of horticultural plants.

Decomposers are an important group, which have the special function within a community of breaking down dead or decaying matter into simpler substances with the release of inorganic salts, making them available once more to the primary producers. **Primary decomposers** are those organisms that attack the freshly dead organic matter. These include earthworms and some species of arthropods and fungi. Fungi are particularly important in the initial decomposition of fibrous and woody material. **Secondary decomposers** are those organisms that live on the waste products of other decomposers and include bacteria and many species of fungi.

Plant roots

These are important as contributors to the organic matter levels in the soil. They move soil particles as they penetrate the soil and grow in size. This rearrangement changes the sizes and shapes of soil aggregates and when these roots die and decompose, a channel is left which provides drainage and aeration. Root channels are formed over and over again unless the soil becomes too dense for roots to penetrate. Roots absorb water from soils and dry it, causing those with a high clay content to shrink and crack. This helps develop and improve structures on heavier soils (see p 311).

Earthworms

There are ten common species of earthworm in Britain that vary in size from *Lumbricus terrestris*, which can be in excess of 25 cm, to the many small species less than 3 cm long (see Figure 18.1). The main food of earthworms is dead plant remains. Casting species of earthworms are those that eat soil, as well as organic matter, and their excreta consist of intimately mixed, partially digested, finely divided organic matter and soil. Many species never produce casts and only two species regularly cast on the surface giving the **worm casts** that are a problem on fine grass areas, particularly in the autumn (see Figure 18.2). It has been estimated that in English pastures the production of casts each year is 20–40 t/ha, the equivalent of 5 mm of soil deposited annually. This surface casting also leads to the incorporation of the leaf litter and the burying of stones. However, *L. terrestris* is the organism mainly responsible for the **burying** of large quantities of litter by dragging plant material down its burrows.

Figure 18.2 **Earthworm cast**: comprise a mix of organic matter and finely divided soil which is good for the garden except where it is cast on the surface of turf

The **network of burrows** which develops as a result of worm activity is an important factor in maintaining a good structure, particularly in uncultivated areas and in soils of low clay content. Some species live entirely in the surface layers of the soil others move vertically establishing almost permanent burrows down to two metres.

Earthworm activity and distribution is largely governed by moisture levels, soil pH, temperature, organic matter and soil type. Most species tend to be more abundant in soils where there are good reserves of calcium. Earthworm populations are usually lower on the more acid soils, but most thrive in those near neutral. Worm numbers decrease in dry conditions, but they can take avoiding action by burrowing to more moist soil or by hibernating. Each species has its optimum temperature range; for *L. terrestris* this is about 10°C, which is typical of soil temperatures in the spring and autumn in the UK. Soils with low organic matter levels support only small populations of worms. In contrast, compost heaps and stacks of farmyard manure have high populations. In oak and beech woods where the fallen leaves are palatable to worms, their populations are large and they can remove a high proportion of the annual leaf-fall. This also happens in orchards unless harmful chemicals such as copper have reduced earthworm populations. Light and medium loams support a higher total population than clays, peat and gravelly soils.

Slugs, **snails** and **arthropods** (such as millipedes, springtails and mites), and **nematodes** are also found in high numbers and play an important part in the decomposition of organic matter. Several species are also horticultural pests (see Chapter 14).

Bacteria

Bacteria are present in soils in vast numbers. About 1000 million or more occur in each gram of fertile soil. Consequently, despite their microscopic size, the top 150 mm of fertile topsoil carries about one tonne of bacteria per hectare. There are many different species of bacteria to be found in the soil and most play a part in the **decomposition of organic matter**. Many bacteria attack minerals; this leads to the weathering of rock debris and the release of plant nutrients. **Detoxification** of pesticides and herbicides is an important activity of the bacterial population of cultivated soils.

Soil bacteria are inactive at temperatures below 6°C, but their activities increase with rising temperature up to a maximum of 35°C. Bacteria which are actively growing are killed at temperatures above 82°C, but several species can form thick-walled resting spores under adverse conditions. These spores are very resistant to heat and they survive temperatures up to 120°C. **Partial sterilization** of soil can kill the actively growing bacteria, but not the bacterial spores. The growth rate and multiplication also depends upon the **food supply**. High organic matter levels support high bacteria populations so long as a balanced range of nutrients is present. Bacteria thrive in a range of **pH 5.5–7.5**; fungi tend to dominate the more acid soils. Aerobic conditions should be maintained because the beneficial organisms, as well as plant roots, require oxygen, whereas many of the bacteria that thrive under anaerobic conditions are detrimental.

Fungi

The majority of fungi live saprophytically on soil organic matter. Some species are capable only of utilizing simple and easily decomposable organic matter whereas others attack cellulose as well. There are some important fungi that can decompose **lignin**, making them one of the few primary decomposers of wood and fibrous plant material. Several fungi in the soil are parasites and examples of these are discussed in Chapter 15. Fungi appear to be able to tolerate acid conditions and low calcium better than other micro-organisms and are abundant in both neutral and acid soils. Most are well adapted to survive in dry soils, but few thrive in very wet conditions. Their numbers are high in soils rich in plant residues but decline rapidly as the readily decomposable material disappears. The bacteria persist longer, where present, and eventually consume the fungal remains.

The rhizosphere

The rhizosphere is a zone in the soil that is influenced by roots. Living roots change the atmosphere around them by using up oxygen and producing carbon dioxide (see respiration p118). Roots exude a variety of organic compounds that hold water and form a coating that bridges the gap between root and nearby soil particles. Micro-organisms occur in greatly increased numbers and are more active in proximity to roots. Some actually invade the root cells where they live as **symbionts**. The *Rhizobium spp*. of bacteria lives symbiotically with many legumes (see nitrogen cycle p366).

Symbiotic associations involving plant roots and fungi are known as **mycorrhizae** (see Figure 18.3). There is considerable interest in

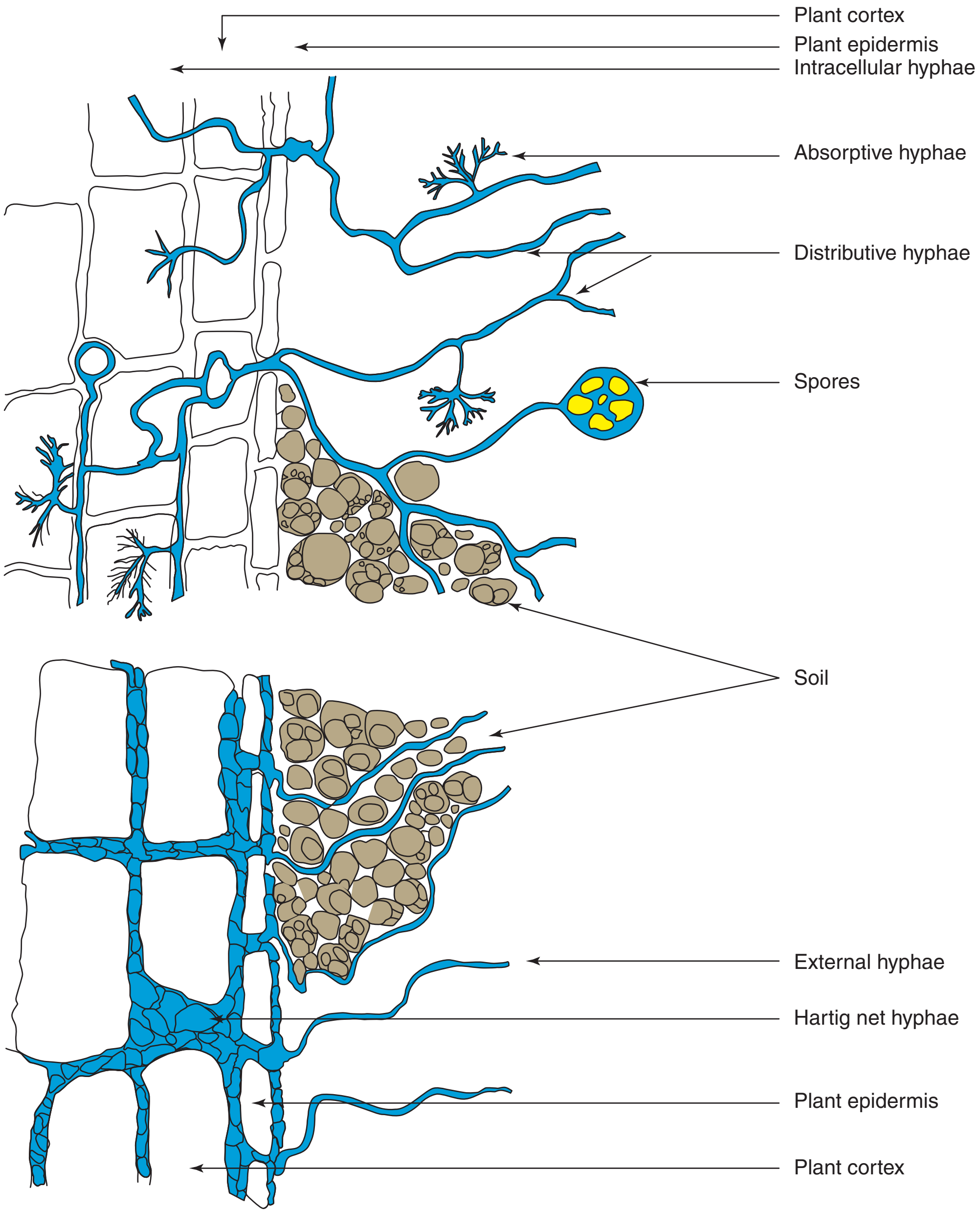

Figure 18.3 **Mycorrhizal structures**. Ectomycorrhizae, top found mainly around tree roots have most of their structure on the outside whereas the Endomycorrhiza have most of their hyphae on the inside of the very wide range of plants with which they are symbiotic

exploiting the potential of **mycorrhizae**, which appear to be associated with a high proportion of plants especially in less fertile soils. In this symbiotic relationship the fungus obtains its carbohydrate requirements from the plant. In turn, the plant gains greater access to nutrients in the soil, especially phosphates, through the increased surface area for absorption and because the fungus appears to utilize sources not available to higher plants. Most woodland trees have fungi covering their roots and penetrating the epidermis. Orchids and heathers have an even closer association in which the fungi invade the root and coil up within the cells. The association appears to be necessary for the successful development of the seedlings. Mycorrhizal plants generally appear to be more tolerant of transplantation and this is thought to be an important factor for orchard and container grown ornamentals.

Nutrient cycles

All the plant nutrients are in continuous circulation between plants, animals, the soil and the air. The processes contributing to the production of simpler inorganic substances, such as ammonia, nitrites, nitrates, sulphates and phosphates, are sometimes referred to as **mineralization**. Mineralization yields chemicals that are readily taken up by plants from the soil solution. The formation of humus, organic residues of a resistant nature, is known as **humification**. Both mineralization and humification are intimately tied up in the same decomposition process, but the terms help identify the end product being studied. Likewise it is possible to follow the circulation of carbon in the carbon cycle and nitrogen in the nitrogen cycle, although these nutrient cycles along with all the others are interrelated.

The carbon cycle

Green plants obtain their carbon from the carbon dioxide in the atmosphere and, during the process of photosynthesis, are able to fix the carbon, converting it into sugar. Some carbon is returned to the atmosphere by the green plants themselves during respiration, but most is incorporated into plant tissue as carbohydrates, proteins, fats, etc. The carbon incorporated into the plant structure is recycled and eventually released as carbon dioxide, as illustrated in Figure 18.4.

All living organisms in this food web release carbon dioxide as they respire. The sugars, cellulose, starch and proteins of **succulent** plant tissue, as found in young plants, are rapidly decomposed to yield plant nutrients and have only a short-term effect. In contrast, the **lignified tissue** of older plants rots more slowly. Besides the release of nutrients, **humus** is formed from this fibrous and woody material, which has a long-term effect on the soil. Plants grown in the vicinity of vigorously decomposing vegetation, e.g. cucumbers in straw bales, live in a carbon dioxide enriched atmosphere. Carbon dioxide is also released on combustion of all organic matter, including the fossil fuels such as coal and oil. Organic materials such as paraffin or propane, which do not produce harmful gases when burned cleanly, are used in protected culture for **carbon dioxide enrichment** (p113).

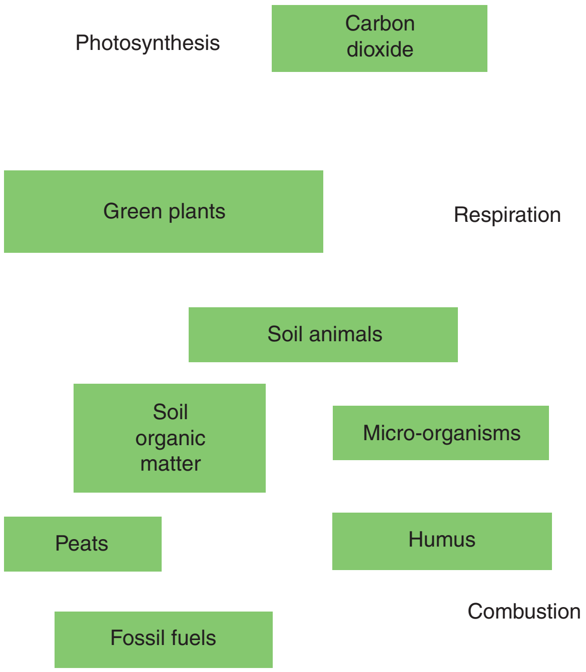

Figure 18.4 **Carbon cycle**. The recycling of the element carbon by organisms is illustrated. Note how all the carbon in organic matter is eventually released as carbon dioxide by respiration or combustion. Green plants convert the carbon dioxide by photosynthesis into sugars which forms the basis of all the organic substances required by plants but also animals and micro-organisms

The nitrogen cycle

The nitrogen cycle similarly follows the fate of nitrogen in its many forms in the plant, the soil and the atmosphere (see p366).

The sulphur cycle

Sulphur is an essential constituent of plants that accumulates in the soil in organic forms (see page 370). This sulphur does not become available to plants until aerobic micro-organisms mineralize the organic form to produce soluble **sulphates**. Under anaerobic conditions there are micro-organisms which utilize organic sulphur and produce hydrogen sulphide, which has a characteristic smell of bad eggs often evident in waterlogged soils in warm conditions.

Carbon to nitrogen ratio (C:N)

All nutrients play a part in all nutrient cycles simply because all organisms need the same range of nutrients to be active. Normally there are adequate quantities of nutrients, with the exception of carbon or nitrogen, which are needed in relatively large quantities. A shortage of nitrogenous material would lead to a hold-up in the nitrogen cycle, but would also slow down the carbon cycle, i.e. the decomposition of organic matter is slowed because the micro-organisms concerned suffer a shortage of *one* of their essential nutrients. A useful way of expressing the relative amounts of the two important plant foods is in the carbon to nitrogen (C:N) ratio.

Plant material has relatively wide C:N ratios, but those of micro-organisms are much narrower. This is because micro-organisms utilize about three quarters of the carbon in plants during decomposition as an energy source. The carbon utilized this way is released as carbon dioxide, whereas, usually, all the nitrogen is incorporated in the microbial body protein. This concentrates the nitrogen in the new organism that is living on the plant material.

Sometimes the C:N ratio is so wide that some nitrogen is drawn from the soil and 'locked up' in the microbial tissue. This is what happens when **straw** (and similar fibrous or woody material such as wood chips and bark) with a ratio of 60:1 is dug into the soil (see Table 18.1). For example, if one thousand 12 kg bales of straw are dug into one hectare of land then the addition to the soil will be 12 000 kg of straw containing 4800 kg of carbon and 80 kg of nitrogen. Three-quarters of the carbon (3600 kg) is utilized for energy and lost as carbon dioxide and a quarter (1200 kg) is incorporated over several months into microbial tissue. Microbial tissue has a C:N ratio of about 8:1, which means that by the time the straw is used up some 150 kg of nitrogen is locked up with the 1200 kg of carbon in the micro-organisms. Since there was only 80 kg of nitrogen in the straw put on the land, the other 70 kg has been 'robbed' from the soil. This nitrogen is rendered unavailable to plants ('locked up') until the micro-organisms die and decompose. To ensure rapid decomposition or to prevent a detrimental effect on crops the addition of straw must be accompanied by the addition of nitrogen.

Nitrogen is released during decomposition if the organic material has a C:N ratio narrower than 30:1, such as young plant material, or with nitrogen-supplemented plant material such as farmyard manure (FYM).

Dead organic matter in the soil

The dead organic matter has an important effect on the soil. The fresh, still recognizable material physically 'opens up' the soil, improving aeration. Active micro-organisms gradually decompose this material until it consists of unrecognizable plant and micro-organism remains. This finer material has less physical effect, but usually improves the water holding capacity of the soil.

In general, succulent ('green', leafy) organic matter decomposes very rapidly, so long as conditions are right, so has only a short-term physical effect, but yields nutrients, especially nitrogen compounds. The fibrous or woody ('brown') plant material tends to decompose very slowly so its physical effect persists, but nutrient contributions are low. The distinction between the 'green' and 'brown' organic matter is a crude but useful one when composting (p333).

Humus

This process of decomposition continues until all the organic matter is reduced to carbon dioxide, water, minerals and humus. The **humus** arises from a small proportion of the fibrous ('brown') organic matter which is highly resistant to decomposition; the lignin and other resistant chemicals form a collection of humic acids which forms a black colloidal (jelly-like) material. The humus coats soil particles and gives topsoil its characteristic dark colour.

This colloidal material has a high **cation exchange capacity** and therefore can make a major contribution to the retention of exchangeable cations, especially on soils low in clay (see sands p304). It also adheres strongly to mineral particles, which makes it a valuable agent in soil **aggregation**. In sandy soils it provides a means of sticking particles together, whereas in clays it forms a clay-humus complex that makes the heavier soils more likely to crumble. Its presence in the soil crumbs makes them more stable, i.e. more able to resist collapse when wetted, and it increases the range of soil **consistency** (see p342). Bacteria eventually decompose humus so the amount in the soil is very dependent on the continued addition of appropriate bulky organic matter.

Organic matter levels

The routine laboratory method for estimating **organic matter** levels depends upon finding the total carbon content of the soil. A simpler method is to dry a sample of soil and burn off the organic matter. After cooling, the soil can be re-weighed and the loss in weight represents destroyed organic matter. These methods give an overall total of soil organic matter excluding the larger soil animals.

Most topsoil contains between 2 per cent and 5 per cent of organic matter, whereas subsoil usually contains less than 2 per cent. The distribution of organic matter under grass in normal temperate areas is shown in Figure 18.5.

The organic matter is concentrated in the topsoil because most of the roots occur in this zone and the plant residues tend to be added to the surface, forming the leaf litter layer. The organic matter level in any part of the soil depends upon how much fresh material is added compared with the rate of decomposition. It is stable when these two processes are balanced and the equilibrium reached is determined mainly by climate, soil type and treatment under cultivation.

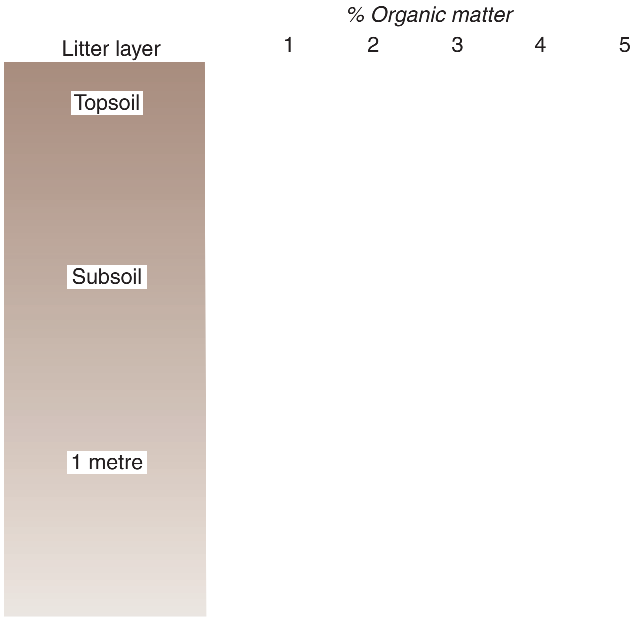

Figure 18.5 **Distribution of organic matter** in an uncultivated soil. Organic matter content of soil decreases from the soil surface downwards. Note that the topsoil is significantly richer in humus, which gives it a characteristically darker colour

Climate

Climate affects both the amount of organic matter added and the rate of decomposition. Below 6°C there is no microbial activity, but it increases with increasing temperature so long as conditions are otherwise favourable. In dry areas there is not only less plant growth, resulting in less organic matter being added to the soil, but also less microbial action. In **warm climates**, where there is adequate moisture, low organic matter results from very much increased decomposition. In **cooler areas** there tends to be an accumulation of organic matter because the decreased plant growth is more than offset by the reduced micro-organism activity that occurs over the long winter periods. Organic matter also tends to accumulate in **wetter conditions**. Where waterlogging is prevalent, 10–20 per cent organic matter levels develop; where waterlogging is permanent organic matter accumulates to give rise to **peat**.

Soil type

Generally, soils with higher clay contents have higher organic matter levels. Coarse sands and sandy loams tend to be warmer than finer textured soils and have better aeration, which results in higher microbial activity. Such soils often support less plant growth because of poor fertility and poor water holding capacity. These factors combine to give soils with low organic matter levels. In cultivation these same soils become a problem unless large quantities of organic matter are applied at frequent intervals to maintain adequate humus levels. Such soils are often referred to as ‘hungry soils’ because of their high demand for manure. On finer-textured soils the higher fine sand, silt or clay content increases water holding capacity. This reduces soil temperature, resulting in less microbial activity. The presence of clay directly reduces the rate of decomposition because it combines with humus and protects it from microbial attack.

Cultivation

Once soil has been cultivated a distinct boundary between topsoil and subsoil is developed as the concentration of organic matter in the surface layers is evened out (see Figures 18.5 and 17.5). On first cultivation the increased aeration and nutrients stimulate micro-organisms and a new equilibrium with lower soil organic matter levels prevails. Once under cultivation grasses and high-producing legumes tend to increase organic matter levels, but most crops, particularly those in which complete plant removal occurs, lead to decreased levels. Only large, regular dressings of bulky organic matter such as compost, straw, farmyard manure or leaf mould can improve or maintain the level of soil organic matter on cultivated soils.

Organic matter can accumulate under grass and form a mat on the surface where the carbon cycle is slowed because of nutrient deficiency usually induced by surface soil acidity or excess phosphate levels. This is part of the reason for the development of ‘thatch’ in turf (see Figure 18.6).

Figure 18.6 **Thatch**. This shows the build-up of organic matter in the surface of the turf

Organic soils

While all soils contain some organic matter, most are classified as mineral soils. However, at levels above about 15 per cent (when the organic matter present dominates the soil properties) they become classified as ‘organic soils’, e.g. organic clay loam. They develop where decomposition is slow because the activity of micro-organisms is reduced by cold, acidity or waterlogged conditions. **Peaty soils** are those where organic matter content is greater than 50 per cent; if content is more than 95 per cent the soil is considered to be a **peat**.

Peat is formed from partially decomposed plant material. This usually develops in waterlogged conditions where decomposition rates are low. There are great differences between peats because of the range of species of plants involved, which in turn depends on the conditions where they occur. Some peat is formed in shallow water, as found in poorly drained depressions or infilling lakes. In such circumstances the water drains from surrounding mineral soils and consequently has sufficient nutrients to support vegetation, often dominated by sedges, giving rise to **sedge peat**. As the waterlogged area, pond or lake becomes full of humified organic matter it forms a bog, moor or fen. In wetter areas, **sphagnum moss**, which is able to live on the very low nutrient levels that prevail, grows on top of the infilled wet land.

The dead vegetation becomes very acid and decomposes slowly. It builds up to form a high moor; sphagnum moss growing on top of very slowly decomposing sphagnum moss.

Some of the peatlands that are enriched with minerals prove very valuable when drained, e.g. the fenlands of eastern England. They are easily worked to produce vegetables and other high value crops. Unfortunately the increased aeration allows the organic matter to be decomposed at a rate faster than it can be replenished. Furthermore, when the surface dries out, the light particles are vulnerable to wind erosion. Consequently the soil level of these areas is falling at a rate of about three metres every hundred years. This can be checked by keeping the water table as high as possible and providing protection against wind.

Benefits of organic matter

Organic matter plays an important part in the management of soils. The main benefits are:

- **living organisms** in the soil play their part in the conversion of plant and animal debris to minerals and humus;
- *Rhizobia* and *Azotobacter spp*. fix gaseous nitrogen;
- plant roots, earthworms and other burrowing organisms improve the soil structure;
- many types of bacteria play an important role in the detoxification of harmful organic materials such as pesticides and herbicides;
- **dead organic matter** is food for soil organisms and increases microbial activity;
- dead but recognizable organic matter physically opens up the soil and improves aeration;
- fine, unrecognizable organic matter helps improve the water holding capacity of the soil;
- decomposing organic matter provides a source of dilute slow release fertilizer;
- **humus** coats soil particles with a black colloid and modifies their characteristics:
  - darker soils warm up faster in the spring;
  - organic matter improves water-holding capacity;
  - cation exchange capacity is increased, which can reduce the leaching of cations from the profile;
  - on sandy and silty soils the humus enables stable crumbs to be formed;
  - the surface charges on humus are capable of combining with the clay particles, thereby making heavy soils less sticky and more friable.

Addition of organic matter

It is normal in horticulture to return plant **residues** to cultivated areas where possible. Whether or not the plant remains are worked into the soil in which they have been grown depends upon their nature. The residue of some crops, such as tomatoes in the greenhouse, is removed to reduce disease carry over and because it cannot easily be incorporated into the soil. Other crops, such as hops, are removed for harvesting and some of the processed remains, spent hops, can be returned or used elsewhere. Wherever organic matter is removed, whether it is just the marketed part, such as top fruit from the orchard, or virtually the whole crop, such as cucumbers from a greenhouse, the nutrients removed must be replaced to maintain fertility (see also fertilizers).

Open, easily worked soils are created by the addition of large quantities of bulky organic matter. Clay soils are made easier to manage and their working range increased by the addition of organic matter. Stable, well-structured sands and silts are only possible under intensive cultivation if high humus levels are maintained by the addition of large quantities of bulky organic matter.

Bulky organic matter, such as compost, straw, farmyard manure and peat, is an important means of maintaining organic matter and humus levels. It also 'opens up' the soil, i.e. improves porosity. The main problem is finding cheap enough sources because their bulk makes transport and handling a major part of the cost. They can be evaluated on the basis of their effect on the physical properties of soil and their small, nutrient content.

Straw

Straw is an agricultural crop residue readily available in many parts of the country, but care should be taken to avoid straw with harmful **herbicide residues**. It is ploughed in or composted and then worked in. There appears to be no advantage in composting if allowance is made for the demand on nitrogen by soil bacteria. About 6 kg of nitrogen fertilizer needs to be added for each tonne of straw for composting to preventing soil robbing (see p325). Chopping the straw facilitates its incorporation and while not decomposed it can open up soils. On decomposition it yields very little nutrient for plant use, but makes an important contribution to maintaining soil humus levels. Straw bales suitably composted on site are the basis of producing an open growing medium for cucumbers.

Farmyard manure (FYM)

This is the traditional material used to maintain and improve soil fertility. It consists of straw or other bedding, mixed with animal faeces and urine. The exact value of this material depends upon the proportions of the ingredients, the degree of decomposition and the method of storage. Samples vary considerably. Much of the FYM is rotted down in the first growing season, but almost half survives for another year and half of that goes on to a third season and so on. A full range of nutrients is released into the soil and the addition of major nutrients should be allowed for when calculating **fertilizer requirements**. The continued release of large quantities of nitrogen can be a problem, especially on unplanted ground in the autumn, when the nitrates formed are leached deep into the soil over the winter and can pollute waterways.

FYM is most valued for its ability to provide organic matter and humus for maintaining or improving soil structure. As with any bulky organic matter, FYM must be worked into soils where conditions are favourable for continued decomposition to occur. Where fresh organic matter is worked into wet and compacted soils, the need for oxygen outstrips supply and anaerobic conditions develop to the detriment of any plants present. Where this occurs a foul smell (see sulphur p325) and grey colourings occur. FYM should not be worked in deep, especially on heavy soil.

Horticultural peats

Sphagnum moss peats have a fibrous texture, high porosity, high water retention and a low pH. They are used extensively in horticulture as a source of bulky organic matter and are particularly valued as an ingredient of potting composts because, with their stability, excellent porosity and high water retention, they can be used to create an almost ideal root environment.

Sedge peats tend to contain more plant nutrients than sphagnum moss. They are darker, more decomposed and have a higher pH level, but also have a slightly lower water-holding capacity. They tend to be used for making peat blocks. Considerable efforts are being made to find alternative materials to replace peat in order to avoid destroying valued wetland habitats from which they are harvested.

Leaves

Leaf mould is made from rotted leaves of deciduous trees. It is low in nutrients because nitrogen and phosphate are withdrawn from the leaves before they fall and potassium is readily leached from the ageing leaf. They are often composted separately from other organic matter and much valued in ornamental horticulture for a variety of uses, such as an attractive mulch, or when well rotted down, as a compost ingredient. They are commonly composted in mesh cages, but many achieve success by putting them in polythene bags well punched with holes. The leaves alone have a high C:N ratio so decomposition is slow and it is not usually until the second year that the dark-brown crumbly material is produced, although the process can be speeded up by shredding the leaves first.

Unless they are from trees growing in very acid conditions, the leaves are rich in calcium and the leaf mould made from them should not be used with calcifuge plants. **Pine needles** are covered with a protective layer that slows down decomposition. They are low in calcium and the resins present are converted to acids. This extremely acid litter is almost resistant to decomposition. It is valued in the propagation and growing of calcifuge plants, such as rhododendrons and heathers, and as a material for constructing decorative pathways.

Air-dried digested sludge

This consists of sewage sludge that has been fermented in sealed tanks, drained and stacked to dry. The harmful organisms and the objectionable smells of raw sewage are eliminated in this process. It provides a useful source of organic matter, but is low in potash. Advice should be taken before using sewage sludges because in some regions they contain high quantities of heavy metals, such as zinc, nickel and cadmium that can accumulate in the soil to levels toxic to plants.

Leys

The practice of **ley** farming involves grassing down areas and is common where arable crop production can be closely integrated with livestock. At the end of the ley period the grass or grass and clover sward is ploughed in. The root action of the grasses and the increased organic matter levels can improve the structure and workability of problem soils. There are some pest problems peculiar to cropping after grass that should be borne in mind (see wireworms), and generally the ley enterprise has to be profitable in its own right to justify its place in a horticultural rotation. It is practiced in some vegetable production and nursery stock areas.

Green manures

Unlike leys, green manuring is the practice of growing a cover crop primarily to incorporate in the soil. It is undertaken to:

Green manuring is the practice of growing plants primarily to develop and maintain soil structure and fertility.

- provide organic matter which can improve soil structure, aeration, water-holding capacity and, on decomposition, increase micro-organism activity in the soil;
- add some nutrients, especially nitrogen (depending on the plants involved), for the following crop;
- take up and store nitrogen that would otherwise be leached from bare soil over the winter period;
- deep rooted plants can bring up nutrients which have become unavailable to shallower plants;
- suppress weeds;
- provide cover to protect the soil from wind or water erosion;
- provide flowers for pollinating insects.

The seeds for green manuring are typically broadcast sown in the autumn when there are no other overwintering plants, but it can be undertaken at other times when the ground is to be left bare for several weeks instead of planting bedding or taking a catch crop. The plants are then dug or ploughed in when the land is needed again.

Plants used are typically agricultural crops that cover the ground quickly and yield a large amount of leaf to incorporate. The choice of plants needs to take into account the time of sowing, growth rate, soil type, winter hardiness, as well as particular characteristics of the species involved, e.g. legumes which fix nitrogen. Most commonly used are:

- **legumes** including bitter lupins, clovers, fenugreek, tares and trefoils;
- **non-legumes** including buckwheat, mustard, phacelia and rye.

Green manuring has many benefits, but there are some points to note in their management. If the plants are left to the stage when they become fibrous or woody, e.g. when allowing flowering to help pollinators, they will not provide extra nitrogen but are likely to 'rob' the soil of it (see C:N ratio p325). There can be difficulties when the following planting requires a fine seedbed, especially if this is to be early in the season; alternative approaches might be to cut and compost the foliage, cut or hoe off and use as a mulch or grow a plant killed by cold and remove the residue. Whilst it is highly valued in organic gardening, the value of the result when the cost of seeds, time and energy is taken into account is less clear cut in other systems.

Composting

Compost is a dark, soil-like material made of decomposed organic matter. Many gardeners depend on composting as a means of using garden refuse to maintain organic matter levels in their soils. On a larger scale there is interest in the use of composted **town refuse** for horticultural purposes. Many councils are now collecting 'green waste' and supplying composting equipment to encourage householders to recycle organic matter, as well as paper, glass and metals. Horticulturists are increasingly concerned with the recycling of wastes and attention is being given to modern composting methods. It is fundamental to successful organic growing.

Composting refers to the rotting down of plant residues before they are applied to soils.

For successful composting, conditions must be favourable for the decomposers. The material must be moist and well aerated throughout. As the heap is built, separate layers of lime and nitrogen are added as necessary to ensure the correct pH and C:N ratio. Organic waste brought together in large enough quantities under ideal conditions and turned regularly can be composted in two to three months. It is an exothermic process (heat is given off in the reactions) so enough heat can be generated to take the temperature to over 70°C within seven days, with the advantage of killing harmful organisms and weed seeds. The high temperatures can lead to a loss of ammonia (nitrogen).

In order to achieve a mix that allows adequate aeration, it is convenient to distinguish between 'green' (leafy or 'tender') and 'brown' (fibrous or 'tough') materials and combine in approximately equal measure (see Table 18.1). Note that shredded cardboard and paper can be added as 'brown' which is useful for recycling waste, but inks should be kept to a minimum. Decomposition is quicker if the ingredients are shredded to increase availability to organisms.

Table 18.1 Compost ingredients

Proposed ingredient	Category
Cardboard	brown
Farmyard manures	intermediate
Fibrous prunings	brown
Haulm (old plants)	brown
Hedge clippings	brown
Herbaceous plants (old)	brown
Grass mowings	green
Grass – long	brown
Kitchen (plant) waste	green
Nettles – young	green
Nettles – old	brown
Paper	brown
Seaweed	green
Straw	brown
Woody prunings	brown

When very large quantities are available the ingredients can be heaped up on a concreted base. This makes it easy to use power equipment to turn the ingredients to maintain good aeration and to mix in the cooler outer layers to ensure all parts heat up and decompose rapidly.

Garden methods

Most gardeners will not be able to obtain enough components at any one time to create the ideal composting process. An alternative approach is to build the heap over time. This is normally done in a slatted bin with a front that opens for access (see Figure 18.7). There should be an open base over soil to allow organisms and air in. A suitable cover is needed to keep some warmth in and rain off once the process has started. This method can produce good compost, but tends to take many months or even years to complete. Because it does not heat up adequately, care should be taken with regard to weeds, pests and diseases which are not killed in the process.

As much material as possible should be collected and prepared for composting. It should be chopped or shredded, ‘green’ and ‘brown’ mixed and water added to the heap. It is difficult to be successful with batches of less than one cubic metre at a time (when less than this the cooling at the surface is greater than the heating at the centre where decomposition is proceeding). It is advantageous to have a second bin alongside so the compost heap can be turned and loosened more easily on a regular basis to maintain good aeration.

Figure 18.7 **Compost bins**. A typical set of bins large enough for efficient composting, slatted to allow in air and to allow easy access to add new material and to turn the contents

Compost tumblers

These are containers that can be rotated on an axis to provide an easy method of turning small batches to create compost in a relatively short time. Batches can heat up sufficiently to kill off weeds and diseases and the enclosed container deters vermin. The compost ingredients should be gathered together and the tumbler filled in a short space of time. Nothing is added until the batch is completed.

Worm composting and wormeries

Worm composting lends itself to handling small quantities which can be added as they arise, such as kitchen waste, especially over the winter period when there is little plant material to accumulate. Compost worms (*Eisenia foetida*), also known as brandling or tiger worms, feed on organic matter. Whilst these can be purchased they are readily found in rotting vegetation such as compost heaps.

The container can be a plastic dustbin, usually equipped with a tap to drain off liquids which can be diluted and used as liquid feed for plants. Smaller containers, wide rather than narrow, can be made out wood, ideally with some insulation to maintain temperatures. Put in a 10 cm layer of sand and cover with a polythene sheet. Bedding material, such as well rotted compost or farmyard manure, may be needed for the worms to live in until the system gets going. Spread chopped waste to a depth of 5 cm. Add 100 or so worms and cover with wet newspaper to keep out the light and maintain moisture levels. A lid is needed to keep out the rain. Ideally, temperatures should be maintained between 20°C and 25°C and the pH kept between 6 and 8; lime can be added if the compost becomes too acid. The worms eat the vegetation as it starts to rot which means that once in balance there is no smell.

The compost is removed when ready; the decomposing top layer is separated off and used to start the next run. The compost is spread out to dry in the sun and the worms are recovered by placing a wet newspaper on the compost where they will congregate under it.

On a larger scale, wormeries are used to compost farmyard manure with continuous systems available that separate the composted material from the worms which can be recycled, with surpluses being available as animal feed.

Mulching

Many organic materials are used as mulches including farmyard manure, leaf mould, bark, compost, lawn clippings and spent mushroom compost.

Mulches are materials applied to the surface of the soil to suppress weeds, modify soil temperatures, reduce water loss, protect the soil surface and reduce erosion.

Organic mulches increase earthworm activity at the surface, which promotes better and more stable soil structure in the top layers. Soil compaction by water droplets is reduced and, as the organic mulches are incorporated, the soil structure can be improved. If thick enough mulches can suppress weed growth, but it is counter-productive to introduce a material that contains weeds. Likewise, care should be taken not to introduce pests and diseases or use a material such as compost where slugs can be a problem.

When organic matter is added as a mulch it is acting, in effect, as an extra layer of loose soil. Thus, water loss from the soil surface is reduced because it is covered with a dry layer (see evaporation). Soil temperatures lag behind the surface temperatures because of its insulating properties, with the greater lag at greater depth. They tend to reduce soil temperatures in the summer, but retain warmth later in the autumn.

Manufactured materials, such as paper, metal foil or, most commonly, polythene, are also used. In response to the demand for this type of material, woven polypropothene mulches are available. Whilst these have very little insulating effect they are particularly effective in reducing water loss by evaporation at the surface (see water conservation). The colour of the mulch is important because light-coloured material will reflect radiation whereas dark material will absorb it and can thus lead to earlier cropping by warming up the soil earlier.

Check your learning

1. Describe how organic matter is decomposed.
2. State the conditions required for the rapid breakdown of organic matter.
3. List the benefits of humus in soils of different types.
4. Describe one method of composting that can be adopted in a small garden.
5. Compare organic mulches with alternatives that can be used in the garden.

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Chapter 19 Soil water

Summary

This chapter includes the following topics:

- **The wetting of a dry soil**
- **Saturation point**
- **Field capacity**
- **Symptoms of poor drainage**
- **Drainage of soil**
- **The drying of a wet soil**
- **Permanent wilting point**
- **Irrigation**

with additional information on the following:

- **Rainfall**
- **Water tables**
- **Soil consistency**
- **Soil moisture deficit**
- **Water quality**
- **Water conservation**

Figure 19.1 **Drainage pipes**. Modern clay pipes shown in the centre are butted up close together. An older method is shown below it and modern plastic piping is shown above. In the top left is a view of the modern clay pipe alongside the old 'horse shoe' tile (it would have sat on a 'mug plate' to prevent moving water washing away soil) and at the bottom are smaller examples of this type of old pipe

Wetting of a dry soil

Rainfall is recorded with a rain gauge (see Figure 2.13) and is measured in millimetres of water. Thus ‘1 mm of rain’ is the amount of water covering any area to a depth of 1 mm. Therefore ‘1 mm of rain’ on one hectare of land is equivalent to 10 m^3 or 10 000 litres of water per hectare (area 10 000 m^2 × depth 0.001 m). As rain falls on a dry surface the water either soaks in (**infiltration**) or runs off over the surface as **surface run-off**. Accumulation of water on the surface (ponding) is a result of infiltration rates slower than rainfall. **Ponding** leads to soil capping, which further reduces infiltration rates. Soil surfaces can be protected with mulches (see p335) and care should be taken with water application rates during irrigation.

Saturated soils

The **saturation point** of a soil is when water has filled all the soil pores.

As water soaks into the dry soil, air is forced out of the surface layers which become **saturated** (waterlogged).

As water continues to enter the soil it moves steadily downwards, with a sharp boundary between the saturated zone and the dry, air-filled layers, as shown in Figure 19.2. So long as water continues to soak into the soil, this wetting front moves to greater depths and air is forced out of this zone.

When rainfall ceases the water in the larger soil pores continues to move downwards under the influence of gravity. Water is held in the soil in the form of water films around all the soil particles and aggregates. Forces in the surface of the water films, surface tension, hold water to the soil particles against the forces of gravity and the suction force of roots.

As the volume of water decreases, its surface area and hence its **surface tension** becomes proportionally greater until, in very thin films of water, it prevents the reduced volume of water from being removed by gravity. A useful comparison can be seen when your hands are lifted from a bowl of water. They drip until the forces in the surface of the thin film become equal to the forces of gravity acting on the remaining small volume of water over the hands.

Figure 19.2 **Wetting front**. As water is added to a dry soil it soaks into the soil with a clear line that can be seen between the unchanged (dry) soil and the saturated soil above

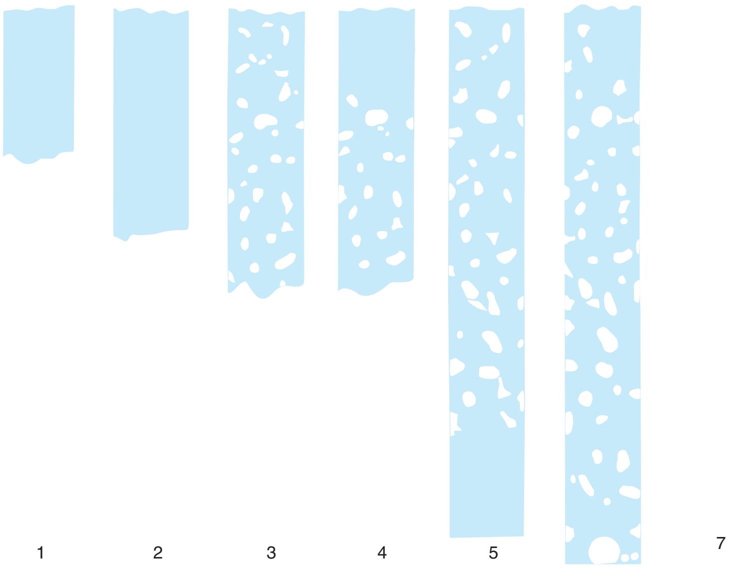
Field capacity (FC)

Gravitational water is the water that can be removed by the force of gravity.

Field capacity is the amount of water the soil can hold against the force of gravity.

As **gravitational water** (sometimes referred to as ‘excess water’) is removed, air returns in its place. On sandy soils this may take a matter of hours after the rain has stopped, but may take far longer on clay where the process may continue for many days. The soil is then said to be at **field capacity** (FC). More precisely, it is a soil that has been saturated, then allowed to drain freely without evaporation until drainage effectively ceases. In practice it is assessed after two days.

At field capacity the **micropores** (those less than about 0.05 mm diameter) remain full of water; whereas in the **macropores** (greater than about 0.05 mm) air replaces the gravitational water, as illustrated in



1 Dry soil wetted.
2 Saturated zone extends downward as rain continues.
3 No rain; gravitational water moves downwards until water film tension equal to pull of gravity.
4 Further rain saturates top layers before more soil wetted.
5 Water table forms if obstruction to gravitational water.
6 Drained soil, at FIELD CAPACITY down to drains.
7 At PERMANENT WILTING POINT.

🟦 = Water
= Rain

Figure 19.3 Water in the soil

Table 19.1 **Soil water holding capacity**: the amount of water in a given depth of soil at field capacity can be calculated by simple proportion

	Water held in 300 mm soil depth (mm)		
Soil texture	**at field capacity (FC) i.e. water holding capacity (WHC)**	**at permanent wilting point (PWP)**	**Available water (AW)**
Coarse sand	26	1	25
Fine sand	65	5	60
Coarse sandy loam	42	2	40
Fine sandy loam	65	5	60
Silty loam	65	5	60
Clay loam	65	10	55
Clay	65	15	50
Peat	120	30	90

Figure 19.3. The air expelled has been replaced by ‘fresh’ air which is higher in oxygen and lower in carbon dioxide content.

The amount of water held at field capacity is known as the **water-holding capacity** (**WHC**) or moisture-holding capacity (MHC). Examples are given in Table 19.1 The WHC is expressed in millimetres of water for a given depth of soil. Thus a silty loam soil 300 mm deep holds 65 mm of water when at field capacity. Conversely, if a silty loam had become completely dry to 300 mm depth, it would require 65 mm of rain or irrigation water to return it to field capacity; about an average month's rainfall in many parts of the British Isles. Since 1 mm of water is equivalent to 10 m^3/ha, a hectare of silty loam would hold 650 m^3 water in the top 300 mm when at field capacity. The principle described enables water-holding capacity or irrigation requirement to be determined for any soil depth. The amount of water required to return a soil to field capacity is called the **soil moisture deficit** (SMD).

Water tables

Groundwater occurs where the soil and underlying parent material are saturated (see Figure 19.3) and the **water table** marks the top of this saturated zone, which fluctuates over the seasons, normally being much higher in winter. In wetlands the water table is very near the soil surface and the land is not suitable for horticulture until the water table of the whole area is lowered (see drainage). Where water flows down the soil profile and is impeded by an impermeable layer, such as saturated clay or silty clay, a **perched** (or crown) **water table** is formed. Water from above cannot drain through the impermeable barrier and so a saturated zone builds up above it. **Springs** appear at a point on the landscape where an overlying porous material meets an impermeable layer at the soil surface, e.g. where chalk hills or gravel mounds overlie clay.

Capillary rise

Water is drawn upwards from the water table through a continuous network of pores. The height to which water will rise and the rate of movement depends on the continuity of pores and their diameter. In practice the rise from the water table is rarely more than 2 cm for coarse sands, typically 15 cm in finer textured soils, but it can be substantially greater in silty soils and in chalk. The upward movement of water in these very fine pores is very slow. Capillary rise is used to aid the watering of plants grown in containers (see capillary benches). Several 'self-watering' containers also depend on capillary rise from a water store in their base (see aggregate culture p397).

Drying of a wet soil

Soil water is lost from the soil surface by evaporation and from the rooting zone by plant transpiration.

Evaporation

The rate of water loss from the soil by **evaporation** depends on the drying capacity of the atmosphere just above the ground and the water content in the surface layers. The evaporation rate is directly related to the **net radiation** (see p26) from the sun which can be measured with a solarimeter (see p43). Evaporation rates increase with higher air temperatures and wind speed or lower humidity levels. As water evaporates from the surface, the water films on the soil particles become thinner. The surface tension forces in the film surface become proportionally greater as the water volume of the film decreases. This leaves water films on the particles at the surface with a high surface tension compared with those in the films on particles lower down in the soil. The increased suction gradient causes water to move slowly upwards to restore the equilibrium. Whilst the surface layers are kept moist by water moving slowly up from below, the losses by evaporation, in contrast, are quite rapid. Consequently the surface layers can become dry and the evaporation rate drops significantly after 5 to 10 'mm of water' is lost. Evaporation virtually ceases after the removal of 20 'mm of water' from the soil. Maintaining a dry layer on the soil surface helps conserve moisture in the soil below. Evaporation from the soil surface is almost eliminated by a **leaf canopy** that shades the surface, thus reducing air flow and maintaining a humid atmosphere over the soil. **Mulches** (see p335) can also reduce water loss from the soil surface.

Evapotranspiration

As a leaf canopy covers a soil the rate of water loss becomes more closely related to transpiration rates. The potential transpiration rate represents the estimated loss of water from plants grown in moist soil with a full leaf canopy. It can be calculated from weather data (see Table 19.2).

Table 19.2 **Potential transpiration rates**. The calculated water loss (mm) from a crop grown in moist soil with a full leaf canopy, over different periods of time and based on weather data collected in nine areas in the British Isles

Area	April	May	June	July	Aug	Sept	Summer	Winter	Annual
Ayr	46	81	90	83	65	38	405	70	475
Bedford	50	78	89	91	80	43	430	70	500
Cheshire	53	75	83	88	76	44	420	80	500
Channel Isles	51	86	91	99	84	46	457	103	560
Essex (NE)	50	79	98	98	83	45	450	80	530
Hertford	49	79	91	94	80	43	435	75	510
Kent (Central)	50	79	93	96	83	44	445	65	510
Northumberland	44	64	81	76	60	34	360	70	430
Dyfed	46	75	84	81	74	44	405	105	510

As roots remove water it is slowly replaced by the water film equilibrium, but rapid water uptake by plants necessitates root growth towards a water supply in order to maintain uptake rates. At any point when water loss exceeds uptake, the plant loses turgor and may wilt. This tends to happen in very drying conditions, even when the growing medium is moist. Wilting is accompanied by a reduction in carbon dioxide movement into the leaf, which in turn reduces the plant's growth rate (see photosynthesis). The plant recovers from this **temporary wilt** as the rate of water loss falls below that of the uptake, which usually occurs in the cool of the evening onwards. Continued loss of water causes the soil to reach the permanent wilting point because roots can extract no more water within the rooting zone.

The **permanent wilting point** (PWP) is the soil's water content when a plant growing in it does not regain turgor overnight.

When the soil has reached its **permanent wilting point (PWP)** there is still water in the smallest of the soil pores, within clay particles and in combination with other soil constituents, but it is too tightly held to be removed by roots. Typical water contents of different types of soil at their permanent wilting point (PWP) are given in Table 19.1.

Available water

Roots are able to remove water held at tensions up to 15 atmospheres within the rooting zone, and gravitational water drains away. Consequently the available water for plants is the moisture in the rooting depth between field capacity and the permanent wilting point. The available water content (AWC) of different soil textures is given in Table 19.1. Fine sands have very high available water reserves because they hold large quantities of water at FC and there is very little water left in the soil at PWP (see sands p304). Clays have lower available water reserves because a large proportion of the water they hold is held too tightly for roots to extract (see clay p305).

Available water (to the plant) is the water held in the soil between field capacity and the permanent wilting point.

Roots remove the water from films at field capacity very easily. Even so, plants can wilt temporarily and any restriction of rooting makes wilting more likely. Water uptake is also reduced by high soluble salt concentrations (see osmosis) and by the effect of some pests and diseases (see vascular wilt diseases). As the soil dries out, the water films become thinner and the water is more difficult for the roots to extract. After about half the available water content has been removed, temporary wilting becomes significantly more frequent. Irrigating before available water falls to this point helps maintain growth rates. Plants grown under glass are often irrigated more frequently to keep the growing medium near to field capacity. This ensures maximum growth rates since the roots have access to 'easy' water, i.e. water removed by low suction force.

Soil consistency

The number of days each year that are available for soil cultivation depends on the weather, but more specifically on soil consistency (sometimes referred to as the workability of the soil). It also influences the timing and effect of cultivations on the soil.

Soil consistency describes the effect of water on those physical properties of the soil.

It is assessed in the field by prodding and handling the soil. A very wet soil can lose its structure and flow like a thick **fluid**. In this state it has no **load-bearing strength** to support machinery. As the soil dries out it becomes **sticky**, then plastic. When **plastic** the soil is readily moulded. In general, the soil is difficult to work in this condition because it still tends to stick to surfaces, has insufficient load-bearing strength, is readily compacted and is easily smeared by cultivating equipment. As the soil dries further it becomes **friable**. At this stage it is in the ideal state for cultivation because it has adequate load-bearing strength, but the soil aggregates readily crumble. If the soil dries out further to a **harsh** (or hard) **consistency** the load-bearing strength improves considerably, but whilst coarse sands and loams still readily crumble in this condition, soils with high clay, silt or fine sand content form hard resistant clods. The **friable range** can be extended by adding organic matter (see humus). At a time when bulky organic matter is more difficult to obtain it is important to note that a fall in soil humus content narrows the friable range. This allows less latitude in the timing of cultivations and increases the chances of cultivations being undertaken when they damage the soil structure.

Timeliness is the cultivation of the soil when it is at the right consistency.

Whereas many sands and silts can be cultivated at field capacity, clays and clay loams do not become friable until they have dried out to well below field capacity, i.e. heavier soils need more time for evaporation to remove water through the soil surface.

Drainage

As gravitational (excess) water leaves the macropores, the air that takes its place ensures that the root zone is replenished with ‘fresh air’. Horticultural soils should return to at least 10 per cent air capacity in the top half metre within one day of being saturated (see porosity). Some soils, notably those over chalk or gravel, are naturally free draining.

Drainage is the removal of gravitational (excess) water from the root zone.

However, many have underlying materials which are impermeable or only slowly permeable to water, and in such cases **artificial drainage**, sometimes referred to as field drainage or under drainage, is put in to carry away the gravitational water (see Figure 19.3). This helps the soil to restore air content rapidly without reducing the available water content. **Well-drained soils** are those that are rarely saturated within the upper 90 cm except during or immediately after heavy rain. Uniform brown, red, or yellow colours indicate an **aerobic** soil, i.e. a soil in which oxygen is available. **Poorly-drained** soils are saturated within the upper 60 cm for at least half the year and are predominantly grey which is typical of **anaerobic** soil conditions. Between these extremes, **imperfectly drained** soils are those that are saturated in the top 60 cm for several months each year. These soils tend to have less bright colours than well-drained soil; grey and ochre colours are usually seen at 450 mm giving a characteristic rusty mottled appearance (see Figure 17.7).

Symptoms of poor drainage

Symptoms of poor drainage include:

- grey or mottled soil colours;
- restricted rooting;
- reduced working days for cultivation;
- weed problems;
- pest and disease problems;

- excess fertilizer requirements;
- topsoils water-logged for long periods in warm conditions have a smell of bad eggs (see sulphur cycle p325).

Soil pits dug in appropriate places reveal the extent of the drainage problem and help pinpoint the cause, which is the basis of finding the solution. The level of water that develops in the pit indicates the current water table. Further indications of poor drainage are the presence of high organic matter levels (see organic soils) and small black nodules of manganese dioxide.

Soil colours show the history of water-logging in the soil. Whereas free drainage is indicated by uniform red, brown or yellow soil throughout the subsoil, the iron oxide which gives soil these colours in the presence of oxygen is reduced to grey or blue forms in **anaerobic** conditions, i.e. when no oxygen is present. Zones of soil that are saturated for prolonged periods have a dull grey appearance, referred to as **gleying** (see Figure 17.7). Reliance on colour alone as an indication of drainage conditions is not recommended, because it persists for a long time after efficient drainage is established (see also soil types p301–3).

Structural damage, whether caused by water (see stability), machinery (see cultivation), or by accumulations of iron (see natural pans), is an obstruction to water flow in the soil profile. Pans or platy structures near the surface can be broken with cultivating equipment on arable land or spiking on grassland; but subsoiling is used to burst those deeper in the soil. If water cannot soak away from well-structured rooting zones, artificial drainage is required.

Artificial drainage

The low permeability of many subsoils, which create a perched water table, is the major reason for artificial drainage in horticultural soils. Clay, clay loam and silty clays, when wetted, become almost impermeable as the clay swells and the cracks close; clay is ‘puddled’ to form a liner for ponds. This ‘top water problem’ is dealt with by putting in pipes to intercept the trapped gravitational water. Straight lines of pipes are placed at an even **gradient** from the highest point to the outfall in a ditch or main drain (see Figure 19.4). The pipes are laid below cultivation depth in a series of parallel lines across the slope to the headland of the area to be drained. Where a valley or the lower areas lie within the area to be drained, a herringbone pattern is used.

Silt traps should be placed at regular intervals to help to service the system at points where there is a change of gradient or direction (see Figure 19.4). The spacing between the lines of pipes depends on the permeability of the soil, a maximum of 5 metre intervals being necessary in clay subsoils. Soil permeability and the land use dictate the **depth of the drains** which is normally more than 60 cm. Drains should be set deeply in cultivated land where heavy equipment and deep cultivation will not disturb the pipes. Shallow drains can be used where rapid drainage is a high priority and the pipes are not likely to be crushed by heavy vehicles or severed by cultivating equipment, e.g. gardens and sports grounds. Pipe drainage is usually combined with secondary treatments, such as mole drainage or subsoiling, to achieve effective drainage at reasonable cost. Deep subsoiling improves soil permeability and the pipes carry the water away. Installation costs can be reduced because pipes can be laid further apart. Similarly mole drainage over and at right angles to the pipes enables them to be spaced 50–100 metres apart.

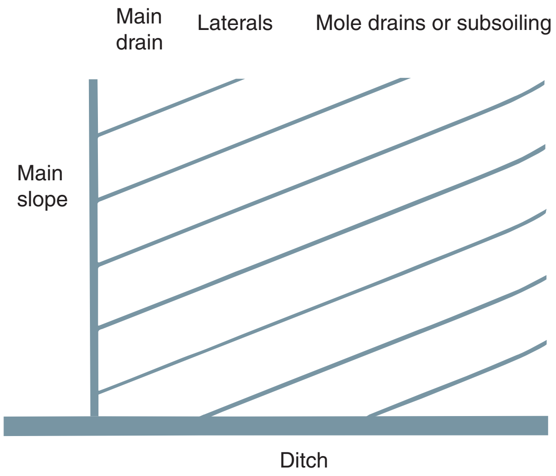
The pipes are made of clay or plastic. The **diameter** of the pipe depends on the gradient available and the amount of water to be carried when wet conditions prevail. Tiles (clayware) are usually 300 mm pipes either 75 mm or 100 mm in diameter (see Figure 19.1). These lead into a ditch or a larger main drain. The tiles are butted tightly together to allow entry of water, but not soil particles. It is recommended that they are covered with permeable fill, usually stones or clinker, to improve water movement into the drains. Plastic pipes consist of very long lengths of pipe perforated by many small holes and usually covered with a rough felt to keep out soil particles.

An outlet into a ditch is very vulnerable to damage and so it should consist of a strong, long pipe set flush in a concrete or brick headwall so that it is neither dislodged by erosion in the ditch nor by people using it as a foothold. Outlet pipes should be glazed to prevent frost damage. Vermin traps should be fitted to prevent pipes being blocked by nests or dead animals (see Figure 19.4).

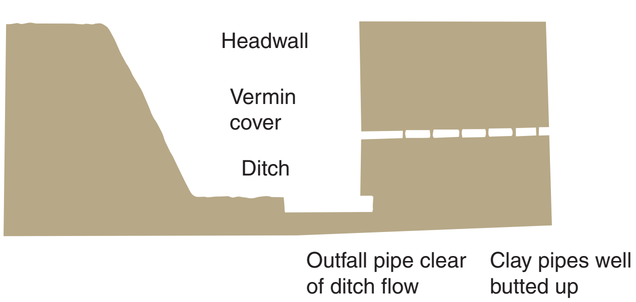
Mole drainage is very much cheaper than pipe drainage. A mole plough draws a 75 mm ‘bullet’, followed by a 100 mm plug, through the soil at a depth of 500–750 mm from a ditch up the slope of a field or across a pipe drain system with permeable backfill (see Figure 19.4). The soil should be plastic at the working depth so that a tunnel to carry water is created. The soil above should be drier so that some cracks are produced as the implement is drawn slowly along. These cracks improve the soil structure and conduct water to the mole drain. Sandy and stony areas are unsuitable because tunnels are not properly formed or collapse as water flows. Tunnels drawn in clay soils can remain useful for 10–15 years, but in wetter areas their useful life may be nearer 5 or even as little as 2 years.

Sandslitting is used on sports grounds to remove water from the surface as quickly as possible. It involves cutting narrow trenches at frequent intervals in the soil and infilling with carefully graded sand that conducts water from surface to a free draining zone under the playing surface.

(a) ***Simple Interceptor Drainage System:***



(b) ***Outfalls***



(c) ***Silt trap/Inspection Chamber***

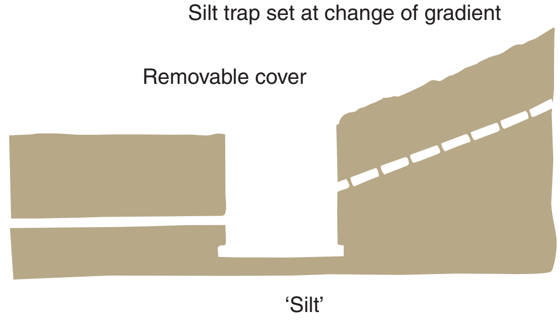


Figure 19.4 Drainage

French drains can be placed around impermeable surfaces, such as concrete hard standings and patios, to intercept the run-off.

Maintenance of drainage systems

Artificial drainage is very expensive to install and must be serviced to ensure that the investment is not wasted. **Ditches** need regular attention because they are open to the elements (see Figure 19.5). Weed growth should be controlled; rubbish cleared out and collapsed banks repaired, because obstructions lead to silting up or undercutting of the bank. The design of the ditches depends on the soil type and should be maintained when being repaired. The batter (the slope of the sides) on sandy soils has to be less steep than on clays.

Drain outlets are a particularly vulnerable part of the drainage system, especially if not set into a headwall. They should be marked with a stake (holly trees were traditionally used in some areas) and inspected regularly after the soil returns to field capacity. Blockages should be cleared with rods and vermin traps refitted where appropriate.

Figure 19.5 **Ditch**. This is open to the elements and easily choked if not regularly maintained

Silt traps need to be cleaned out regularly to prevent accumulated soil being carried into the pipes. Wet patches in the field indicate where a blockage has occurred. The pipe should be exposed and the cause of the obstruction removed. Silted-up pipes can be rodded, broken sections replaced, or dislodged pipes realigned.

At all times it should be remembered that the drains only carry away water that reaches the pipes. Every effort must be made to maintain good soil permeability and to avoid compaction problems. Subsoilers (see p315) should be used to remedy subsoil structural problems. Once drainage has been installed the soil dries more quickly, leading to better soil structure because cracks appear more extensively and for longer periods. Deeper layers of the soil are dried out as roots explore the improved root environment, which adds to the improving cycle.

Groundwater (‘bottom water’) problems occur where the water table is too high and drains at the desired depth are of no use, because there is nowhere low enough to discharge the water. An artificially low water table can be created by pumping water out of the ditches up into a network of waterways. A line of windmills that provided the required energy was a familiar sight in lowland areas such as the Fens, where such land reclamation was undertaken. Goundwater problems are a common feature of many gardens where attempts to introduce drainage systems are thwarted by there being nowhere suitable (or legal) to discharge the water.

Irrigation

Irrigation is used to prevent plant growth being limited by water shortage.

Irrigation should be seen as a husbandry aid in addition to otherwise sound practice. It is assumed in the following that water is being added to a well-drained soil. The need for irrigation depends mainly on available water in the rooting zone and the effect of water stress on the plant’s stage of growth. The very large quantities of water required for commercial production are illustrated clearly in the estimates for growing in protected culture, where all the requirements have to be delivered to the crop by irrigation. In the British Isles, the daily consumption of water from a full cover crop, such as tomatoes or cucumbers, is about 20 000 litres per hectare in March rising to double that in June. This amounts to about 9000 cubic metres per year (approximately 750 000 gallons per acre). A more exact estimate can be obtained by measuring the light levels outside the greenhouse; 2200 litres per hectare are required for each megajoule per square metre (see p43). This can be compared with the 6000 cubic metres of rainfall that could be collected, on average, from the roof of a hectare of glass in the south-east of England (see p338). To take advantage of this contribution there would need to be substantial storage facilities and the water quality issues would need to be addressed.

Response periods are the growth stages when the use of irrigation during periods of rainfall deficiency is likely to be worthwhile. In general all plants benefit from moist seedbeds and eliminating water stress maximizes vegetative growth. Initiation of flowering and fruiting is favoured by drier conditions. The response periods of a range of plants grown in the UK is given in Table 19.3.

Irrigation plans

In general, water should not be added to outdoor soils until moisture levels fall to 50 per cent of available water content in the rooting zone. Outdoors 25 mm of water is the minimum that should be added at any one time in order to reduce the frequency of irrigation, to reduce water loss by evaporation and to prevent the development of shallow rooting. On most soils the amount of water added should be such as to return the soil to field capacity. Addition of water to clays and clay loams should be minimized so as not to reduce the vital drying and wetting cycles, and if they have to be irrigated they should not be returned to field capacity in case rain follows (see ponding). Irrigation should never result in fertilizers being leached from the rooting depth unless it is the specific objective, as in flooding of greenhouse soils (see conductivity).

Most recommendations are given in a simplified form taking the above points into account. The recommended plan is usually expressed in terms of how much water to apply, at a given soil moisture deficit, for a named crop on a soil of stated available water content. Thus for an outdoor grown summer lettuce crop grown on soils of a medium available water content, 25 mm of water should be added when a 25 mm soil moisture deficit occurs. This would require the application of 250 000 litres per hectare or 25 litres per square metre. Further examples are given in Table 19.3.

Soil moisture deficit (SMD) is the amount of water required to return the growing medium to field capacity.

Soil moisture deficit (SMD) can be calculated by keeping a soil water balance sheet. The account is conveniently started after rain returns the soil to field capacity, i.e. when SMD is zero.

Table 19.3 **Irrigation guide**

			Irrigation plan (mm of water at mm SMD)		
	Growth stages at which to irrigate		A	B	C
Plants	**Response periods**	**Time of year when they occur**	**low[*] AWC**	**medium AWC**	**high[**] AWC**
Beans, runner	Early flowering onwards	June to August	25 at 25+	50 at 50+	50 at 75
Brussels sprouts	When lower buttons 15–18 mm diameter	Aug to October	40 at 40	40 at 40	40 at 40
Carrots	Throughout life	June to Sept	25 at 25	40 at 50	
Cauliflowers	Throughout life	April to June	25 at 25	25 at 25	
Flower; perennials	Throughout life	April to Sept	25 at 25	50 at 75	50 at 75
Lettuce summer	Throughout life	April to Aug	25 at 25	25 at 25	25 at 50
Nursery stock trees and shrubs	a. to establish newly planted stock	April to June	25 at 25	25 at 50	25 at 50+
	b. established stock	May to July	25 at 25	25 at 50	25 at 50+
	c. to aid early lifting	September	25 at 25+	25 at 50+	25 at 50+
Potatoes, first early	After tuberization reaches 10 mm dia	May to June	25 at 25	25 at 50	25 at 50
Maincrop and second earlies	From time tubers reach marble stage onwards	June to August	25 at 25	25 at 50	25 at 50
Rhubarb	When pulling has stopped	May to Sept	40 at 50+	40 at 50+	50 at 75+
Strawberries		Sept to Oct	50 at 50	50 at 75	50 at 75
Top fruit			When SMD is more than 50 mm apply 50 mm of water to suffice for two weeks. Then continue irrigation to make the total water supply (rain + irrig) equal to 50 mm/fortnight for the remainder of July, 40mm/fortnight in Aug and 25 mm/fortnight in Sept.		
Apples		July to Sept			
Pears		July to Aug			

[*] *less than 40 mm available water per 300 mm soil, e.g. gravels, coarse sands.*

[**] *more than 65 mm available water per 300 mm soil, e.g. silts, peats.*

In Britain it is assumed that, unless it has been a dry winter, the soil is at field capacity until the end of March. From the first day of April a day-by-day check can be made of water gains and losses. A worked example of a weekly water balance sheet is given in Table 19.4; a daily water balance sheet may be more appropriate in some situations.

Rainfall varies greatly from year to year from one locality to the next and so it should be determined on site (see rain-gauge) or obtained from a local weather station. Water loss for each month does not vary very much over the years and so potential transpiration rates based on past records can be used in the calculation. There are potential transpiration

Table 19.4 A weekly water balance sheet for established nursery stock grown on sandy loam (AWC 55 mm per 300 mm) in Essex. The irrigation plan is to apply 25 mm water if a 50 mm SMD is reached (see Table 19.3). Water loss estimated from Table 19.2.

		Water gains (mm)		
Week beginning	Water loss (mm) (A)	rainfall (B)	irrigation (C)	SMD at end of week (mm) (D)
				D + A − (B + C) = new D
March 31				0
April 7	11	10	0	0 + 11 – (10 + 0) = 1
14	11	8	0	1 + 11 – (8 + 0) = 4
21	12	16	0	4 + 12 – (16 + 0) = 0
28	12	5	0	0 + 12 – (5 + 0) = 7
May 4	16	28	0	7 + 16 – (28 + 0) = 0*
11	17	10	0	0 + 17 – (10 + 0) = 7
18	18	14	0	7 + 18 – (14 + 0) = 11
25	18	4	0	11 + 18 – (4 + 0) = 25
June 1	18	10	0	25 + 18 – (10 + 0) = 33
8	23	14	0	33 + 23 – (14 + 0) = 42
15	23	18	0	42 + 23 – (18 + 0) = 47
22	23	20	0	47 + 23 – (20 + 0) = 50**
29	23	10	25	50 + 23 – (10 + 25) = 38
July 6	22	8	0	38 + 22 – (8 + 0) = 52**
13	22	18	25	52 + 22 – (18 + 25) = 31
20	22	24	0	31 + 22 – (24 + 0) = 29
27	22	5	0	29 + 22 – (5 + 0) = 46

[*] *Soil Moisture Deficit (SMD) cannot be less than zero because water above FC drains away.*

[**] *Irrigation might have been delayed if prolonged heavy rain forecast.*

rate figures available for all localities having weather stations. Examples are given in Table 19.2. These figures can be used when calculating water loss, but until there is 20 per cent leaf canopy a maximum SMD of 20 mm is not exceeded because in the early stages water loss is predominantly from the soil surface by evaporation (see p340).

In protected cropping all the water that plants require has to be supplied by the grower, who must therefore have complete control over irrigation. With experience the grower can determine water requirements by examining plants, soil, root balls or by tapping pots. A **tensiometer** can be used to indicate the soil water tension but, while this is useful to indicate when to water, it does not show directly how much water is needed. **Evaporimeters** distributed through the planting can give the water requirement by showing how much water has been evaporated. A **solarimeter** measures the total radiation received from the sun and the readings obtained can be used to calculate water losses, often expressed in litres per square metre for convenience.

Methods of applying water

These should be carefully related to plant requirements, climate and soil type. On a small scale, **watering cans** or **hoses** fitted with trigger lances can be used, but care should be taken to avoid damaging the structure of the growing medium. Water can be sprayed from fixed or mobile equipment, but it is essential that the rate of application is related to soil infiltration rate The droplet size in the spray should not be large enough to damage the surface structure (see tilth). Indoors, **spray lines** can be fitted with nozzles to control the direction and quantity of water. Overhead lines can lead to very high humidity levels and wet foliage, predisposing some plants to disease (see grey mould). Consequently, it should be restricted to watering low level crops, e.g. lettuce, deliberately increasing humidity ('damping down' or 'spraying over'), or winter flooding (see conductivity). **Trickle** lines deliver water very slowly to the soil, leaving plant foliage and the soil surface dry, which ensures a drier atmosphere and reduced water loss. However, care is needed because there is very little sideways spread of water into coarse sand, loose soil, or a growing medium that has completely dried out. **Drip** irrigation is a variation on the trickle method, but the water is applied through pegged down thin, flexible 'spaghetti' tubes to exactly where it is needed, e.g. in each pot or at the base of each plant.

Simple **flooded benches** are sometimes used to water pot plants. The shallow tray of the benched area is filled with water which the pots absorb, after which the excess water is drained off ('ebb and flow'). This tends to produce a high humidity around the plants and **capillary benches** have come to be preferred. The pots stand on, and the contents make contact with, a level 50 mm bed of sand kept saturated at the base by an automatic water supply. Water lost by evaporation at the surface and from the plant is replaced by **capillary rise**. The sand must be fine enough to lift the water but coarse enough to ensure that the flow rate is sufficient. **Capillary matting** made of fibre woven to a thickness and pore size to hold, distribute and/or lift water has many uses in watering containerized crops both indoors and outside. Containers with built-in water reserves and easy watering systems utilize capillarity to keep the rooting zone moist. Sub-irrigated sand beds are used for standing out container plants in nursery production and are less wasteful of water than the more usual overhead spray lines.

Water quality

Water used in horticulture is taken from different sources and has different dissolved impurities. Soft water has very few impurities, whereas **hard water** contains large quantities of calcium and/or magnesium salts which raise the pH of the growing medium, especially where impurities accumulate (see liming). Even small quantities of **micro-elements,** such as boron or zinc, have to be allowed for when making up nutrient solutions which are to be re-circulated (see hydroponics). Water taken from boreholes in coastal areas can have high concentrations of salt that can lead to **salt concentration problems**. The quantity of dissolved salt in water can be measured by its conductivity; the higher the salt concentration the greater its electrical conductivity. Providing the levels of useful salts are not too high, the water can be used, but the additional nutrient levels (fertilizers) must be suitably adjusted (see conductivity).

In the re-circulation systems that are again becoming more prevalent in protected culture, the salts not used by plants can become concentrated in the water. These dissolved salts can interfere with the uptake of useful salts such as potassium, making it difficult to create a balanced feed within the safe conductivity limits and to reduce the plant growth rates as they become too concentrated. Water drawn from rivers, lakes or even on-site reservoirs may contain algal, bacterial or fungal pollution, which can lead to blocked irrigation lines or plant disease (see hygienic growing).

Rainwater is increasingly being used as a major source of water. It is usually of high quality, i.e. low conductivity, but there can be contamination related to the location or the method of collection or storage, e.g. high levels of zinc when collected through galvanized gullies. Good quality rainwater can be used to dilute otherwise unsuitable water to bring it into use. Alternatively, poor quality water can be treated using reverse osmosis; water under pressure is forced through a membrane which holds back most of the dissolved salts. Alternatively, deionization can be used, this involves passing the water over resins to remove the unwanted salts. In both cases, an environmentally sound method for disposal of the concentrated solution produced remains a problem. High energy distillation and electrodialysis methods are generally too expensive for cleaning water for growing. To avoid disease problems, water supplies can be sterilized. On a commercial scale this is usually done by heat sterilization. Ultra-violet light or ozone treatments are usually more expensive and the use of hydrogen peroxide tends to be less effective.

Water conservation

The need to manage water efficiently is a major concern in the use of scarce resources. Responsible action is increasingly supported by legislation and the higher price of using water. Clearly the major factors that determine the level of water use are related to the choice of plant species to be grown and the reasons for growing. **The selection of drought-tolerant rather than water intensive plantings is fundamental**. Some growing systems are inherently less water intensive, but in most of them there are many ways in which water use can be reduced if certain principles are kept in mind and acted upon appropriately:

- **Whenever possible, the use of artificial water should be avoided**.
- **Use recycled water**. The recycling of water and the capture of rainwater are important considerations in the choice of water source.

- **Minimize evaporation of water**. This is best achieved by not spraying water into the air and by minimizing the time when the soil surface is moist. When water does have to be applied overhead, this should be undertaken in cool periods.
- **Increase the water reservoir of the soil**. The application of water can be reduced by increasing the growing medium's water holding capacity; most soils can be improved by the addition of suitable organic matter.
- **Encourage plant root systems**. Plants should be encouraged to establish as quickly as possible but, after the initial watering-in, infrequent applications will encourage the plant to put down deep roots by searching for water. Most importantly, soil pans should be eliminated and good soil structure maintained to increase the rooting depth.
- **Minimize water lost through drainage**. Where application is partially controlled, the correct relationship between water applied and water holding (see water-holding capacity) helps to prevent leaching, which leads to nutrient loss (see nitrogen), as well as wasting water. Thus returning an outdoor soil to less than field capacity helps avoid losses by drainage or run-off in the event of unexpected rainfall.

Water is lost more rapidly from a moist than from a dry soil surface. After just 10 mm of water has been lost from the surface, the rate of evaporation falls significantly. Infrequent application thus helps, but even more effective is the delivery of water to specific spots next to plants (see trickle lines) or from below through pipes to the rooting zone. Avoid bringing moist soil to the surface. If hoeing is undertaken it should be confined to the very top layers; this also reduces the risk of root damage. Losses from the surface can be reduced considerably by plant cover and almost eliminated by the use of mulches. Loss of water from the plants themselves is reduced when they are grouped together rather than spaced out.

Unless maximum growth rates are the main consideration, **reduced application** saves water, money and staff time without detriment to most plantings. In production horticulture, the introduction of sophisticated moisture-sensing equipment and computer controls has enabled water to be delivered more precisely when and where it is needed. This has led to considerable reduction in water use.

Nutrient loss and run-off from **overhead watering** used in container nursery stock production can be minimized by matching application to rainfall, growing medium, container size, plant species, stage of growth and time of year. Nozzles should be maintained to ensure even water application. Loss from sub-irrigated capillary sand beds tends to be lower. Recirculation (closed) systems should be considered in new developments. The quantity of water required for **flooding** soils in protected culture (e.g. to remove excess nutrients when a crop sensitive to high salt levels, such as lettuce, is to be grown after a tolerant one, such as tomatoes), can be reduced by discontinuing the liquid feeding of the previous crop as soon as possible.

In non-recirculating (open) **hydroponics systems** excessive water waste should be avoided by using flow meters to measure the quantity of run-off and comparing it with standard figures for the growing system used. A run-off of over 30 per cent is usually considered to be excessive and the amount and frequency of nutrient applications delivered by the nozzles or drippers should be reviewed. Closed systems (see NFT p394) recirculate the nutrient solution, but this is not always practical. Where they are used, the system must not be emptied illegally into watercourses or soakaways. It is recommended that the volume in the system be run down before discharge and the waste nutrient solution be sprayed on to crops during the growing season. Permission to empty into public sewers might be granted, but it is usually subject to a charge depending on volume and contamination level.

Check your learning

1. Define field capacity and available water.
2. State four symptoms of poor drainage.
3. State what is meant by drainage.
4. Explain what is meant by soil moisture deficit.
5. Explain what is meant by irrigation response periods.

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Chapter 20 Soil pH

Summary

This chapter includes the following topics:

- **The importance of soil pH**
- **The pH scale**
- **Acidity and alkalinity**
- **Nutrient availability**
- **Plant selection**
- **Changing pH**

with additional information on:

- **Measuring pH**
- **Lime requirement**
- **Types of lime**

Figure 20.1 **Hydrangeas**. Blue flowers are produced by plants in a growing medium at a low pH whereas pink occurs in those nearer neutral; with less determinate colours in between

The importance of soil pH

pH is the negative log of the hydrogen ion concentration of a solution, e.g. soil water.

The pH scale is a means of expressing the degree of acidity or alkalinity of the soil. Temperate area soils are usually between pH 4 and 8; the vast majority are between 5.5 and 7.5.

The ideal growing condition for most plants is a soil of about pH 6.5, which is slightly acid. At this level most of the plant nutrients are available for uptake by the roots. Alkaline conditions are usually created by the presence of large quantities of calcium ('lime'), which interferes with the uptake and utilization of several plant nutrients.

Acidity, alkalinity and the pH scale

Pure water is neutral, i.e. neither acid nor alkaline. It is made up of two hydrogen atoms and one oxygen atom, expressed as the familiar formula H_20. Most of the water is made up of water molecules in which the atoms stay together, but a tiny proportion dissociates, i.e. they form ions (see p129). Equal numbers of positive ions, cations, and negative ions, anions, are formed. In the case of water, an equal number of hydrogen cations, H^+, and hydroxyl anions, OH^-, exist within the clusters of water molecules (H_20). When, as in water, the concentration of hydrogen ions is the same as that of hydroxyl ions, there is neutrality.

Many compounds form ions as they dissolve and mix with water to produce a solution. If the concentration of hydrogen ions is increased, the concentration of hydroxyl ions decreases and **acidity** increases. Likewise, the addition of hydroxyl ions and a decrease in hydrogen ions leads to increased **alkalinity**. All acids release hydrogen ions when dissolved in water. Whereas a **strong acid** (such as hydrochloric acid) fully dissociates when dissolved (i.e. every molecule splits into ions), only a part of a **weak acid** (such as carbonic or acetic acid) breaks up into ions. Bases, such as caustic soda, dissolve in water and increase the concentration of hydroxyl ions.

The **pH scale** expresses the amount of acidity or alkalinity in terms of hydrogen ion concentration. pH values less than 7 are acid and the lower the figure the greater the acidity. Values greater than 7 indicate increasing alkalinity and pH 7 is neutral. In order to present the scale simply, negative logarithms are used: **'pH' is the negative logarithm**, the mathematical symbol for which is 'p', **of the hydrogen ion concentration**, abbreviated as 'H'. It is important to note that, as the scale is logarithmic, a one-unit change represents a ten-fold increase or decrease in hydrogen ion concentration and a change of two units represents a hundred-fold change. Thus a solution of pH 3 is ten times more acid than one of pH 4, one hundred times more acid than pH 5, and a thousand times more than pH 6.

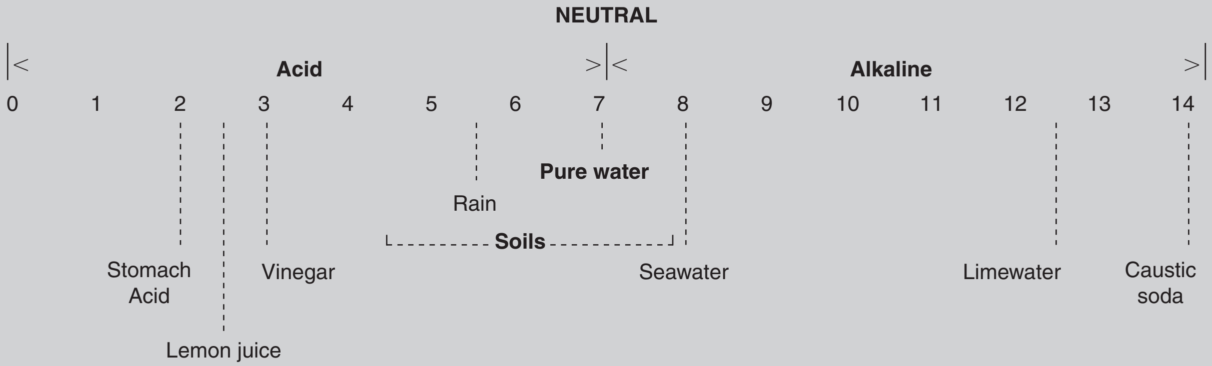


Figure 20.2 The pH scale

Measuring pH

pH can be measured using a pH meter or by the use of indicators; both are used for testing soils. Soils sent to laboratories for analysis would normally be tested with pH meters. Colour indicator methods are most commonly used by growers and gardeners who do their own testing.

Colour indicator method

Required:

- Clean test-tubes; ideally ones that have stoppers that can be removed top and bottom for easy cleaning;
- BDH soil pH indicator;
- BDH pH colour chart (kept in an envelope to prevent fading);
- Distilled water;
- Barium sulphate;
- Clean spatula or similar.

The soil to be tested should be a **representative sample** of the area being analysed? (see p379). Before the pH test is started, its texture should be identified (see p307).

- The soil, preferably dried and sieved, is now added to the test-tube; for 'loams' this should be to a depth of 2 cm (see below for heavier and lighter soils).
- Add to this the same depth of barium sulphate (2 cm).
- Shake together.
- Half fill the test-tube with distilled water (some specially designed tubes have a mark to fill to).
- Add soil pH indicator; for most soils only a few drops are required (more can be added later).
- Place bung in top of tube and shake.
- Leave to stand.
- Find the soil pH by matching the **hue** of the colour with one of the colours on the chart. This should be done by having the light coming over the shoulder whilst holding the tube against the white background alongside the colour square on the chart.
- If the colour is too concentrated to see the hue add a little distilled water; a few more drops of indicator if too weak.

This procedure is suitable for most soils, but it should be noted that the barium sulphate is added to help clear the water in order to see the colour clearly (by flocculating the clay so that it sinks more quickly to the bottom). If the soil texture indicates a very light

Figure 20.3 **Soil pH testing**. Equipment required includes test tubes, spatula, barium sulphate, pH indicator, colour chart. 1 Barium sulphate added to soil. 2 Distilled water added. 3 Shake. 4 Add indicator and leave to stand. 5,6,7,8 Check colour against the chart to find soil pH soil (low clay) or a very heavy one (high clay) then the proportions should be altered as follows:

	Soil:Barium sulphate
'Loams'	2 cm:2 cm
Light soils	3 cm:1 cm
Heavy soils	1 cm:3 cm

Changes in soil pH

The balance of hydrogen ions and basic ions determines soil acidity. A clay particle with abundant hydrogen ions acts as a weak acid, whereas if fully charged with bases (such as calcium, Ca) it has a neutral or alkaline reaction. In practice, soil pH is usually regulated by the presence of calcium cations; **soils become more acid as calcium is leached from the soil** faster than it is replaced. This is the tendency in temperate areas where rainfall (carbonic acid see p297) exceeds evaporation over the year.

Soil pH falls and becomes more acid as 'lime' is lost from the soil.

Hydrogen ions take over the soil's cation exchange sites (see p305) and the pH falls. Soils with large reserves of calcium (containing pieces of chalk or limestone) do not become acid because they are kept base-saturated. In contrast, calcium ions are readily leached from free-draining sands in high rainfall areas and these soils tend to go acid rapidly (see podsols p302). In addition to the carbonic acid in rainfall, there are several other sources of acid that affect the soil:

- **Acid rain** (polluted rain and snow) is directly harmful to vegetation, but also contributes to the fall in soil pH.
- **Organic acids** derived from the microbial breakdown of organic matter, e.g. humic acids, also lead to an increase in soil acidity.
- **Fertilizers**. The bacterial nitrification of **ammonia** to nitrate yields acid hydrogen ions. Consequently fertilizers containing ammonium salts prevent calcium from attaching to soil colloids and cause calcium loss in the drainage water. Other fertilizers have much less effect.
- **Crop removal**. Calcium and magnesium are plant nutrients and the soil's lime reserves are therefore gradually reduced by the removal of plants.

In climates where the evaporation exceeds rainfall over the year, the dissolved salts are brought to the surface. As the water is lost from the soil by evaporation, the dissolved salts accumulate on the surface. These are usually basic (alkaline) in action so the soil pH rises. An extreme example of this is the salt (sodic) desert, e.g. Utah Salt Flats.

Buffering capacity

Buffering capacity is the ability of water to maintain a stable pH. Pure water has no buffering capacity; the addition of minute quantities of acid or alkali has an immediate effect on its pH. In the laboratory buffer tablets can be added to water to enable the solution to be maintained at a specified pH which would resist change despite the addition of some acid or alkali. This is useful for standardizing a pH meter, usually setting the instrument at precisely pH 7 and pH 4 for work on soil pH.

The buffering capacity of soil water reduces the effect of acidity coming from rainfall or from pollution, e.g. acid rain. Chalky or limestone soils, for instance, are very alkaline and can neutralize acids more effectively than acid peat soils. The cation exchange capacity of clays reduces the effect because the hydrogen ions exchange with calcium ions on the clay's colloid surface. Since the number of hydrogen ions being released or absorbed is small compared with the clay's reserve, the pH changes very little. High humus soils similarly have the advantage of a high buffering capacity. A related buffer effect is seen when acids, such as the carbonic acid of rain, are incorporated into soils with 'free' lime present; the acid dissolves some of the carbonate with no accompanying change in pH.

Effects of soil pH

Nutrient availability

The influence of soil pH on plant **nutrient availability** is demonstrated in Figure 20.4. It can be seen that for mineral soils the most favourable level for ensuring the availability of all nutrients is pH 6.5, while peat soils should be limed to pH 5.8 in order to maximize overall nutrient availability. In acid conditions some nutrients, such as manganese, and other soil minerals, such as aluminium, may become toxic.

Other effects on soil

Beneficial **soil organisms** (see p320) are affected by soil acidity and liming. A few soil-borne disease-causing organisms tend to occur more frequently on lime deficient soils (see clubroot), whereas others are more prevalent in well-limed soils. Calcium sometimes improves soil structure and soil stability. It is probable that this is mainly because it encourages **root activity** and creates conditions favourable for decomposition of organic matter, yielding **humus** (see p326). Free lime in clay soils sometimes, but not always, leads to better crumb formation on drying and shrinking.

Plant selection

Plant tolerance to soil pH and calcium levels varies considerably, but all plants are adversely affected when the soil becomes too acid. At very low pH some elements, such as aluminium, become soluble at levels that are toxic to plants. Table 20.1 shows the point below which the growth of common horticultural plants is significantly reduced. Although aluminium is not an essential nutrient for plants it is required to produce

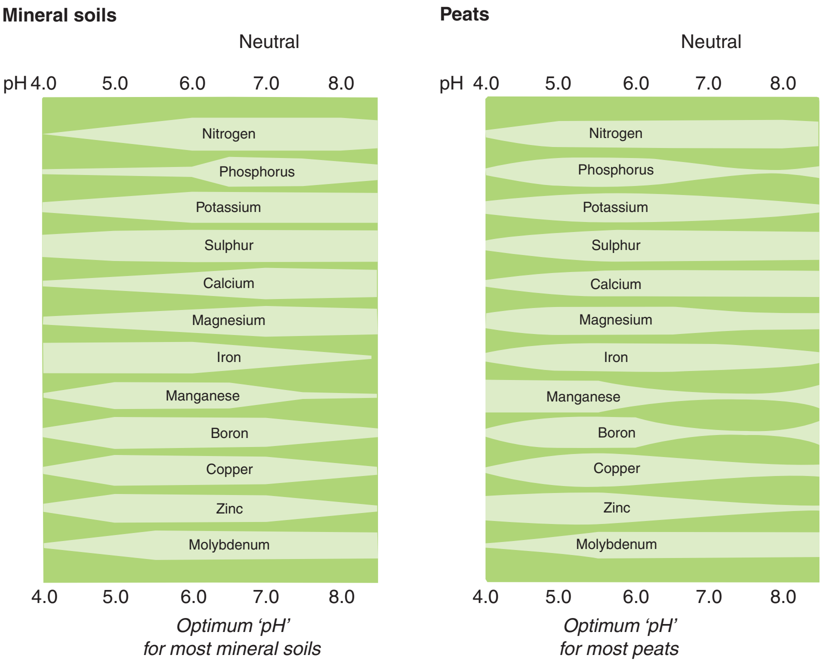


Figure 20.4 **Effect of soil pH on nutrient availability**. The availability of a given amount of nutrient is indicated by the width of the band. The growing media should be kept at a pH at which all essential nutrients are available. For most plants the optimum pH is 6.5 in mineral soils and 5.8 in peats

Table 20.1 Soil acidity and plant tolerance

pH below which plant growth may be restricted on mineral soils:			
Celery	6.3	Rose	5.6
Daffodil	6.1	Raspberry	5.5
Bean	6.0	Cabbage	5.4
Lettuce	6.1	Strawberry	5.1
Carnation	6.0	Tomato	5.1
Chrysanthemum	5.7	Apple	5.0
Carrots	5.7	Potato	4.9
Hydrangea (pink)	5.9	Hydrangea (blue)	4.1

a blue flower rather than a pink one in hydrangeas (see Figure 20.1). Commercially, growers do not just use a compost with a low pH, but also add aluminium sulphate to get the blue colouring.

In the case of **calcifuges** the highest point before growth is affected by the presence of calcium should be noted, e.g. for *Rhododendrons* and some *Ericas* this is at pH 5.5 in mineral soils. Such plants are unable to metabolize many of the nutrients when there is more calcium present; typically they show signs of lime induced chlorosis (see p372).

In contrast, **calcicoles** are well adapted to utilizing soil nutrients in the presence of calcium, but are unable to survive in acid conditions where they shown signs of aluminium toxicity (dead tissues) and phosphate deficiency (stunting and blue or reddish stem and leaves).

Calcifuge or 'lime-hating' plants do not tolerate the level of calcium in soils normally found at pH 5.5. Consequently, they must be grown in more acid conditions.

Calcicoles, or 'lime-loving' plants, have evolved a different metabolism and are tolerant of high soil pH.

Changing soil pH

Raising soil pH

Soil pH can be raised by the addition of lime. Lime is most commonly applied as ground chalk, ground limestone or slaked lime. When lime is added to an acid soil it neutralizes the soluble acids and the calcium cations replace the exchangeable hydrogen on the soil colloid surface (see cation exchange). Eventually hydrogen ions are completely replaced by bases and **base saturation** is achieved, producing a soil of pH 7 or more. However, care should be taken not to overlime a soil because of its effect on the availability of plant nutrients.

Lime requirement is expressed as the amount of calcium carbonate in tonnes per hectare required to raise the pH of the top 150 mm of soil to the desired pH.

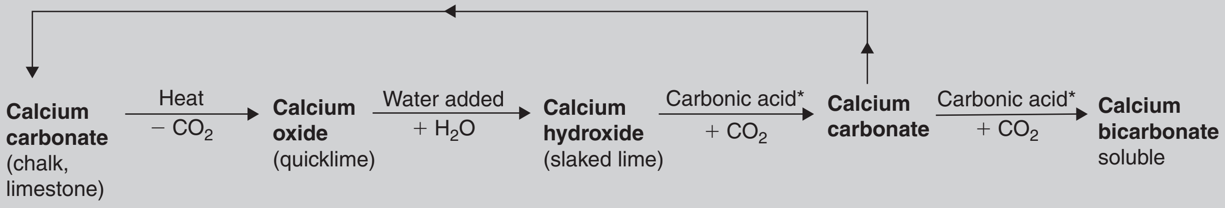
The **lime requirement** of soil can be estimated from knowledge of the required increase in pH and the soil texture (see buffering capacity p358). A pH of 6.5 is recommended for temperate plants on mineral soils; pH 5.8 on peats. The amount of a liming material needed to meet the lime requirement will depend on the neutralizing value of the lime chosen and its fineness.

Liming materials

Neutralizing Value (NV) is determined in the laboratory by comparing a materials ability to neutralize soil acidity with that of the standard, pure calcium oxide.

Liming materials can be compared by considering their ability to neutralize soil acidity, fineness, and cost to deliver and spread. The neutralizing value (NV) of a lime indicates its power to overcome acidity.

A neutralizing value of 50 signifies that 100 kg of that material has the same effect on soil acidity as 50 kg of calcium oxide. The **fineness** of the lime is important because it indicates the rate at which it affects the soil acidity (see surface area p304). It is expressed, where relevant, in terms of the percentage of the sample that will pass through a 100 mesh sieve. Liming materials commonly used in horticulture are listed below with some of their properties. The relationship between the different forms of calcium is shown in Figure 20.5.



*as in rain

Figure 20.5 Forms of calcium

Calcium carbonate is the most common liming material. Natural soft **chalk** (or **limestone)** that is high in calcium carbonate is quarried and ground (NV = 48). It is a cheap liming material, easy to store and safe to handle. A sample in which 40 per cent will pass through a 100 mesh sieve can be used at the standard rate to meet the lime requirement. Coarser samples although cheaper to produce, easier to spread and longer lasting in the soil, require heavier dressings. **Shell sands**, mainly calcium carbonate, have neutralizing values from 25 to 45, i.e. whilst the purest samples can be used at nearly the same rate as chalk, up to twice as much of a poorer sample is required to have the same effect.

Calcium oxide (also known as quicklime, burnt lime, cob lime or caustic lime) is produced when chalk or limestone are very strongly heated in a lime kiln. Calcium oxide has a higher calcium content than calcium carbonate and, consequently, a higher neutralizing value. Pure calcium oxide is used as the standard to express neutralizing value (100) and the impure forms have lower values (usually 85–90). If used instead of ground limestone, only half the quantity needs to be applied.

In contact with moisture, lumps of calcium oxide slake, i.e. react spontaneously with water to produce a fine white powder, calcium hydroxide, with release of considerable heat. This was an effective way of obtaining a fine lime from the quarried material before there was heavy rolling machinery to grind the coarse lumps. The lime kilns that were used are still a common sight, especially in small ports round the coast (see Figure 20.6) Although rarely used now, calcium oxide has to be used with care because it is a fire risk, 'burns' flesh and scorches plant tissue.

Calcium hydroxide, hydrated or slaked lime, is derived from calcium oxide by the addition of water. The fine white powder formed is popular in horticulture. It has a higher neutralizing value than calcium carbonate and its fineness ensures a rapid effect on the growing medium. Once exposed to the atmosphere it reacts with carbon dioxide to form calcium carbonate.

It should be noted that all forms of processed lime quickly revert to calcium carbonate when added to the soil. Calcium carbonate, which is

Figure 20.6 **Lime kilns**. Used to 'burn' (heat) chalk or limestone (calcium carbonate) to produce quicklime (calcium oxide) insoluble in pure water, gradually dissolves in the weak carbonic acid of the soil solution around the roots (see Figure 20.5).

Magnesian limestone, also known as Dolomitic limestone, is especially useful in the preparation of composts because it both neutralizes acidity and introduces magnesium as a nutrient. Magnesium limestone has a slightly higher neutralizing value (50–55) than calcium limestone, but tends to act more slowly.

Liming materials also provide the essential nutrients calcium and, when present, magnesium to the soil. Bicarbonate is formed from the carbonate in carbonic acid, e.g. rainwater or soil water, around respiring roots to provide a soluble form that can be taken up by plants (see Figure 20.5).

Lime application

Unless very coarse grades are used, lime raises the soil pH over a one- to two-year period, although the full effect may take as long as four years; thereafter pH falls again. Consequently lime application should be planned in the planting programme. It is normally worked into the top 15 cm of soil. If deeper incorporation is required, the quantity used should be increased proportionally. The lime should be evenly spread and regular moderate dressings are preferable to large infrequent applications. Very large applications needed in land restoration work should be divided for application over several years.

Care should be taken that the surface layers of the soil do not become too acid even when the lower topsoil has sufficient lime. Top layers are the first to become depleted with consequent effect on plant establishment. This tendency has to be carefully looked for in turf management as this can lead to the formation of ‘thatch’ (see Figure 18.6). Applications of organic manures or ammonium fertilizers should be delayed until lime has been incorporated. If mixed they react to release **ammonia** which can be wasteful and sometimes harmful.

Decreasing soil pH

Soil pH can be lowered by the addition of acids or sulphur to reduce the base saturation of the mineral soil. Some acid industrial by-products can be used, but the most usual method is to apply agricultural **sulphur**, which is converted to sulphuric acid by soil micro-organisms. The sulphur requirement depends on the pH change required and the soil’s buffering capacity. The application of large quantities of **organic matter** gradually makes soils more acid. Acid fertilizers such as ammonium sulphate reduce soil pH over a period of years in outdoor soils and can be used in liquid feeding to offset the tendency of hard water to raise pH levels in composts. In some circumstances it has been appropriate to grow plants in a raised bed of **acid peat** or to work large quantities of peat into the topsoil; an approach that is not sympathetic to avoiding the destruction of peat wetlands.

Check your learning

1. State what is meant by pH.
2. State the range of pH that is suitable for most garden plants.
3. Describe how a crop of beans can be grown successfully on an allotment which has been tested and the soil found to have a pH of 5.5.
4. Describe the effect of 'overliming' an allotment soil.
5. Explain how plant selection is affected by the pH of the garden soil.

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Chapter 21 Plant nutrition

Summary

This chapter includes the following topics:

- **Major nutrients**
- **The nitrogen cycle**
- **Minor nutrients**
- **Sources of nutrients in soil**
- **Organic and inorganic fertilizers**
- **Types of fertilizers**
- **Methods of applying fertilizers**
- **Green manures**

with additional information on the following:

- **Fertilizer programmes**
- **Soil conductivity**

Figure 21.1 Range of fertilizers to supply plant nutrients

Major nutrients

Nitrogen is needed by plants to form **proteins** and is associated with **leafy growth**.

Nitrogen

Nitrogen is taken up by plants as the nitrate and, to a lesser extent, the ammonium ion. Nitrates and ammonium ions are utilized in the plant to form protein. Plants use large quantities of nitrogen; it is associated with vegetative growth. Consequently large dressings of nitrogen are given to leafy crops, whereas fruit, flower or root crops require limited nitrogen balanced by other nutrients to prevent undesirable characteristics occurring.

The nitrogen cycle

Although plants live in an atmosphere largely made up of nitrogen they cannot utilize gaseous nitrogen. They are able to take up soluble nitrogen from the soil water as nitrates and ammonium ions. Both are derived from proteins by a chain of bacterial reactions as shown in Figure 21.2.

Ammonifying bacteria convert the proteins they attack to ammonia. **Ammonia** from the breakdown of protein in organic matter or from **inorganic nitrogen** fertilizers is converted to **nitrates** by **nitrifying bacteria**. This is accomplished in two stages. Ammonia is first converted to nitrites by *Nitrosomonas spp*. **Nitrites** are toxic to plants in small quantities, but they are normally converted to nitrates by *Nitrobacter spp*. before they reach harmful levels. Ammonifying and nitrifying bacteria thrive in aerobic conditions. Where there is no oxygen, anaerobic organisms dominate. Many anaerobic bacteria utilize nitrates and in doing so convert them to **gaseous nitrogen**. This **denitrification** represents an important loss of nitrate from the soil, which is at its most serious in well-fertilized, warm and waterlogged land.

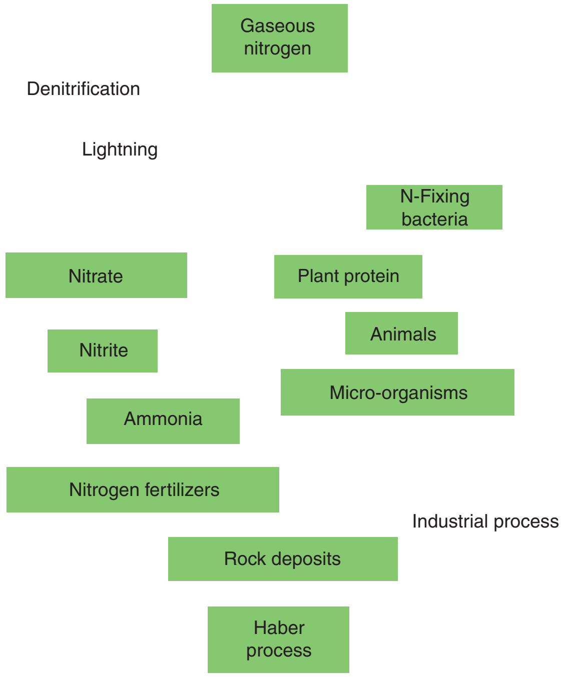


Figure 21.2 Nitrogen cycle. The recycling of the element nitrogen by organisms is illustrated. Note the importance of nitrates that can be taken up and used by plants to manufacture protein. Micro-organisms also have this ability but animals require nitrogen supplies in protein form. Gaseous nitrogen only becomes available to organisms after being captured by nitrogen-fixing organisms or via nitrogen fertilizers manufactured by man. In aerobic soil conditions, bacteria convert ammonia to nitrates (nitrification) whereas in anaerobic conditions nitrates are reduced to nitrogen gases (denitrification)

Nitrogen fixation

Although plants cannot utilize gaseous nitrogen, it can be converted to plant nutrients by some micro-organisms. *Azotobacter* are free-living bacteria that obtain their nitrogen requirements from the air. As they die and decompose, the nitrogen trapped as protein is converted to ammonia and then to nitrates by other soil bacteria. *Rhizobia spp.* which live in root nodules on some **legumes** (see Figure 21.3) also trap nitrogen to the benefit of the host plant. Finally, nitrogen gas can be converted to ammonia industrially in the **Haber process**, which is the basis of the artificial nitrogen fertilizer industry.

Excess nitrogen produces soft, lush growth making the plant vulnerable to pest attack and more likely to be damaged by cold. Very large quantities of nitrogen are undesirable since they can harm the plant by producing high salt concentrations at the roots (see **conductivity**) and are lost by leaching. Large quantities are usually applied as a split dressing, e.g. some in base dressing and the rest in one or more top dressings.

Nitrates are mobile in the soil, which makes them vulnerable to leaching. In the British Isles it is assumed that all nitrates are removed by the winter rains so that virtually none are present until the soils warm up and nitrification begins or artificial nitrogen is applied (see nitrogen cycle). Nitrates leached through the root zone may find their way into the groundwater that is the basis of the water supply in some areas. Nitrification also leads to the **loss of bases**; for every 1 kg N in the ammonia form that is oxidized to nitrate and leached, up to 7 kg of calcium carbonate or its equivalent is lost. Nitrogen is also lost from the root zone by denitrification, especially in warm, waterlogged soil conditions. When in contact with calcareous material, ammonium fertilizers are readily converted to ammonia gas which is lost to the soil unless it dissolves in surrounding water. For this reason urea or ammonia-based fertilizers should not be applied to such soils as a top dressing or used in contact with lime. **Nitrogen fertilizers** used in horticulture and their nutrient content are given in Table 21.2.

Figure 21.3 **Rhizobium nodules** on legume

Ammonium nitrate is now commonly used in horticulture. In pure form it rapidly absorbs moisture to become wet; on drying it 'cakes' and can be a fire risk. Pure ammonium nitrate can be safely handled in polythene sacks and as prills. **Ammonium sulphate** has a highly acid reaction in the growing medium. **Urea** has a very high nitrogen content and in contact with water it quickly releases ammonia. Its use as a solid fertilizer is limited, but it is utilized in liquid fertilizer or foliar sprays. The addition of a sulphur coating to urea not only creates a controlled release action, but also a fertilizer with an acid reaction. Other manufactured organic fertilizers include urea formaldehydes (nitroform, ureaform, etc.) which release nitrogen as they are decomposed by micro-organisms, isobutylidene urea (IBDU) which is slightly soluble in water and releases urea and crotonylidene (CDU, e.g. Crotodur). The latter breaks down very slowly and evenly, which makes it ideal for applying to turf.

Natural organic sources of nitrogen, including dried blood, hoof and horn and shoddy, amongst others, are generally considered to provide slow release nitrogen, but in warm greenhouse conditions decomposition is quite rapid.

Phosphorus

Phosphorus is taken up by plants in the form of the phosphate anion $H_2PO_4^{3-}$. Phosphorus is mobile in the plant and is constantly being recycled from the older parts to the newer growing areas. In practice this means that, although seeds have rich stores of phosphorus, phosphate is needed in the seedbed to help establishment. Older plants have a very low phosphate requirement compared with quick growing plants harvested young. **Most soils contain very large quantities of phosphorus, but only a small proportion is available to plants.** The concentration of available phosphate ions in the soil water and on soil colloids is at its highest between pH 6 and 7. Phosphorus is released from soil organic matter by micro-organisms (see mineralization), but most of it and any other soluble phosphorus, including that from fertilizers, is quickly converted to insoluble forms by a process known as **phosphate fixation**. Insoluble aluminium, iron and manganese phosphates are formed at low pH and insoluble calcium phosphate at high pH. The carbonic acid in the vicinity of respiring roots and organisms in the rhizosphere, such as mycorrhizae (see p322), facilitate phosphorus uptake. The low solubility of phosphorus in the soil makes it virtually immobile, with the result that roots have to explore for it. Soils should be cultivated to allow roots to explore effectively; compacted or waterlogged areas deny plants phosphorus supplies. Phosphate added to the soil should be placed near developing roots (see band placement) in order to reduce phosphorus fixation and ensure that it is quickly found. If applied to the surface, phosphate fertilizers should be cultivated into the root zone.

Unlike soils, most artificial growing media have no reserves of phosphorus and when added in soluble form it remains mobile and subject to leaching. Incorporating phosphorus in liquid feeds in hard water is complicated by the precipitation of insoluble calcium phosphates that lead to blocked nozzles. Slow release phosphates are often selected in these situations to reduce losses and to eliminate the need for phosphorus in the liquid feeds.

Phosphorus nutrition used to be based on organic sources such as bones, but now phosphate fertilizers are mainly derived from rock phosphate ore (see Table 21.2). **Slow-acting forms**, such as rock phosphate, bone meal and basic slag, can be analysed in terms of their ‘citric soluble’ phosphate content, this being a good guide to their usefulness in the first season. Such materials should be finely ground to enhance their effectiveness. These phosphates are applied mainly to grassland, tree plantings and in the preparation of herbaceous borders, to act as long-term reserves, particularly on phosphate deficient soils. Magnesium ammonium phosphate (MagAmp, Enmag), calcium metaphosphate and potassium metaphosphate contain other nutrients, but are slow release phosphates for use in soilless growing media. Treating rock phosphates with acids produces **water-soluble phosphates**. Superphosphate, derived from rock phosphate by treating with sulphuric acid, is composed of a water-soluble phosphate and calcium sulphate (gypsum), whereas triple superphosphate, derived from a phosphoric acid treatment, is a more concentrated source of phosphorus with fewer impurities. Both superphosphate and triple superphosphate are widely used in horticulture and are available in granular or powder form. Whilst they have a neutral effect on soil pH they tend to reduce the pH of composts. High-grade monoammonium phosphate is used as a phosphorus source in liquid feeds because it is low in iron and aluminium impurities that lead to blockage in pipes and nozzles.

Potassium

Potassium is taken up by the roots as the potassium cation and is distributed throughout the plant in inorganic form where it plays an important role in plant metabolism. For balanced growth the nitrogen to potassium ratio should be 1:1 for most crops, but 2:3 for roots and legumes. Leafy crops take up large amounts of potassium, especially when given large amounts of nitrogen. Where potassium supplies are abundant some plants, especially grasses, take up 'luxury' levels, i.e. more than needed for their growth requirements. Consequently, if large proportions of the plant are taken off the land, e.g. as grass clippings, there is a rapid depletion of potassium reserves. Potassium forms part of clay minerals and is released by chemical weathering. The potassium in soil organic matter is very rapidly recycled and exchangeable potassium **cations** (see p371), held on the soil colloids and in the soil solutions, are readily available to plant roots. Potassium is easily leached from sands low in organic matter and from most soilless growing media (see Figure 21.4).

Figure 21.4 Potassium deficiency

Potassium and magnesium ions mutually interfere with uptake of each other. This **ion antagonism** is avoided when the correct ratio between 3:1 and 4:1 available potassium to magnesium is present in the growing medium. Availability of potassium is also reduced by the presence of calcium (see induced deficiency).

The main potassium fertilizers used in horticulture are detailed in Table 21.2. Although cheaper and widely used in agriculture, potassium chloride causes scorch in trees and can lead to salt concentration problems because the chloride ion accumulates as the potassium is taken up. Commercial potassium sulphate can be used in base dressings for composts, but only the more expensive refined grades should be used in liquid feeding. More usually potassium nitrate is used to add both potassium and nitrate to liquid feeds, but it is hygroscopic. Most potassium compounds are very soluble so that the range of slow release formulations is limited to resin-coated compounds.

Magnesium

Magnesium is an essential plant nutrient in leaves and roots and is taken up as a cation. There are large reserves in most soils, especially clays, and those soils receiving large dressings of farmyard manure. Deficiencies (see Figure 21.5) are only likely on intensively cropped sandy soils if little organic manure is used. Magnesium ion uptake is also interfered with by large quantities of potassium or calcium ions because of **ion antagonism**. Chalky and over-limed soils are less likely to yield adequate magnesium for plants. Magnesium fertilizers include magnesian limestones containing a mixture of magnesium and calcium carbonate that raise soil pH (see liming). Magnesium sulphate, as kieserite, provides magnesium ions without affecting pH levels and in a purer form, Epsom salts, is used for liquid feeding and foliar sprays (see Table 21.2).

Figure 21.5 Magnesium deficiency

Calcium

Calcium is an essential plant nutrient taken up by the plant as calcium cations. Generally a satisfactory pH level of a growing medium indicates suitable calcium levels (see liming). Gypsum (calcium sulphate) can be used where it is desirable to increase calcium levels in the soil without affecting soil pH. Deficiencies are infrequent and usually caused by lime being omitted from composts. Inadequate calcium in fruits is a more complex problem involving the distribution of calcium within the plant (see page 258). Calcium nitrate or chloride solutions can be applied to apples to ensure adequate levels for safe storage (see plant tissue analysis).

Sulphur

Sulphur taken up as sulphate ions is a nutrient required in large quantities for satisfactory plant growth. It is not normally added specifically as a fertilizer because the soil reserves are replenished by re-circulated organic matter and a steady supply from winds off the sea in the form of dimethyl sulphide (DMS) that gives the distinctive smell of the seaside. Air pollution has added considerably to the supply reaching the land. Several fertilizers used to add other nutrients are in sulphate form, e.g. ammonium sulphate, superphosphate and potassium sulphate, and as such supply sulphur as well (see Table 21.2). However, as air pollution is reduced and fewer sulphate fertilizers are used, it is becoming necessary for growers in some parts of the world to take positive steps to include sulphur in their fertilizer programme.

Minor nutrients

Minor nutrients, also known as trace elements or micro-elements, are present in plants in very small quantities, but are just as essential for healthy growth as major elements. However, they can be toxic to plants if too abundant. This means that rectifying deficiencies with soluble salts has to be undertaken carefully.

Deficiencies

Simple deficiencies are those in which too little of the nutrient is present in the growing medium. Most soils have adequate reserves of trace elements, so simple deficiencies in them are uncommon, especially if replenished with bulky organic matter. Sandy soils tend to have low reserves and so too have several organic soils from which trace elements have been leached. In horticulture simple deficiencies of trace elements are mainly associated with growing in soil-less composts which require careful supplementation.

Induced deficiencies are those in which sufficient nutrients are present, but other factors, such as soil pH or **ion antagonism**, interfere with plant

nutrient availability. On mineral soils boron, copper, zinc, iron and manganese become less available in alkaline soils, whereas molybdenum availability is reduced severely in soils with pH levels below 5.5, as shown in Figure 20.4. Trace element problems are aggravated in dry soils or where waterlogging, root pathogens or poor soil structure reduces root activity.

Iron deficiency is induced by the presence of large quantities of calcium and this **'lime induced' chlorosis** (yellowing) occurs on over-limed soils and calcareous soils. The natural flora of chalk and limestone areas is calcicoles. Other plants grown in such conditions usually have a typically yellow appearance. Deficiencies can also be induced by high levels of copper, manganese, zinc and phosphorus. Top fruit and soft fruit are particularly susceptible, as well as crops grown in complete nutrient solutions. The problem is overcome by using iron chelates.

Boron deficiency tends to occur when pH is above 6.8. It is readily leached from peat. Crops grown in peat are particularly susceptible when pH levels rise (Figure 20.4). Boron can be applied to soils before seed sowing in the form of borax or 'Solubor'.

Manganese deficiency is more frequent on organic and sandy soils of high pH. Plant uptake can be reduced by high potassium, iron, copper and zinc levels. Manganese availability is greatly increased at low pH and can reach toxic levels which most commonly occur after steam sterilization of acid, manganese-rich soils. High phosphorus levels can be used to reduce the uptake of manganese in these circumstances.

Copper deficiency usually occurs on peat and sands, notably reclaimed heath-land, and in thin organic soils over chalk. High rates of nitrogen can accentuate the problem. Soils can be treated with copper sulphate or plants can be sprayed with copper oxychloride.

Zinc deficiencies are not common and are usually associated with high pH.

Molybdenum deficiency occurs in most soil types at a low pH (see Figure 20.4). Availability becomes much reduced below pH 5.5, especially in the presence of high manganese levels. Cauliflowers are particularly susceptible and soils are limed to solve the problem. Sodium or ammonium molybdate can be added to growing media or liquid feeds where molybdenum supplies are inadequate.

Basic chemistry

Some knowledge of chemistry can give insights into biology and thus horticulture. Chemistry deals with the reactions that occur when different chemical substances are brought into contact with each other.

Elements. All substances are made up of elements. There are 92 stable elements, such as oxygen and hydrogen. Each element occurs in nature as atoms.

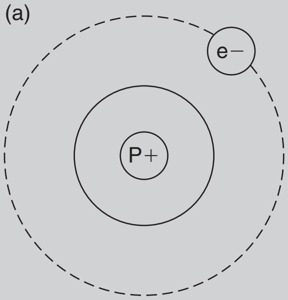
Atoms. The first step in chemical understanding involves the atom and its structure. All substances are made of atoms. Atoms are about one ten millionth of a millimetre in size. Each one may be considered to have a central nucleus (containing protons and neutrons), and one or more outer shells (or orbitals) of circulating electrons (see Figure 21.6). Each proton and each neutron contributes a unit of 1 to the atomic weight of the element. In the carbon atom, there are 6 protons and 6 neutrons giving carbon an atomic weight of 12. The proton has a positive charge whilst the neutron has no charge. The circulating electrons can be considered to have no measurable weight, but have a negative charge equal but opposite to the proton. In each element, the number of electrons equals the number of protons. In the carbon atom, there are 6 protons and 6 electrons.

At its simplest, the chemistry of an element may be considered in terms of the group of electrons' 'quest for stability'. The first (inner) orbital is described as stable when it has either zero or two electrons. Outer orbitals are considered stable when they have zero or eight electrons. Four examples are used to illustrate this principle.

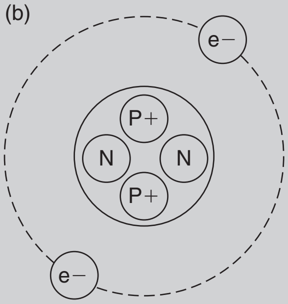
Hydrogen is the simplest of the elements. It has one proton and one electron in its one (inner) orbital. Its atomic weight is 1. For stability, it can pair its electron with another hydrogen atom's electron. In this way the two atoms have a stable orbital of two electrons. **Helium** is an inert (non-reacting) gas. It has two protons and two electrons and therefore does not react with other substances (see Figure 21.4).

Ionic compounds. Ionic compounds, such as salts, are made up of charged atoms (ions). In the case of common salt (sodium chloride), the **sodium** and **chlorine** atoms react together (see Figure 21.7). The metallic sodium atom gives away its negative electron, thus becoming a positively charged ion called a **cation**. At the same time, the chlorine atom receives the negative electron from the sodium, thus becoming a negatively charged ion called an **anion**. Ionic substances, such as sodium chloride and many fertilizers, allow an electric current to pass through them when they are dissolved in water. Horticulturists are able to assess the strength of dissolved fertilizers in soils and composts by measuring this current (conductivity see p380).

Compound ions. Some anions occur in a compound form. Carbonate (CO_3^{2-}), Nitrate (NO_3^-), Nitrite (NO_2^-), phosphate (PO_4^{3-}) and sulphate (SO_4^{2-}) are some examples. One cation, ammonium (NH_4^+) is commonly found in fertilizers. In contrast to ionic compounds, the element carbon **shares** electrons with the element it reacts with to produce molecules, many of which are very large (see **carbon chemistry** p111).



Hydrogen atom is reactive



Helium atom is stable

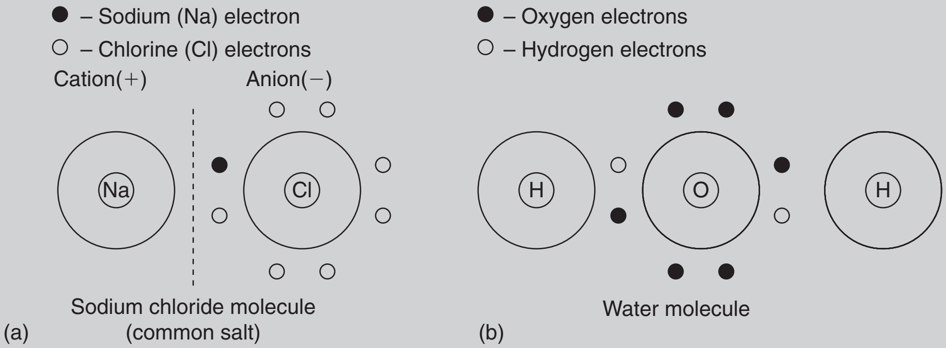
P = proton
N = neutron
e = electron

Figure 21.6 **Atoms**.
(a) hydrogen (b) helium

Oxygen is a gas like hydrogen but differs from it in several ways. It is much heavier, having 8 protons and 8 neutrons (and 8 electrons) and an atomic weight of 16. Its inner electron orbital is stable, with 2 electrons, leaving six electrons in the second orbital. Oxygen therefore needs to receive two electrons to become stable. It can be seen that oxygen's combining power is twice that of hydrogen. Oxygen is thus said to have a **valency** (combining power) of two while hydrogen's valency is one. When oxygen and hydrogen react together, it becomes clear from the description above that the substance produced by the reaction is H_2O, or **water**, since the two hydrogens are needed to fill oxygen's orbital.

Horticultural plants require 15 elements for their growth. Table 21.1 lists the atomic weights and valency for each of the elements.

Molecular weight. Examples of simple molecules are given in the 'common compounds' section of Table 21.1. The molecular weight of a substance can be calculated by adding the individual atomic weights of the elements within it. For example, the molecular weight of ammonium nitrate (NH_4NO_3) is $14 + 1 + 1 + 1 + 1 + 14 + 16 + 16 + 16 = 80$. Note that there are two nitrogen atoms in the compound, contributing 28 parts out of the total of 80 i.e. 35 per cent. Fertilizers of this type are not quite as pure and typically contain 33 per cent nitrogen (see p325).



Sodium chloride molecule (common salt)

Water molecule

Figure 21.7 (a) Ionic bonding; sodium chloride (common salt). Sodium loses an electron and becomes a sodium cation; chlorine gains an electron and becomes an anion; (b) covalent bonding, e.g. water; one oxygen and two hydrogen atoms share electrons in their outer orbits (shells) to gain stability.

Table 21.1 Chemical information on horticulturally useful elements

Element	Symbol	Atomic weight	Valency	Common compound
Hydrogen	H	1	1	Water (H_2O)
Boron	B	11	3	Borax
Carbon	C	12	4	Carbon dioxide (CO_2)
Nitrogen	N	14	2,4	Ammonium nitrate
Oxygen	O	16	2	Oxides
Magnesium	Mg	24	2	Kieserite
Phosphorus	P	31	3	Superphosphate
Sulphur	S	32	2	Ammonium sulphate
Potassium	K	40	1	Potassium nitrate
Calcium	Ca	41	2	Lime
Manganese	Mn	55	2	Manganese sulphate
Iron	Fe	56	2,3	Ferrous sulphate
Copper	Cu	64	1,2	Copper sulphate
Zinc	Zn	65	2	Zinc sulphate
Molybdenum	Mo	96	2–5	Ammonium molybdate

Sources of nutrients

Nutrients are supplied naturally from the decomposition of organic matter and are released as clay weathers in the soil. In horticulture, additional supplies are made by the use of organic and inorganic fertilizers, bulky organic matter and through green manuring.

Fertilizers

Fertilizers are concentrated sources of plant nutrients that are added to growing media.

Straight fertilizers are those that supply only one of the major nutrients: nitrogen, phosphorus, potassium or magnesium (see Table 21.2). The amount of nutrient in the fertilizer is expressed as a percentage. Nitrogen fertilizers are described in terms of percentage of the element nitrogen in the fertilizer, i.e. per cent N. Phosphate fertilizers have been described in terms of the equivalent amount of phosphoric oxide, i.e. per cent P_2O_5, or increasingly as percentage phosphorus, per cent P. Likewise potash fertilizers, i.e. per cent K_2O, or percentage potassium, per cent K. Magnesium fertilizers are described in terms of per cent of Mg. The percentage figures clearly show the quantities of nutrient in each 100 kg of fertilizer.

Compound fertilizers are those that supply two or more of the nutrients nitrogen, phosphorus and potassium. The nutrient content expressed as for straight fertilizers is, by convention, written on the bag in the order nitrogen, phosphorus and potassium. For example, 20–10–10 denotes 20 per cent N, 10 per cent P_2O_5 and 10 per cent K_2O.

Table 21.2 Nutrient analysis of fertilizers

	N %	P_2O_5 (P) %	K_2O (K) %	Mg %	Ca %	S %	Na %
Ammonium nitrate	33–35						
Ammonium sulphate	20–21					24	
Bone meal	3	20 (9)					
Calcium nitrate	15.5				20		
Calcium sulphate					23	18	
Chilean potassium nitrate	15		10 (8)				20
Dried blood	12–14						
Hoof and horn	12–14						
Kieserite				15		21	
Meat and bone meal	5–10	18 (8)					
Monoamm phosphate	12	37 (15)					
Phosphoric acid		54 (24)					
Potassium chloride			59 (49)				
Potassium nitrate	14		46 (38)				
Potassium sulphate			50 (42)			17	
Shoddy (wool waste)	2–15						
Superphosphate		18–20 (8–9)			20	12–14	
Triple superphosphate		47 (20)			14		
Urea	46						

Fertilizer regulations require that further details of trace elements, pesticide content and phosphorus solubility should appear where applicable on the invoice. Fertilizers and manures are available in many different forms. Generally the term **organic** implies that the fertilizer is derived from living organisms, whereas **inorganic** fertilizers are those derived from non-living material. However, in the context of organic growing it is necessary to look at specific requirements of the regulations (Table 21.3).

Application methods

Fertilizers are applied in several different ways.

- **Base dressings** are those that are incorporated in the growing medium. Combine drilling with seeds and fertilizer running into the same drill can achieve this. In horticulture, however, **band placement** of fertilizers is far more common, involving equipment that drills the seeds in rows and places a band of fertilizer in parallel a few centimetres below and to one side. The risk of retarded germination

Table 21.3 Sources of nutrients for use in organic growing

Farmyard and poultry manure	Rock potash
Slurry or urine	Sulphate of potash*
Composts from spent mushroom and vermiculture substrates	Limestone
Composts from organic household refuse	Chalk
Composts from plant residues	Magnesium rock
Processed animal products from slaughterhouses and fish industries	Calcareous magnesium rock
Organic by-products of foodstuffs and textile industries	Epsom salt (magnesium sulphate)
Seaweeds and seaweed products	Gypsum (Calcium sulphate)
Sawdust, bark and wood waste	Trace elements (boron, copper, iron, manganese, molybdenum, zinc)*
Wood ash	Sulphur*
Natural phosphate rock	Stone meal
Calcinated aluminium phosphate rock	Clay (bentonite, perlite)
Basic slag	

*Need recognized by control body.

or scorch of young plants due to high soluble fertilizers placed near seeds is thus avoided (see salt concentration). There is much less risk if fertilizer is **surface broadcast**, i.e. scattered on prepared soil surface, or broadcast on the surface to be cultivated-in during the final stages of seedbed preparation.

- **Top dressings** are fertilizers added to the soil surface but not incorporated. Such fertilizers must be soluble and not fixed by soil because the nutrient is carried to the roots by soil water. Nitrogen is the material most frequently applied by this method mainly because the large applications to crops require a base dressing and one or more top dressings to minimize the risk of scorch and loss by leaching.
- **Liquid feeding** is the application of fertilizer diluted in water to the root zone; fertigation if incorporated in irrigation system.
- **Foliar feeding** is the application of a liquid fertilizer in suitably diluted form to be taken up through leaves. This technique is usually restricted to the application of trace elements.

Formulations

Quick-acting fertilizers contain nutrients in a form which plant roots can take up, and dissolve as soon as they come in contact with water, e.g. ammonium nitrate and potassium chloride. Many are obtainable as powders or crystals. These are difficult to spread or place evenly, but several are formulated this way to help in the preparation of liquid feeds. For this purpose they must be readily soluble and free of impurities that might lead to blockages in the feed lines. Some of the less soluble fertilizers, as well as lime, are spread in a finely divided form for maximum effect on soil. One of the major problems with many of the fertilizers is their **hygroscopic** nature, i.e. they pick up water from the atmosphere and create storage and distribution problems. Powdered forms, in particular, go sticky as they take up water then ‘cake’ (form hard lumps) as they dry. Fertilizers formulated as **granules** are more satisfactory for accurate placement or broadcasting. They flow better, can be metered, and are thrown more accurately. **Prilled** fertilizers represent an improvement on granules because of their uniform spherical shape.

Slow release fertilizers are those in which a large proportion of the nutrient is released slowly. Several of these fertilizers, such as rock phosphate, are insoluble or only slightly soluble and the nutrients are released only after many months, even years. Micro-organisms break down organic products and the rate at which nutrients become available depends on their activity (see bacteria). Some slow release artificial fertilizers, such as those based on urea formaldehyde, dissolve slowly in the soil solution whilst others are formulated in such a way that the soluble fertilizer they contain diffuses slowly through a resin coat, e.g. Osmocote, or sulphur coating. Some of these slow-release fertilizers have been formulated in such a way as to release nutrients at a rate that matches a plant’s uptake and as such are sometimes referred to as **controlled-release** fertilizer. **Frits**, made from fine glass powders containing nutrient elements, are used either to release soluble materials slowly or to overcome the trace element problem caused by the narrow limits between deficiency and toxicity (see trace elements). Frits ease the difficulties experienced in mixing tiny amounts evenly through large volumes of compost. **Ion-exchange resins** release their nutrients by exchange with cations in the surrounding water. These resins help to overcome the problems of high salt concentration and leaching of nutrients from growing media based on inert materials (see aggregate culture).

Some plant nutrients are formed as **chelates** to maintain availability in extreme conditions where the mineral salt is ‘locked up’. There are many different chelating or sequestrating agents selected, for each element to be protected and for each unavailability problem. Iron is chelated with EDDHA to form the product Chel 138 or Sequestrine 138 which releases the element in all soils including those with a high pH (see iron deficiency). EDTA, effective where there are high levels of copper, zinc and manganese, is used to chelate iron to be applied in foliar sprays.

Bulky organic matter

Compost, straw, farmyard manure, bark and peat are important in horticulture as a means of maintaining organic matter and humus levels (see p329–30). However, they tend to be low in nutrients and some, such as straw and bark, lead to locking up of nutrients (see C:N ratio p325). They can be evaluated on the basis of their effect on the physical properties of soil and their small, nutrient content.

Green manures

Green manuring is the practice of growing plants primarily to develop and maintain soil structure and fertility (see p330). The plants used are typically agricultural crops that cover the ground quickly and yield a large amount of leaf to incorporate. The seeds are normally broadcast sown in the autumn when there are no other overwintering plants. The plants are then dug or ploughed in when the land is needed again.

Fertilizer programmes

The fertilizer applications required to produce the desired plant growth vary according to the type of plant, climate, season of growth, other sources of nutrients applied and the nutrient status of the soil. General advice is available in many publications including those of the national advisory services and horticultural industries. Examples are given in Table 21.4.

Growing medium analysis

The nutrient status of growing media varies greatly between the different materials and within the same materials as time passes. The nutrient levels change because they are being lost by plant uptake, leaching and fixation and gained by the weathering of clay, mineralization of organic matter, and the addition of lime and fertilizers.

There are many visual symptoms which indicate a deficiency of one or more essential nutrients (see minerals), but unfortunately by the time they appear the plant has probably already suffered a check in growth or change in the desired type of growth. The concentration of minerals in the plant and the nature of growth are linked so that **plant tissue analysis**, usually on selected leaves, can provide useful information, particularly in the diagnosis of some nutrient deficiencies; e.g. it is used to identify the calcium levels in apples in order to check their storage qualities. However, nutrient supply is usually assessed by analysis of the growing medium. There is general agreement about the methodology for **analyzing soils**. However, there needs to be some care where analysis of other growing media is undertaken, because there are considerable differences between the methods particularly with regard to dilution of the nutrient extractant.

A representative sample of the growing medium is taken and its nutrient status determined. This involves extracting the **available nutrients** and measuring the quantities present. The **pH level** is determined and, where appropriate, the **lime requirement**. The **conductivity** of growing media from protected culture is also measured. The **nitrogen status** of soils is usually determined from previous cropping because, outdoors, nitrates are washed out over winter and their release from organic matter reserves is very variable. In protected planting, nitrate and ammonia levels are usually determined. Results are often given in the form of an index number in order to simplify their presentation and interpretation. The ADAS soil analysis index is based on a ten point scale from 0 (indicating levels which correspond

Table 21.4 Examples of fertilizer requirements

Carrots

N, P or K index			0	1	2	3	4	over 4
			(kg/ha)					
Carrots, early bunching		N	60	25	Nil	–	–	–
		P_2O_5	400	300	250	150	125	Nil
		K_2O	200	125	100	Nil	Nil	Nil
Carrots, (maincrop)	fen peats	N	Nil	Nil	Nil	–	–	–
	other soils	N	60	25	Nil	–	–	–
	all soils	P_2O_5	300	250	200	125	60	Nil
		K_2O	200	125	100	Nil	Nil	Nil

Carrots on sandy soils respond to salt: 150 kg/ha Na (400 kg/ha salt) should be applied and potash reduced by 60 kg/ha K_2O. Salt must be worked deeply into the soil before drilling or be ploughed in.

Dessert apples: mature trees

	Summer rainfall	Cultivated or overall herbicide	Grass/herbicide strip	Grass
		(kg/ha per year)		
Nitrogen (N)	more than 350 mm	30	40	90
	less than 350 mm	40	60	120

P, K or Mg index	0	1	2	3	over 3
		(kg/ha per year)			
P_2O_5	80	40	20	20	Nil
K_2O	220	150	80	Nil	–
Mg	60	40	30	Nil	–

For the first 3 years, fertilizer is not required by *young trees* grown in herbicide strips, provided that deficiencies of phosphate, potash and magnesium are corrected before planting by thorough incorporation of fertilizer.

Lettuce: base dressings for border soils under glass

Nitrate P, K or Mg index	Ammonium nitrate	Triple superphosphate	Sulphate of potash	Kieserite
		g/m^2		
0	30	150	160	110
1	15	140	110	80
2	Nil	130	50	30
3	Nil	110	Nil	Nil
4	Nil	80	Nil	Nil
5	Nil	45	Nil	Nil
Over 5	Nil	Nil	Nil	Nil

Increase the nitrogen application by 50 per cent for summer grown crops. Lettuce is sensitive to low soil pH and the optimum pH is the range 6.5–7.0. It is also sensitive to salinity, and growth may be retarded on mineral soils when the soil conductivity index is greater than 2.

to probable failure of plants if nutrient is not supplied) to 9 (indicating excessively high levels of nutrient present); most outdoor soils normally give levels of 1 to 3.

Fertilizer recommendations

The results of the **growing medium analysis** are interpreted with the appropriate **nutrient requirement tables** to determine the actual amount of fertilizer to apply. These tables usually have growing medium nutrient status indices to aid interpretation and results are normally given in kg of nutrient per hectare or grams of nutrient per square metre (Table 21.4). In some cases the amount of named fertilizer required is stated; if another fertilizer is to be used to supply the nutrient the quantity needed must be calculated using the nutrient content figures (Table 21.2). It is important that throughout the fertilizer planning process the same units are used, i.e. per cent P_2O_5 *or* P per cent; K_2O *or* per cent K. Conversion figures are:

$$\begin{array}{lll} \%P_2O_5 = \%P & \times 2.29 \\ \%P = \%P_2O_5 & \times 0.44 \\ \%K_2O = \%K & \times 1.20 \\ \%K = \%K_2O & \times 0.83 \end{array}$$

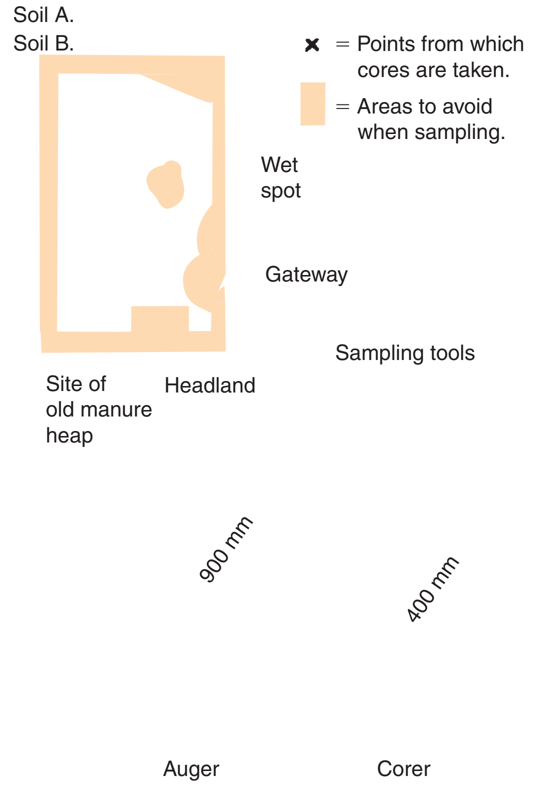


Figure 21.8 **Sampling growing media**. Suitable tools to remove small quantities of growing media are corers or augers which have the advantage of removing equal quantities from the top and bottom of the sampled zone. The material to be sampled must be clearly identified, then 25 cores should be removed in a zigzag that avoids anything abnormal

Sampling

Normally only a small proportion of the whole growing medium is submitted for analysis and therefore it must be a **representative sample** of the whole. This is not easy because of the variability of growing media, particularly soils. It is recommended that each sample submitted for testing should be taken from an area no greater than 4 hectares (see Figure 21.8). The material sampled must itself be uniform and so only areas with the same characteristics and past history should be put in the same sample. Irrespective of the area involved, from small plot to 4 hectare field, at least 25 sub-samples should be taken by walking a zigzag path, avoiding the atypical areas such as headlands, wet spots, old paths, hedge lines, old manure heaps, etc. The same amount of soil should be taken from each layer to a depth of 150 mm. This is most easily achieved with a soil auger or tubular corer.

Peat bags should be sampled with a cheese-type corer by taking a core at an angle through the planting hole on the opposite side of the plant to the drip nozzle from each of 30 bags chosen from an area up to a maximum of 0.5 hectares. Discard the top 20 mm of each core and if necessary take more than 30 cores to make up a one litre sample for analysis. Samples should be submitted to analytical laboratories in clean containers capable of completely retaining the contents. They should be accompanied by name and address of supplier, the date of sampling and any useful background information. All samples must be clearly identified. Further details of sampling methods in greenhouses or orchards, bags, pots, straw bales, water, etc., are obtainable from the advisory services used. Remember, the result of the analysis can be no better than the extent to which the sample is representative of the whole.

Soil conductivity

The **soil solution** is normally a weaker solution than the plant cell contents. In these circumstances plants readily take up water through their roots by osmosis. As more salt, such as soluble fertilizer, is added to the soil solution, **salt concentrations** are increased and less water, on balance, is taken up by roots. When salt concentrations are balanced as much water passes out of the roots as into them. When salt concentrations are greater in the soil the roots are plasmolyzed. The root hairs, then the roots, are 'scorched', i.e. irreversibly damaged, and the plant dries up.

Symptoms of high salt concentration above ground are related to the water stress created. Plants wilt more often and go brown at the leaf margin. Prolonged exposure to these conditions produces hard, brittle plants, often with a blue tinge. Eventually severe cases become desiccated.

Salt concentration levels are measured indirectly using the fact that the solution becomes a better conductor of electricity as salt concentration is increased. The conductivity of soil solution is measured with a **conductivity meter** (see ionic compounds, p373).

Salt concentration problems are most common where fertilizer salts accumulate, as in climates with no rainfall period to leach the soil and in protected culture. Periods when rainfall exceeds evaporation, as in the British Isles during winter, ensure that salts are washed out of the ground. Any plant can be damaged by applications of excess fertilizer. Some plants, such as tomatoes and celery, are more tolerant than others, but seedlings are very sensitive. Young roots can be scorched by the close proximity of fertilizer granules in the seedbed (see band placement).

In **protected culture** large quantities of fertilizer are used and residues can accumulate, particularly if application is not well adjusted to plant use. Sensitive plants, such as lettuce, are particularly at risk when following heavily-fed, more tolerant plants, such as tomatoes or celery. Salt concentration levels should be carefully monitored and feeding adjusted accordingly, applying water alone if necessary. Soils can be **flooded** with water between plantings to leach excess salts. Large quantities of water are needed, but should be applied so that the soil surface is not damaged. Every effort should be made to minimize the effect on the environment and quantities of water needed to flush out the excess salts by reducing the nutrient levels as the crop comes to an end.

Check your learning

1. Describe the main effect that nitrogen has on plant growth.
2. Describe how gaseous nitrogen may become used by plants.
3. Explain why phosphates are needed in seedling compost.
4. Describe the symptoms of potash deficiency in plants.
5. Describe the advantages of using organic fertilizers.
6. Distinguish between base and top dressings.
7. Explain what is meant by controlled release fertilizers and give examples.
8. Explain why green manures are used.

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Chapter 22 Alternatives to growing in the soil

Summary

This chapter includes the following topics:

- **Alternative growing media**
- **Air-filled porosity, stability and water holding**
- **Compost ingredients**
- **Peat alternatives**
- **Compost mixes**

with additional information on the following:

- **Compost mixing**
- **Plant containers**
- **Hydroculture**

Figure 22.1 **Hanging baskets** are both popular for the garden, but are also used in public areas by Local Authorities and businesses wishing to make a good impression

Alternative growing media

In addition to open ground or greenhouse borders, plants may be grown in pots, troughs, bags and other containers where restricted rooting makes more critical demands on the growing medium for air, water and nutrients. Soil is an inappropriate material to use in containers as it tends to collapse when kept wet; try watering a pot full of soil and note that it is not long before the container is only half full of soil. Soil is replaced in this situation by alternative growing media generally called **composts**. These materials are also called plant substrates, plant growing media, or just ‘mixes’ or ‘media’.

Compost ingredients need to ensure adequate air space after wetting, with a stability to withstand prolonged watering without collapse. The need for the material to have good water-holding capacity depends on the irrigation system to be used. The nutrient content of the soil alternative needs to be allowed for and it is often advantageous to use one that has none as they can be added more precisely. The material should also be ‘partially sterile’ (free from pest and diseases) and free from toxics. Increasingly, in intensive production, the preferred alternative to growing in the soil is to use hydroponics (see p394). The weaknesses of soil for sportsground construction leads to its replacement with alternatives, e.g. graded sand on golf greens (see p397–8).

Air-filled porosity (AFP)

Air-filled porosity is the proportion of the volume of a growing medium which contains air, after it has been saturated and allowed to drain.

The importance of supplying water to plants in a restricted root volume is usually understood, but the difficulties associated with achieving it whilst maintaining adequate **air-filled porosity (AFP)** are less well appreciated. Roots require oxygen to maintain growth and activity. As temperatures rise the plant requires more, but the amount of oxygen that is dissolved in water decreases. Even in cool conditions, the oxygen that can be extracted from the water provides only a fraction of the roots requirements. So, unless the plants have special modifications to transport oxygen through their tissues, as in aquatic plants, there has to be good gaseous movement through the growing medium. Many large interconnected pores allow rapid entry of oxygen (see soil structure). Creating successful physical conditions depends on the use of components that provide a high proportion of macropores.

It is generally considered that 10–15 per cent AFP is needed for a wide range of plants. Azaleas and epiphytic orchids require 20 per cent or more, whereas others, including chrysanthemums, lilies and poinsettia, tolerate 5–10 per cent AFP and carnations, conifers, geraniums, ivies and roses can be grown at levels as low as 2 per cent.

Ensuring that a growing medium in a container has adequate air-filled porosity is made difficult because water does not readily leave the container unless it is in good contact through its holes with similar-sized pore spaces as when placed on sand or capillary matting. However, when standing out on gravel or wire the water will cling to the particles in the container (see surface tension p338). This can be tested by fully watering a pot of compost, holding it until it has finished dripping then touching the compost through a hole; normally a stream of water will run down your finger. Furthermore, unless stood out on appropriate material, the lower layers of the compost remain saturated (i.e. no air) irrespective of the height or width of the container. This makes it particularly difficult to get good aeration in shallow trays, modules and blocks. (You may understand this better if you fully wet a washing sponge and leave it to drain. After water has left the sponge under the influence of gravity, the lower layers remain saturated.)

Stability

Very large quantities of water have to be applied to composts over the course of a season, so the materials chosen must have very good **stability**. Fine sand and silt soils collapse too quickly and reduce the size of the pore spaces. Even clay crumbs, unless reinforced with high humus content, collapse quite quickly. The sizes of the components used must be selected carefully to ensure that they create macropores, but also so that the gaps between the larger particles are not subsequently filled in by smaller particles ('fines'). This is most easily achieved by using closely graded coarse particles. The reverse is achieved when combining many different-sized particles, as one would in mixing concrete, where the object is to minimize the air spaces as shown in Figure 22.2.

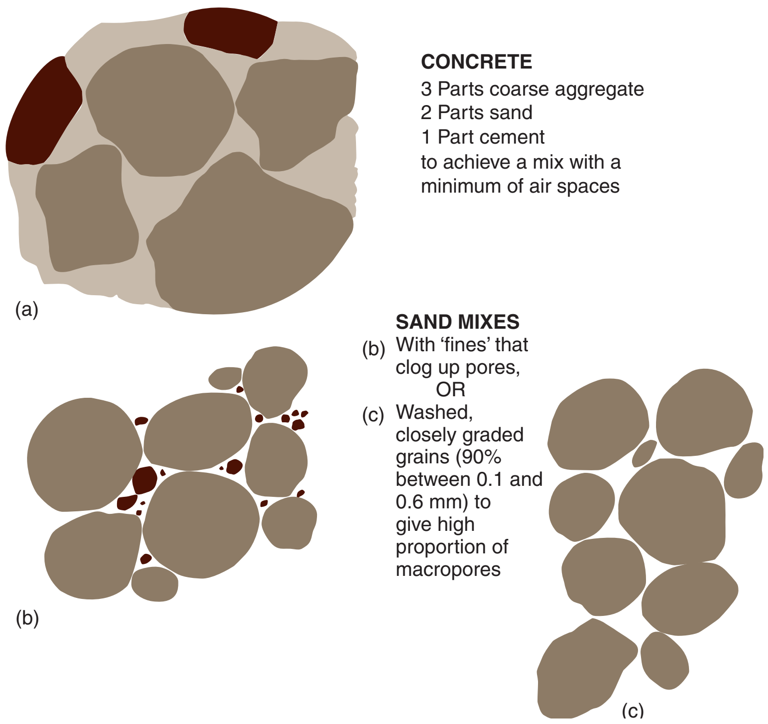

Figure 22.2 **Pore spaces** in (a) concrete mix (b) and (c) sand mixes

Water-holding capacity

The water-holding capacity of compost ingredients varies enormously. Peat is significantly better than most others. However, the importance of this depends on how the plants in the compost are to be irrigated. It is a major consideration if the plants are in small hanging baskets watered by hand and there are benefits in using absorbent polymers (see p390) that improve water-holding more than peat alone. Peat presents a problem if it dries out, because it does not rewet easily unless treated with wetters (see p390). On the other hand, if there is to be a constant supply of water through one of the many self-watering systems (see p350), this water-holding capacity is far less significant and the emphasis should be on choosing material that is stable and provides the right air-filled porosity.

Compost ingredients

Over the years growers have added a wide variety of materials, such as leaf mould, pine needles, spent hops, old mortar, crushed bricks, composted animal and plant residues, peat, sand and grit, to selected soils to produce a compost with suitable physical properties. To supplement the nutrient released from the materials in the compost, if any, various slow release organic manures or small dressings of powdered soluble inorganic fertilizers have been added to the mixtures to provide the necessary nutrition.

The correct physical and nutritional conditions are vital to successful growing in a restricted rooting volume. Significant developments occurred as a result of the work done in the 1930s at the John Innes Institute, where the importance of 'sterile' (pest and disease free), stable and uniform ingredients was demonstrated. The range of composts that resulted from this work established the methods of achieving uniform production and reliable results with a single potting mixture suitable for a wide range of plant species.

Loam composts

Loam composts, typified by John Innes composts, are based on loam sterilized to eliminate the soil-borne fungi (see damping off) and insects that largely caused the unreliable results from traditional composts. There is a risk of ammonia toxicity developing after sterilization of soil with pH greater than 6.5 or very high in organic matter (see nitrogen cycle). Induced nutrient deficiencies are possible in soils with a pH greater than 6.5 or less than 5.5. Furthermore, loam should have sufficient clay and organic matter present to give good structural stability (the original specification identifies 'turfy clay loam'). Peat and sand are added to further improve the physical conditions: the peat gives a high water-holding capacity and the coarse sand ensures free drainage and therefore good aeration. There are two main John Innes composts, one for seed sowing and cuttings, the other for potting.

John Innes seed compost consists of 2 parts loam, 1 part peat and 1 part sand by volume. Well-drained turfy clay loam low in nutrients and with a pH between 5.8 and 6.5; undecomposed peat graded 3 mm to 10 mm with a pH between 3.5 and 5.0; and lime-free sand graded 1–3 mm should be used. 1200 g of superphosphate and 600 g of calcium carbonate (lime) are added to each cubic metre of compost.

John Innes potting (JIP) composts consist of 7 parts by volume turfy clay loam, 3 parts peat and 2 parts sand. To allow for the changing nutritional requirements of a growing plant, the nutrient level is adjusted by adding appropriate quantities of JI base fertilizer which consists of 2 parts by volume hoof and horn, 2 parts superphosphate and 1 part potassium sulphate. To prepare JIP 1, 3 kg JI Base fertilizer and 600 g of calcium carbonate are added to one cubic metre of compost. To prepare JIP 2 and JIP 3, double and treble fertilizer levels respectively are used.

Whilst the standard JI composts are suitable for a wide range of species, some modification is required for some specialized plants. For example, calcifuge plants such as *Ericas* and *Rhododendrons* should be grown in a JI(S) mix in which sulphur is used instead of calcium carbonate. All loam-based composts should be made up from components of known characteristics and according to the specification given. Such composts are well proven and are relatively easy to manage because of the water-absorbing and nutrient-retention properties of the clay present.

These composts are commonly used by amateurs, for valuable specimens, and for tall plants where pot stability is important; but loam-based composts have been superseded in horticulture generally by cheaper alternatives. The main disadvantage of loam-based composts has always been the difficulty of obtaining suitable quality loam ('turfy clay loam'), as well as the high costs associated with steam sterilizing. Furthermore, the loam must be stored dry before use and the composts are heavy and difficult to handle in large quantities. Many of the loam-based composts currently produced have relatively low loam content and consequently exhibit few of its advantages.

Loamless or soilless composts

Loamless composts introduced the advantages of a uniform growing medium, but with components that are lighter, cleaner to handle, cheaper to prepare and which do not need to be sterilized (unless being used more than once). Many have low nutrient levels which enable growers to manipulate plant growth more precisely through nutrition, but the control of nutrients is more critical, as many components have a low **buffering capacity**. **Peat** has until recently been the basis of most loamless composts. It is used alone or in combination with materials, such as sand, to produce the required rooting environment. Peats are derived from partially decomposed plants and their characteristics depend on the plant species and the conditions in which they are formed (see Chapter 18). Peats vary and respond differently to herbicides, growth regulators and lime. All peats have a high cation exchange capacity, which gives them some buffering capacity. The less decomposed sphagnum peats have a desirable open structure for making composts and all peats have high water-holding capacities.

Alternatives to peat

Whilst peat remains a popular choice as a compost ingredient, great efforts are being made to find alternatives in order to preserve the wetland habitats where peat is harvested. A list of some of the materials used is given in Table 22.1. Much progress has been made by using suitably processed bark or coconut fibre in composts. Along with several other organic sources they are waste-based and recycling them helps in conserving resources. All such alternatives must be free of toxics and pathogens. Several inorganic materials, such as sand and grit, have always been used in composts, but there is now a wider choice available. Most of the inorganic alternatives are made from non-renewable

Table 22.1 Alternatives to peat

Organic materials	Inorganic materials
Pine	Expanded aggregates
Coir	Extracted minerals
Garden compost	Hydroponics
Heather/bracken	Perlite
Leaf-mould	Polystyrene
Lignite	Rockwool
Recycled landfill	Dredgings/warp
Refuse-driven humus	Vermiculite
Seaweed	Topsoil
Sewage sludge	
Spent hops and grains	
Spent mushroom compost	
Straw	
Vermicomposts	
Wood chips	
Woodwastes	
Wood fibre	

resources (sand, loam, pumice) or consume energy in their manufacture (plastic foams, polystyrene) or both (vermiculite, perlite, rockwool).

Where possible an environmentally friendly alternative is used, but there is considerable debate about the relative merits of some of those being used because of the associated energy use in their manufacture or transport. However, peat is being replaced successfully by different substitutes, many only available locally, according to the needs of the various sectors of the industry.

Sand, **grit or gravel** is used in composts, frequently in combination with peat. They have no effect on the nutrient properties of composts except by diluting other materials. They are used to change physical properties. As sand or gravel is added to lightweight materials the density of the compost can be increased, which is important for ballast when tall plants are grown in plastic pots. Sand is also used as an inert medium in aggregate culture. Sand should be introduced with caution because it tends to reduce the air-filled porosity (AFP) of the final mix. It is important that the sands used should have low lime levels; otherwise they may induce a high pH and associated mineral deficiencies (see trace elements).

Pulverized bark has been used as a mulch and soil conditioner for many years. More recently it has been tried in compost mixtures as a replacement for peat. There are many different types of bark and they have different properties. Its problems include the presence of toxics, overcome by composting, and a tendency to 'lock-up' nitrogen (see carbon to nitrogen ratio), which can be offset by extra nitrogen in the feed. When composted with sewage sludge, a material suitable as a plant-growing medium is produced. It is increasingly being incorporated into growing mixes in the attempt to reduce the use of peat.

However, the great variation of barks, especially when they are from a mixed source, makes it difficult to incorporate into growing mixes. Much of the conifer bark tends to be stringy. Consequently the main role of bark is in mulching. The import of bark is strictly controlled by the Forestry Commission to prevent the introduction of pests and diseases. Wood-fibres based on stabilized shredded wood are being used to increase the air-filled porosity of mixes, but they tend to be dusty and not easily dispersed in compost mixes. Sawdust and off-cuts from the chipboard industry are also being tested for use in growing, but there are problems associated with their stability and fungal growth in the freshly stored material.

Coconut wastes such as **coir** (the dust particles) are proving to be useful in growing mixes. The material has good water-holding capacity, rewetting and air-filled porosity characteristics. It has a pH between 5 and 6, which makes it suitable for a wide range of plants, but it cannot replace peat directly in mixes for calcifuges. It has a carbon:nitrogen ratio of 80:1 which means that allowance has to be made for its tendency to ‘lock-up’ nitrogen (see p325).

Perlite is a mineral that is crushed and then expanded by heat to produce a white, lightweight aggregate (see Figure 22.3). The granules are porous and the rough surface holds considerably more water than gravel or polystyrene balls. It tends to be used to improve aeration of growing media generally and for the rewetting of peat. It is devoid of nutrients and has no cation exchange capacity. Graded samples may be used in aggregate culture, but it tends to be used to add to mixes to improve the uptake of water.

Vermiculite is a mica-like mineral expanded to twenty times its original size by rapid conversion to steam of its water content. The finished product is available in several grades, all of which produce growing media with good aeration and water-holding properties (see Figure 22.3). There is a tendency for the honeycomb structure to break down and go ‘soggy’. Consequently, for long-term planting, it tends to be used in mixtures with the more stable peat or perlite. Some vermiculites are alkaline, but the slightly acid samples are preferred in horticulture. Vermiculite has a high cation exchange capacity, which makes it particularly useful for propagation mixes. Most samples contain some available potassium and magnesium.

Rockwool is an insulation material derived from a granite-like rock crushed, melted, and spun into threads. The resulting slabs of lightweight, spongy, absorbent, inert and sterile rockwool provide ideal rooting conditions with high water-holding capacity and good aeration. Shredded rockwool can be used in compost mixes (see Figure 22.3). Its pH is high but is easily reduced by watering with a slightly acid nutrient solution. It is frequently used in tomato and cucumber production and film-wrapped cubes are available for plant raising and pot plants. It is necessary to use a complete nutrient feed (see aggregate culture). It has some buffering capacity, but this is very low on a volume basis. The main problem areas lie in calcium and phosphorus supply and the control of pH and salt concentration. Some rockwool has been formulated with clay to overcome some of these problems. This increases its cation exchange properties, making it very suitable for interior landscaping. Rockwool is also available in water-absorbent and water-repelling forms. Mixtures of these enable formulators to achieve the right balance between air-filled porosity, water-holding and capillary lift. Rockwool is available as granules that provide a flexible alternative for those who produce their own mixes. However, it is most usually supplied as wrapped slabs,

Figure 22.3 **Growing media**. Top to bottom: rockwool, perlite, vermiculite, expanded clay aggregates cubes, propagation blocks and plugs that are modularized to create a complete growing system.

Pumice is a porous volcanic rock that is prepared for use as a growing medium by crushing, washing (to remove salt and 'fines') and grading. It is most commonly used to grow long-term crops such as carnations in troughs or polysacks.

Expanded polystyrene balls or flakes provide a very lightweight inert material, which can be added to soils or composts as a physical conditioner. It is non-porous and so reduces the water-holding capacity of the growing medium while increasing its aeration, thus making it less liable to waterlogging when over-watered. This has made it an attractive option for winter propagation mixes. However, it is less popular than it might be because it is easily blown away and sticks to most surfaces.

Plastic foams of several different types are becoming popular for propagation because of their open porous structure. They are available as flakes and balls for addition to composts or as cubes into which the cuttings can be pushed.

Chopped straw has been used with some success. Generally the main types available, wheat and barley, break down too easily and a practicable method of stabilizing them has not yet been found. Stable, friable material has been derived from bean and oil seed rape straws, although care is needed in mixes because of the high potassium levels.

Lignite is very variable soft brown coal formed from compressed vegetation; often found at the base of the larger peat bogs. The dusts, 'fines', have been used as carriers for fertilizers and the more granular material can be used to replace grit in mixes, often bringing an improved water retention.

Absorbent polymers have the ability to hold vast quantities of water that is available to plants. However, this is considerably reduced in practice because water absorption falls as the salt concentration of the water increases and the release patterns appear to be very similar to that of some compost ingredients, such as sphagnum moss peats.

Wetters, **or non-phytotoxic detergents**, are included in mixes to enable water to wet dry composts. They reduce the surface tension of the water, which improves its penetration of the pores. This speeds up the wetting process and maximizes the water-holding capacity of the materials used. Wetters should be selected with care because the different types need to be matched with the peat in the mix and above all must not be harmful to the plants.

Compost mixes

Materials alone or in combination are prepared and mixed to achieve a rooting environment that is free from pests and disease organisms and has adequate air-filled porosity, easily available water, and suitable bulk density for the plant to be grown. While lightweight mixes are usually advantageous, ‘heavier’ composts are sometimes formulated to give pot stability for taller specimens. This should not be achieved by compressing the lightweight compost, but by incorporating denser materials such as sand. Quick-growing plants are normally the aim and loosely filling containers with the correct compost formulation, consolidated with a presser board and settling it with applications of water obtain this. Firming with a rammer reduces the total pore space whilst increasing the amount of compost and nutrients in the container. The reduction in air-filled porosity and available water with an increase in soluble salt concentration leads to slower growing, harder plants (see conductivity).

The addition of nutrients must take into account not only the plant requirements, but also the nutrient characteristics of the ingredients used. Most loamless composts require trace element supplements and many, including those based on peat, need the addition of all major nutrients and lime. The Glasshouse Crops Research Institute developed **general purpose potting composts** based on a peat/sand mix (see Table 22.2). They contain different combinations of nutrients and consequently their storage life differs. One of the range of composts has a slow release phosphate, removing the need for this element in a liquid feed (see phosphorus). The **GCRI seed compost** contains equal parts by volume of sphagnum peat and fine, lime-free sand. To each cubic metre of seed compost is added 0.75 kg of superphosphate, 0.4 kg potassium nitrate and 3.0 kg calcium carbonate. Variations on these mixtures are

Table 22.2 GCRI composts

			Potting composts		
			Urea formaldehyde types*		
Constituents	**Seed composts**		**Winter use**	**Summer use**	**High P type****
Peat:sand (per cent by volume)	50:50	75:25	75:25	75:25	75:25
Base dressings (kg/m^3)					
Ammonium nitrate	Nil	0.4	Nil	Nil	0.2
Urea formaldehyde	Nil	Nil	0.5	1.0	Nil
Magnesium ammonium phosphate	Nil	Nil	Nil	Nil	1.5
Potassium nitrate	0.4	0.75	0.75	0.75	0.4
Superphosphate	0.75	1.5	1.5	1.5	Nil
Ground chalk	3.0	2.25	2.25	2.25	2.25
Ground magnesian limestone	Nil	2.25	2.25	2.25	2.25
Fritted trace elements (WM225)	Nil	0.4	0.4	0.4	0.4

*Composts containing urea formaldehyde should not be stored longer than seven days.

**For longer term crops where there is a risk of phosphorus deficiency and liquid feeding with phosphate is not desired, use commercial magnesium ammonium phosphate. This also contains 11 per cent K_2O.

formulated with alternatives to peat, taking into account their different properties particularly with regard to their particle size, water-holding capacity and final air-filled porosity.

Compost mixing

It is most important when making up the desired compost formulation to achieve a uniform product and, commercially, it must be undertaken with a minimum labour input. The ingredients of the compost must be as near as possible to the specification for the chosen formulation. Materials must not be too moist when mixing because it then becomes impossible to achieve an even distribution of nutrients. There are several designs of **compost mixer**. Continuous mixers are usually employed by specialist compost mixing firms and require careful supervision to ensure a satisfactory product. Batch mixers of the ‘concrete mixer’ design are produced for a wide range of capacities to cover most nursery needs. Many of the bigger mixers have attachments which aid filling. Emptying equipment is often linked to automatic tray or pot-filling machines.

Ingredients used in loamless composts or growing modules do not normally require partial sterilization unless they are being reused, but **sterilizing equipment** is certainly needed to prepare loams for inclusion in loam-based composts. Where steam is used it is injected through perforated pipes on a base plate and rises through the material being sterilized. In contrast a steam–air mixture injected from the top under an air-proof covering is forced downwards to escape through a permeable base.

Storage of prepared composts should be avoided if possible and should not exceed three weeks if slow release fertilizers are incorporated. If nitrogen sources in the compost are mineralized, **ammonium ions** are produced followed by a steady increase in **nitrates** (see p366). These changes lead to a rise in compost pH followed by a fall. As nitrates increase, the salt concentration rises towards harmful levels (see conductivity). Peat-based composts can become infested during storage by sciarid flies.

Plant containers

The characteristics of the container affect the root environment, as does the standing-out area. There is an enormous range of containers used to meet the many different requirements of growing plants (Figure 12.2). **Clay pots** are porous and water is lost from the walls by evaporation. Consequently clay pots dry out quicker than plastic pots, especially in the winter and, although air does not enter through the walls, this can help improve air-filled porosity. The higher evaporation rate also keeps the clay pots slightly cooler, which can be beneficial in hot conditions. Likewise the contents of white plastic pots can be as much as 4°C lower than in other colours. Pots of white or light green plastic can transmit sufficient light to adversely affect root growth and encourage algal growth.

Biodegradable containers such as those made from paper have become popular because they can be planted directly. Some materials decompose more rapidly than others and there can be a temporary 'lockup' of nitrogen, but most peat containers are now manufactured with added available nitrogen. It is essential that these containers are soaked and surrounding soil is kept moist after planting or the roots fail to escape from the dry wall.

The air to water characteristics of the mixture in the container depend not only on the nature of the contents, but also on the characteristics of the base on which the container stands. If containers are stood out on wire mesh or on stones, relatively little water leaves so the oxygen content remains poor. **It is also important to retain contact between the compost and the standing out material through adequate holes in the base, whether to help drainage or to ensure the uptake of water if irrigated from below.**

Blocks

Blocks are made of a suitable compressed growing medium into which the seed is sown with no container or simply a net of polypropylene. Aeration tends to be poorer than in pots, but the high surface area helps make this a successful means of growing some vegetables on a large scale. One type of block comes in the form of a dry compressed disc that expands quickly on soaking ready to receive the seed in the shallow depression in the top surface. This technique has been replaced in large measure by the use of rockwool blocks, particularly when these are to be grown on in rockwool modules (see Fig. 22.3).

Modules

Increasingly, traditional seedbed, bare-rooted or block transplant techniques have been replaced by raising a wide variety of plants in modules. A module is made by adding a loose growing medium mix to a tray of cells. The cells are variously wedge or pyramid-shaped, so designed to enable a highly mechanized transplanting process to be used. Fine, free-flowing mixes of peat, polystyrene or bark are used to fill the cells, which have large drainage holes and no rim to hold free water. Roots in the wedge-shaped cells are 'air-pruned' as they reach the edge of the cell, which encourages secondary root development. 'Plugs' are mini-modules in which each transplant develops in less than 10 cm^3 of growing medium and are used for bedding plants, as well as vegetable production. The rate of establishment is largely determined by the water stress experienced by the transplant. Irrigation of the module or plug is found to be more successful than applying water to the surrounding growing medium.

Hydroponics

Hydroponics (water culture) involves the growing of plants in water. The term often includes the growing of plants in solid rooting medium watered with a complete nutrient solution, which is more accurately called '**aggregate culture**'. Plants can be grown in nutrient solutions with no solid material so long as the roots receive oxygen and suitable anchorage and support is provided. The advantages of hydroponics, compared with soil, in temperate areas includes accurate control of the nutrition of the plant and hence better growth and yield. There is a constant supply of available water to the roots. Evaporation is greatly reduced and loss of water and nutrients through drainage is minimal in recirculating systems. There can be a reduction in labour and growing medium costs and a quicker 'turn round' time between crops in protected culture. The disadvantages include the high initial costs of construction and the controls of the more elaborate automated systems. Active roots require a constant supply of oxygen, but oxygen only moves slowly through water. This can be resolved by pumping air through the water that the plants are grown in, but it is usually achieved on a large scale by growing in thin films of water as created in the nutrient film technique (NFT) or a variation on the very much older aggregate culture methods.

Figure 22.4 **A hydroponics system**

Nutrient film technique (NFT)

This is a method of growing plants in a shallow stream of nutrient solution continuously circulated along plastic troughs or gullies. The method is commercially possible because of the development of relatively cheap non-phytotoxic plastics to form the troughs, pipes and tanks (see Figure 22.5). There is no solid rooting medium and a mat of roots develops in the nutrient solution and in the moist atmosphere above it. Nutrient solution is lifted by a pump to feed the gullies directly or via a header tank. The ideal flow rate through the gullies appears to be 4 litres per minute. The gullies have a flat bottom, often lined with capillary matting to ensure a thin film throughout the trough. They are commonly made of disposable black or white polythene set on a graded soil or on adjustable trays. There must be an even slope with a minimum gradient of 1 in 100; areas of deeper liquid stagnate and adversely affect root growth (see aerobic conditions).

The nutrient solution can be prepared on site from basic ingredients or proprietary mixes. It is essential that allowance be made for the local water quality, particularly with regard to the micro-elements, such as boron or zinc, which can become concentrated to toxic levels in the circulating solution. The nutrient level is monitored with a conductivity

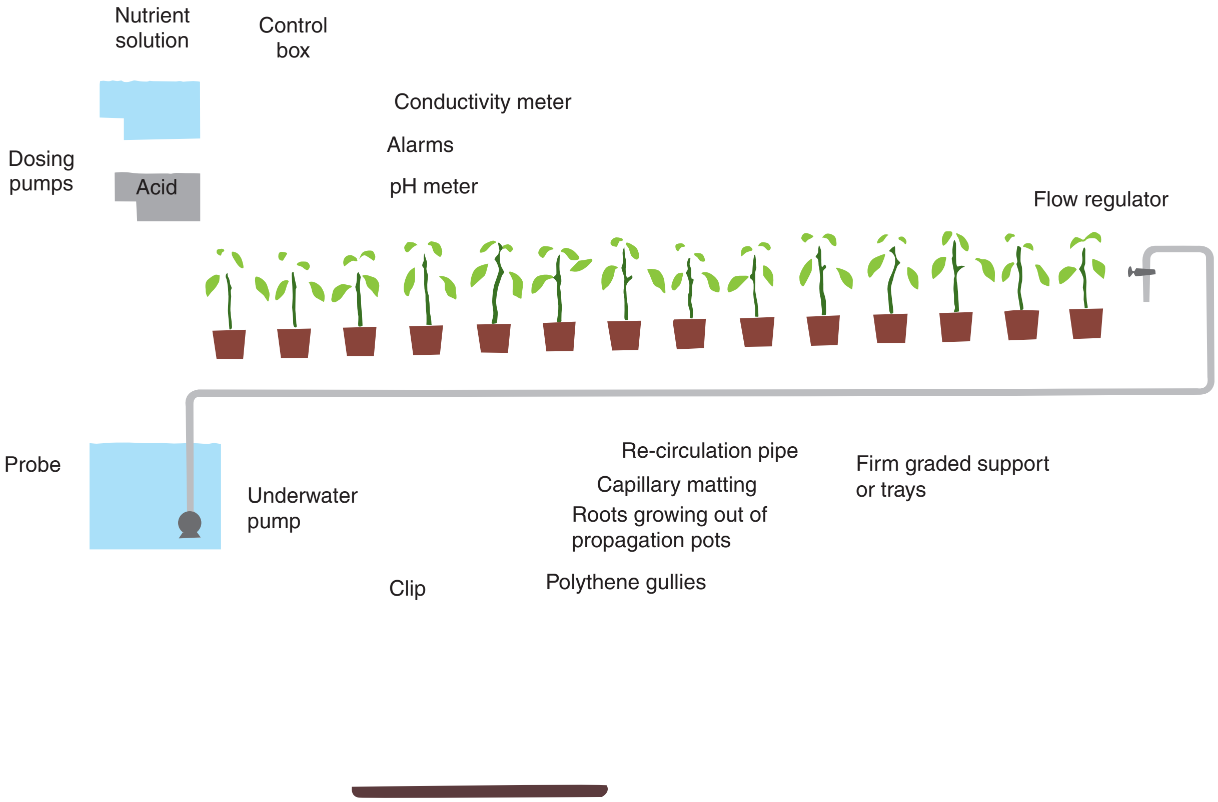

Figure 22.5 **Nutrient film technique layout**. The nutrient solution is pumped up to the top of the gullies. The solution passes down the gullies in a thin film and is returned to the catchment tank. The pH and nutrient levels in the catchment tank are monitored and adjusted as appropriate.

meter and by careful observation of the plants. Maintenance of pH between 6 and 6.5 is also very important. Nutrient and pH control is achieved using, as appropriate, a nutrient mix, nitric acid or phosphoric acid to lower pH and, where water supplies are too acid, potassium hydroxide to raise pH. Great care and safety precautions are necessary when handling the concentrated acids during preparation.

The commercial NFT installations have automatic control equipment in which conductivity and pH meters are linked to dosage pumps. The high and low level points also trigger visual or audible alarms in case of dosage pump failure. Dependence on the equipment may necessitate the grower installing failsafe devices, a second lift pump and a standby generator. A variation on this method is to grow crops such as lettuce in gullies on suitably graded glass house floors (see Figure 22.6).

Aggregate culture

In aggregate culture the nutrient solution is broken up into water films by an essentially inert solid medium, such as coarse sand or gravel. More commonly today materials such as **rockwool**, **perlite**, **polyurethane foam**, **duraplast foam** or **expanded clay aggregates** (see Figure 22.7) are used. These are in the form of polythene wrapped slabs or ‘bolsters’ of granules sitting on a polythene covered floor graded across the row. Polyurethane slabs are often placed underneath them to help create even slopes and insulate them from the cooler soil below. These growing

(a) (b)

Figure 22.6 (a) **NFT lettuce crop** with close up (b) showing gullies and nutrient solution delivery

containers, on which the plants sit, are drip fed with a complete nutrient solution at the top with the surplus running out through slits near the bottom on the opposite side. When this method was first developed the NFT systems were copied, i.e. the water was recirculated, but it was soon found to be difficult where the quality of water was poor and there was a risk of a build-up of water-borne pathogens and trace elements. It was found that the surplus nutrient solution was most easily managed by allowing it to run to waste into the soil. However, this **open system** presents environmental problems and increasingly a **closed system** has had to be adopted. It is now becoming more usual to run the waste to a storage sump via collection gullies or pipes. Some of this can be used to irrigate outdoor crops if nearby. To recirculate the water it is necessary to have equipment to remove the excess salts or accept a gradual deterioration of the nutrient solution and then flush it out to a sump when it becomes unacceptable. Sources of infection such as *Pythium* are minimized by isolation from soil and using clean water; the risks of recirculating pathogens is addressed by using one of the four main methods of sterilization (see water quality).

Figure 22.7 **Tomato crop in rockwool growing system**

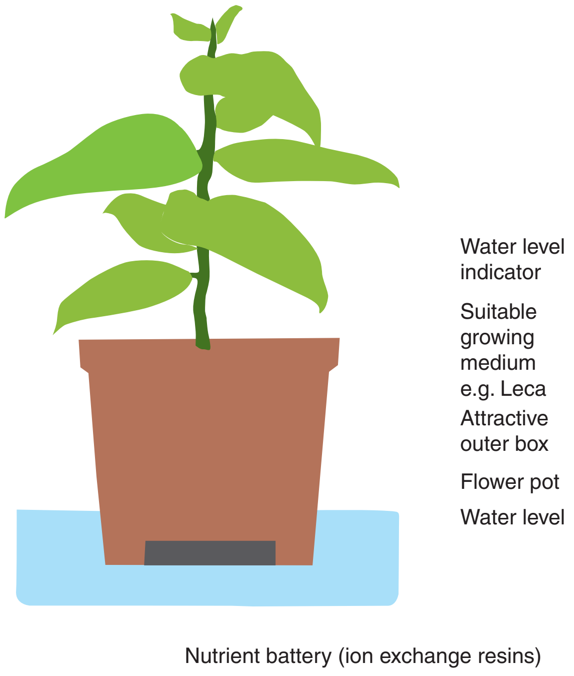

Figure 22.8 **Plant pots with water reserves**. Plants grown in a variety of growing media can be fitted with reservoirs that supply water by capillarity. A water level indicator is frequently incorporated and in some systems the nutrients are supplied from ion exchange resins. While this system can be used for any pot size it is particularly attractive in large displays

Rockwool slabs are a very successful way of growing which lend themselves to a modular system. It is widely used for a range of commercial crops, such as tomatoes, cucumbers, peppers, melons, lettuce, carnations, roses, orchids and strawberries, in protected culture. It is not biodegradable so the vast quantity of rockwool now utilized has produced a serious disposal problem. The slabs can be used successfully several times, if sterilized on each occasion, but eventually they lose their structure. Tearing them up and incorporating them in composts or soils can deal with a limited amount, but far more can now be recycled in the production of new slabs.

Several types of **expanded clay aggregates** used in the building industry, such as Leca or Hortag, have been used particularly in interior landscaping (see Figure 22.3). Smooth but porous granules 4–8 mm in diameter, giving a capillary rise of about 100 mm, are used to create an ideal rooting environment with a dry surface which makes it an attractive method of displaying house plants (see Figure 22.8). All forms of aggregate culture require feeding with all essential minerals. Trace element deficiencies occur less frequently when clay aggregates are used. Ion exchange resins are an ideal fertilizer formulation in these circumstances because the nutrients are released slowly, remove harmful chlorides and fluorides from irrigation water, and aid pH control.

Sports surfaces

The specifications for sports playing surfaces are such that turf has increasingly given way to artificial alternatives, typified by the trend toward playing ‘lawn’ tennis on ‘clay’ courts. This is partly attributable to maintenance requirements, but at the higher levels of sport it is because the users or the management expect play to continue with a minimum of interference by rainfall. The usual problem is that the soil in which the turf grows does not retain its structure under the pounding it receives from players and machinery, especially when it is in the wet plastic state. Turf is still preferred by many, but to achieve the high standards required it has to be grown in a much modified soil (see also sand slitting) or, increasingly, in an alternative such as sand. The most extreme approach is to grow the turf in pure sand isolated from the soil, sometimes within a plastic membrane. The high cost of these methods is such that it is only used to create small areas such as golf greens.

Normally the existing topsoil is removed from the site and the subsoil is compacted to form a firm base and graded to carry water away to drains. Drainage pipes are laid, above which is placed a drainage layer usually

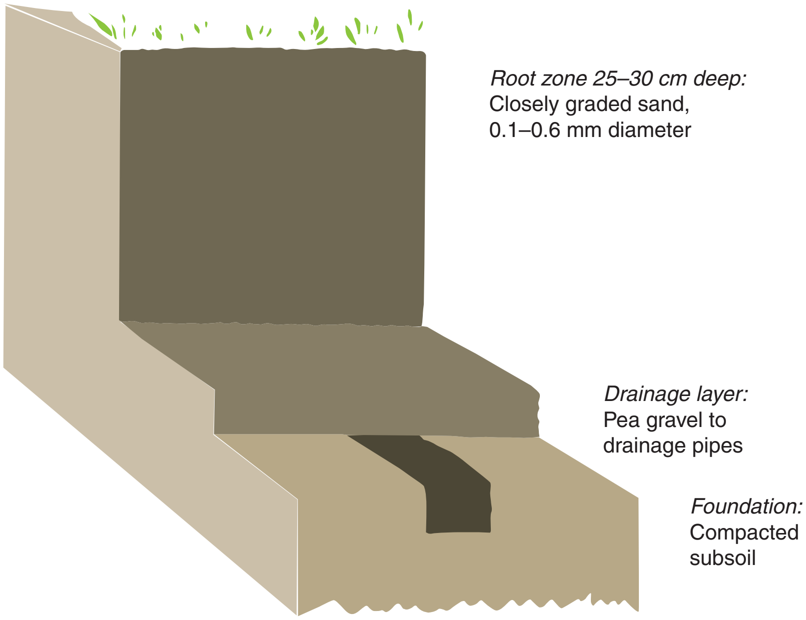

Figure 22.9 **Pure sand root zone** used for sportsground surfaces

consisting of washed, pea-sized gravel, as shown in Figure 22.9. Because it is considerably coarser than the sand placed on it, this layer prevents the downward percolation of water (see water films) and creates a perched water table. This helps to give the root zone a large reserve of available water whilst ensuring that gravitational water, following heavy rain or excess irrigation, is removed very rapidly.

A 25–30 cm root zone of free-draining sand is placed uniformly over the drainage layer, evenly consolidated. Allowance has to be made for continued settling over the first year. It is essential that the sand used has a suitable particle size distribution, ideally 80–95 per cent of the particles being between 0.1 and 0.6 mm diameter. A minimum of 'fines' is essential to avoid clogging up of the pores in the root zone (see Figure 22.2). Sometimes a small amount of organic matter is worked into the top 5 cm to help establish the grass, although success is probably as easily achieved with no more than regular light irrigation and liquid feeding.

Some very sophisticated all-sand systems, such as the **cell system**, are constructed so that the root zone is sub-divided into bays with vertical plastic plates and supplied with drains that can be closed so that the water in each of them can be controlled. Tensiometers are used to activate valves that allow water back into the drainage pipes to sub-irrigate the turf.

Check your learning

1. State the main disadvantages of growing in soils.
2. Describe what is required of a material to be used in a compost.
3. State the advantages and the disadvantages of loam based composts.
4. State the advantages of loamless compost.
5. Explain why alternatives are being sought to replace peat in growing plants.
6. State the advantages of hydroculture growing systems.

Further reading

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