7 Transport in plants

Flowering plants do not have compact bodies like those of animals. Leaves and extensive root systems spread out to obtain the light energy, water, mineral ions and carbon dioxide that plants gain from their environment to make organic molecules, such as sugars and amino acids. Transport systems in plants move substances from where they are absorbed or produced to where they are stored or used. Plants do not have systems for transporting oxygen and carbon dioxide; instead these gases diffuse through air spaces within stems, roots and leaves.

7.1 Structure of transport tissues

Plants have two transport tissues: xylem and phloem.

By the end of this section you should be able to:

a) draw and label from prepared slides plan diagrams of transverse sections of stems, roots and leaves of herbaceous dicotyledonous plants using an eyepiece graticule to show tissues in correct proportions
b) draw and label from prepared slides the cells in the different tissues in roots, stems and leaves of herbaceous dicotyledonous plants using transverse and longitudinal sections
c) draw and label from prepared slides the structure of xylem vessel elements, phloem sieve tube elements and companion cells and be able to recognise these using the light microscope
d) relate the structure of xylem vessel elements, phloem sieve tube elements and companion cells to their functions

Internal transport – the issues

The cells of organisms need a constant supply of **water** and **organic nutrients** such as glucose and amino acids, and most need **oxygen**. The **waste products** of cellular metabolism have to be removed, too. In single-celled organisms and small multicellular organisms, internal distances (the length of diffusion pathways) are small. Here, movements of nutrients and other molecules can occur efficiently by **diffusion** (page 79). However, some substances must be transported across membranes, such as the cell surface membrane, by **active transport** (page 90).

In larger organisms diffusion alone is not sufficient. This is because the amount of gas an organism needs to exchange is largely proportional to its volume (the bulk of respiring cells). At the same time, the amount of exchange that can occur is proportional to the surface area over which diffusion takes place. The surface area to volume ratio decreases as size increases, as we have seen. Consequently, an **internal transport system** is essential. This alone can provide enough of what is required by the cells in larger and more bulky organisms. Also, the more active an organism is the more nutrients are likely to be required in cells and so the greater is the need for an efficient system. Question 2 on page 132 explores these issues of size, shape and mechanisms of internal transport.

Transport in multicellular plants

The flowering plants are the dominant land plants. Some are trees and shrubs with woody stems, but many are non-woody (herbacious) plants. Whether woody or herbaceous, a flowering plant consists of stem, leaves and root.

Internal transport occurs by **mass flow** but here there is no pumping organ. Two separate tissues are involved: water and many ions travel in the **xylem**, whilst manufactured foods (mainly sugar and amino acids) are carried in the **phloem**. Xylem and phloem are collectively known as the vascular tissue. They occur together in the centre of roots and in the **vascular bundles** of stems and leaves of the plant.

The stem

The role of the stem is to support the leaves in the sunlight and to transport organic materials (mainly sugar and amino acids), ions and water between the roots and leaves. This transport occurs in the **vascular bundles**. The vascular bundles of the stem occur in a ring just below the epidermis. To the outside of the vascular bundles lies the cortex and to the inside is the pith. Both cortex and pith mostly consist of living, relatively unspecialised cells with thin cellulose walls (Figure 7.6, page 133).

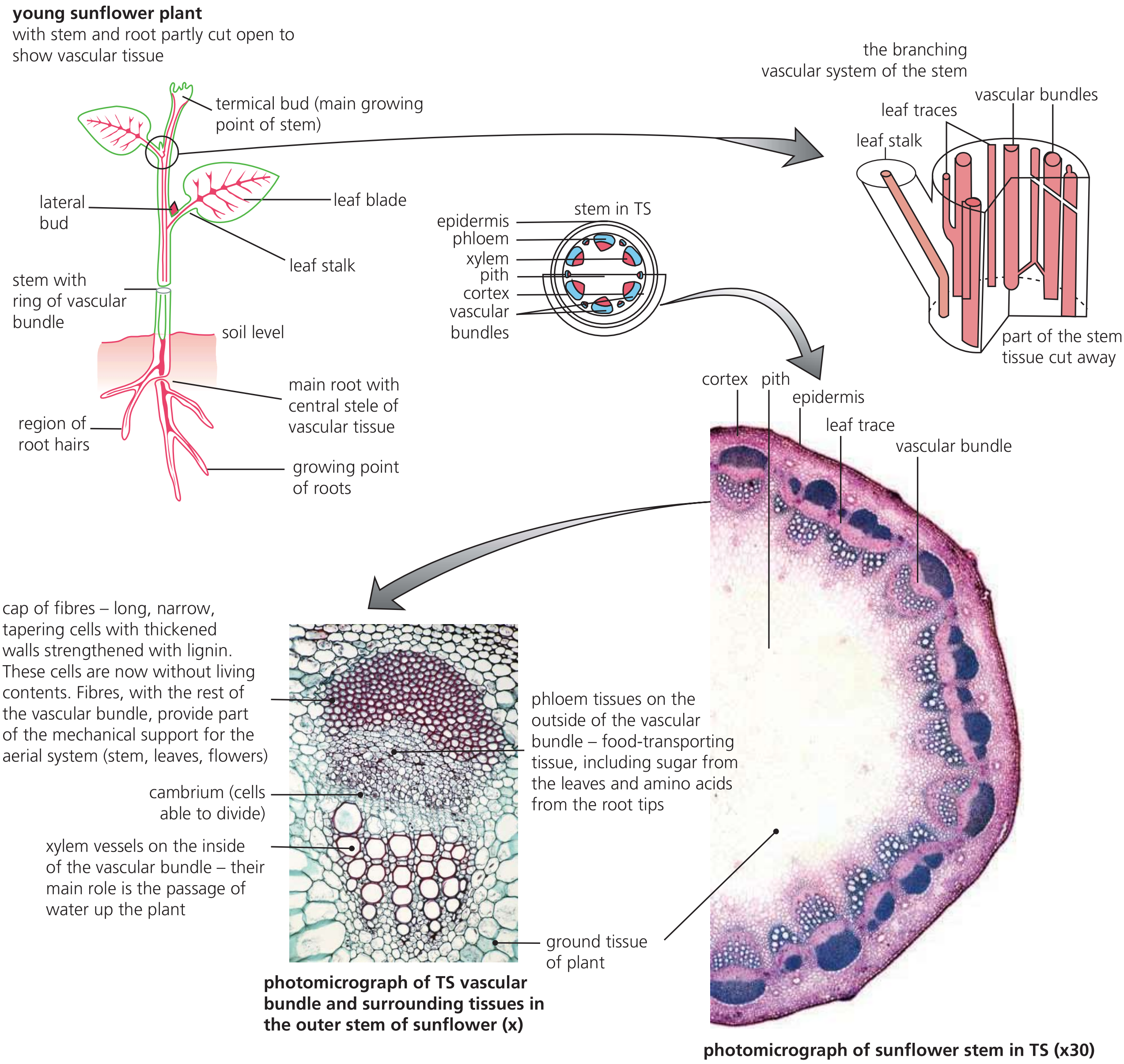


Figure 7.1 The distribution and structure of the vascular bundles of the stem

The leaves

The leaf is an organ specialised for **photosynthesis** – the process in which light energy is used to make sugar. Carbon dioxide from the air and water from the soil are the raw materials used, oxygen is the waste product.

The leaf consists of a leaf blade connected to the stem by a leaf stalk. The blade is a thin structure with a large surface area. Within the leaf blade are **mesophyll** cells that are packed with **chloroplasts** – the organelles in which photosynthesis occurs. There is a thin film of water on the outer surface of these cells. The **epidermis** is a tough, transparent, single layer of cells surrounding the mesophyll tissue. There is an external waxy **cuticle** to the epidermis which is impervious. This reduces water vapour loss from the leaf surface (Figure 7.2).

The epidermis has many tiny pores, called **stomata** – the sites of gas exchange. Within the leaf's mesophyll tissue are continuous **air spaces**. Throughout the leaf blade is a **network of vascular bundles**. These provide mechanical support but the leaf is also supported by the turgidity of all its cells, surrounded as they are by the tough epidermis. Leaves are relatively delicate structures and, at times, they have to withstand destructive forces such as wind and rain.

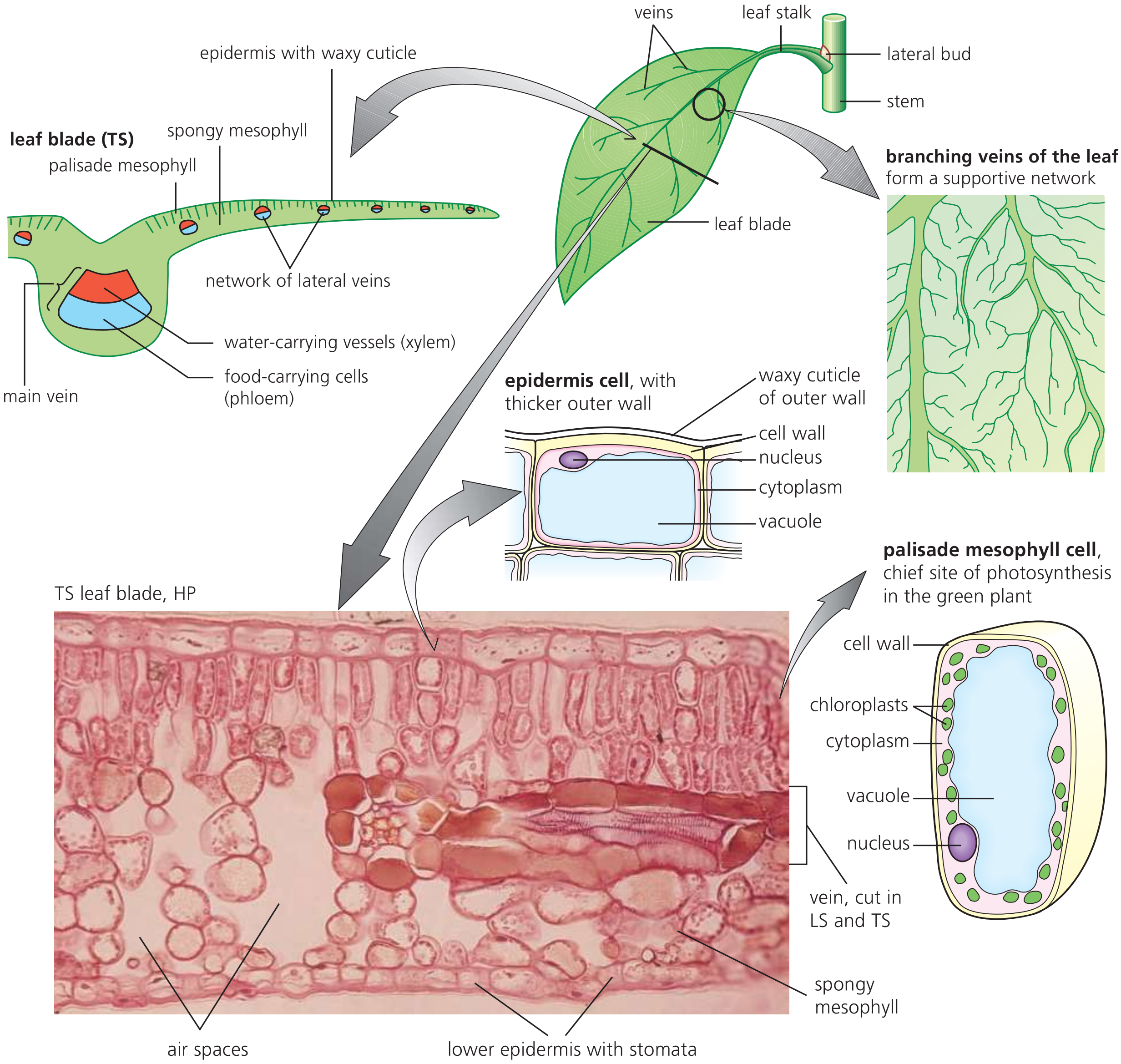


Figure 7.2 The structures of the leaf

The root

The **root** anchors the plant in the ground and is the site of absorption of water and ions from the soil. The main tap root forms lateral roots, and growth continues at each root tip. The growing plant is continuously making contact with fresh soil. This is important because the thin layer of dilute soil solution found around soil particles is where the plant obtains the huge volume of water it requires. Minerals salts as ions are also absorbed from here.

The vascular tissue of the root occurs in a single, central **stele**. Around the stele is a single layer of cells, the **endodermis**. These cells have a waxy strip in their radial walls, known as the **Casparian strip**. Immediately within the endodermis is another single layer of living cells, known as the pericycle (Figure 7.3). Only at the base of the stem is the vascular tissue of the root reorganised into several vascular bundles arranged around the outside of the stem.

Question

1 Outline the properties of cellulose that make it an ideal material for plant cell walls.

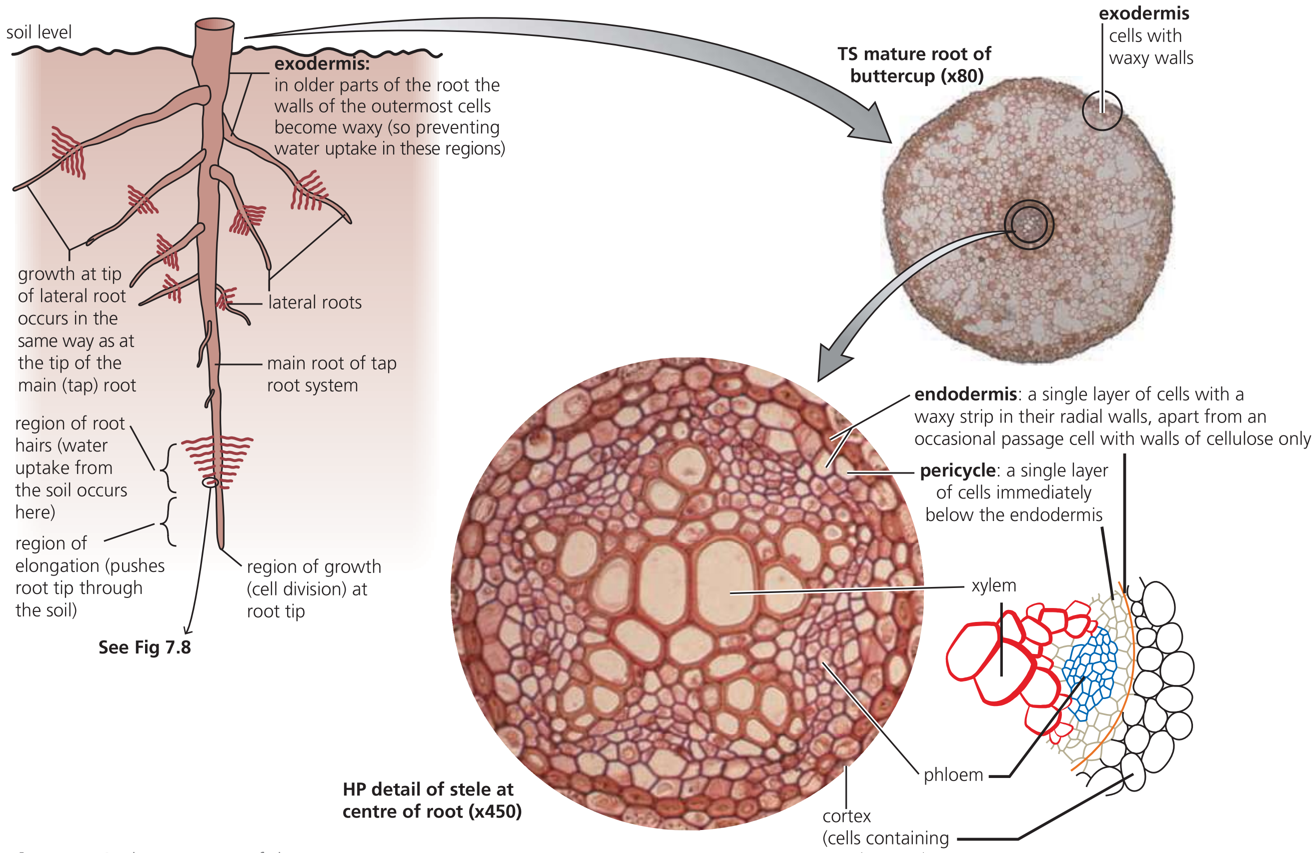


Figure 7.3 The structure of the root

Question

2 The external dimensions, volume and surface area of six geometrically shaped objects – three of a compact shape and three that are flat and thin – are listed in the table below.

	Compact			Flat and thin		
	Small	**Medium**	**Large**	**Small**	**Medium**	**Large**
Dimensions/mm	1 × 1 × 1	2 × 2 × 2	4 × 4 × 4	2 × 1 × 0.5	8 × 2 × 0.5	16 × 8 × 0.5
Volume/mm^3	1	8	64	1	8	64
Surface area/mm^2	6	24	96	7	42	280

a Calculate the surface area to volume ratio of the six objects.

b Comment on the effect of shape on the surface area of an object as the size of the object increases.

c Comment on the effect of shape on the surface area to volume ratio of an object as the size increases.

d If these objects were organisms, what are the implications of their size and shape on the movement of nutrients or waste products by diffusion?

The structure of xylem and phloem tissue

Xylem begins as elongated cells with cellulose walls and living contents, connected end to end.

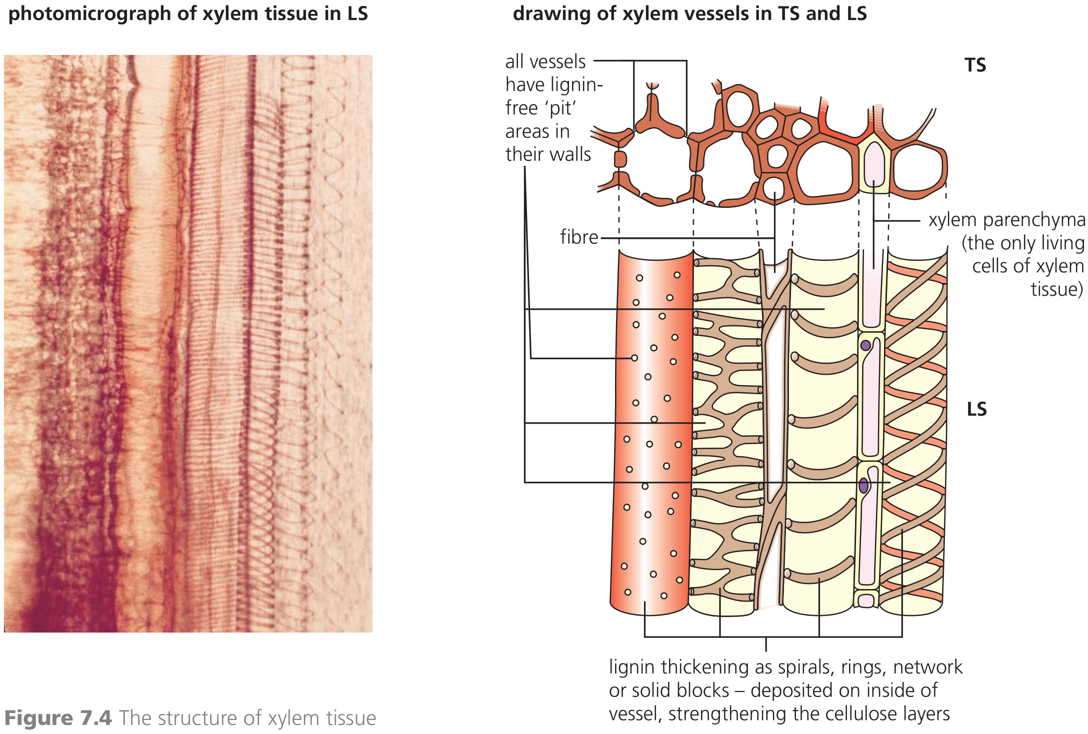
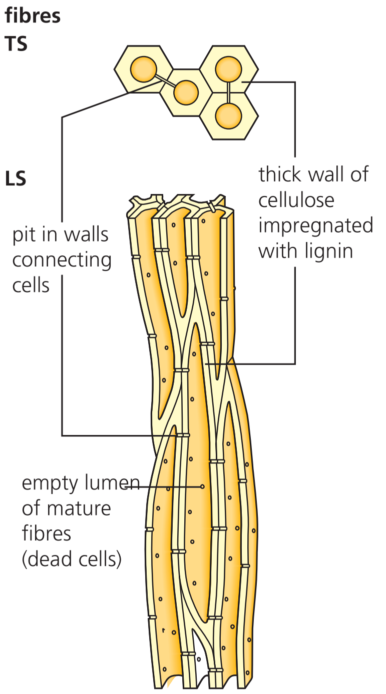


Figure 7.4 The structure of xylem tissue



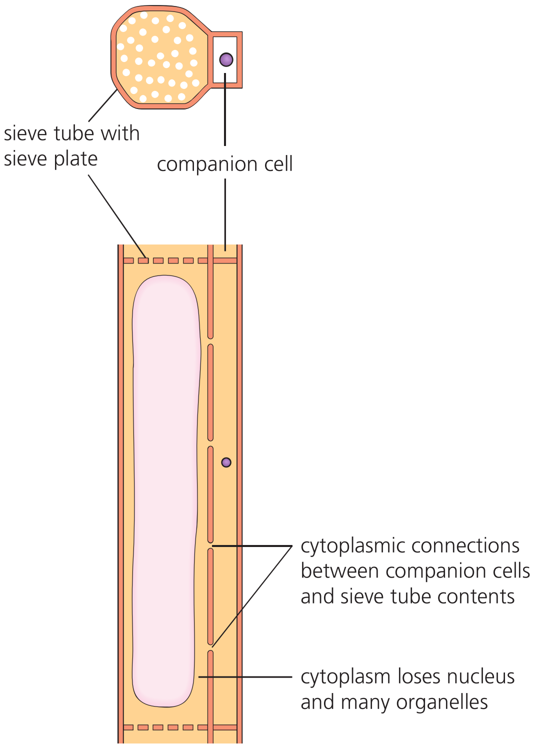
fibres are a thick-walled tissue, with walls of cellulose strengthened by lignin – when mature the cell contents die; fibres are long, narrow, pointed, empty cells with pits in their walls where the living contents once connected

Figure 7.5 The structure of fibres

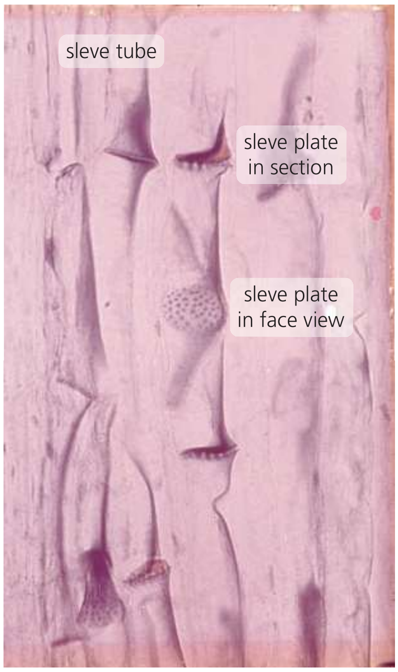
During development, the end walls are dissolved away so that mature xylem vessels are **long, hollow tubes**. The living contents of a developing xylem vessel are used up in the process of depositing cellulose thickening to the inside of the lateral walls of the vessel. This is hardened by the deposition of a chemical substance, **lignin**. Lignin is a substance that makes cross links with the hemicelluloses that fill the gaps between cellulose fibres. This greatly strengthens the cellulose and makes it impermeable to water. Consequently, xylem is an extremely tough tissue. Furthermore, it is strengthened internally, which means it is able to resist negative pressure (suction) without collapsing in on itself. When you examine xylem vessels in longitudinal sections by light microscopy you will see that they may have differently deposited thickening; many have rings of thickening, for example. Other xylem vessels have more massive thickenings. However, all xylem vessels have areas in their lateral walls (including the pits where the cellulose wall is especially thin) in which there is a layer of cellulose but no lignin. Here the walls are entirely permeable and permit lateral movements of water to surrounding tissues. This is role of the xylem – to supply water to the living cells of the plant.

Fibres also occur between xylem vessels, thereby strengthening the whole bundle. Interestingly, in ferns and cone-bearing trees, xylem tissue is absent. Here the water-conducting tissue consists of fibre-like **tracheids** with large pits in their lateral walls through which water passes from tracheid to tracheid (Figure 7.4).

Phloem tissue consists of **sieve tubes** and **companion cells,** and is served by transfer cells in the leaves. Sieve tubes are narrow, elongated elements, connected end to end to form tubes. The end walls, known as sieve plates, are perforated by pores. The cytoplasm of a mature sieve tube has no nucleus, nor many of the other organelles of a cell. However, each sieve tube is connected to a companion cell by strands of cytoplasm called plasmodesmata, that pass through narrow gaps (called pits) in the walls. The companion cells service and maintain the cytoplasm of the sieve tube, which has lost its nucleus. Phloem is a living tissue, and has a relatively high rate of aerobic respiration during transport. In fact, transport of manufactured food in the phloem is an active process, using energy from metabolism (Figure 7.6).



photomicrograph of LS phloem in HP (×200)
phloem is a tissue that may become crushed and damaged as stem tissue is sectioned for microscopy



phloem tubes are the site of movement of sugar and amino acids.

Figure 7.6 The structure of phloem tissue

Observing and recording high power detail of cells

The cells of the ground tissues make up the bulk of stem (and root) of herbaceous (non-woody) plants, around the vascular tissue. These are **collenchyma** and **parenchyma** cells, and they show relatively few structural adaptations. They are concerned with support due to the turgidity of all the living cells contained within the stem. Starch storage also occurs here. **Fibres** are different. Here there are no living contents, but their thickened walls are impregnated with lignin, and are extremely tough (Figure 7.5).

The outermost layer of the stems (and leaves) of herbaceous plants is a continuous layer of compact, tough cells, one cell thick, called the **epidermis** (Figure 7.2). These cells have a layer of wax deposited on the external walls, and their strength and continuity provides mechanical support by counteracting the internal pressure due to turgidity.

You will be examining prepared slides of sections through plant organs in the laboratory, using the light microscope. With guidance, the different types of xylem vessels, sieve tubes and companion cells, fibres, parenchyma and collenchyma ground tissue can be identified in longitudinal and transverse sections and their structures recorded. Follow the guidance on recording observations in drawings on page 8.

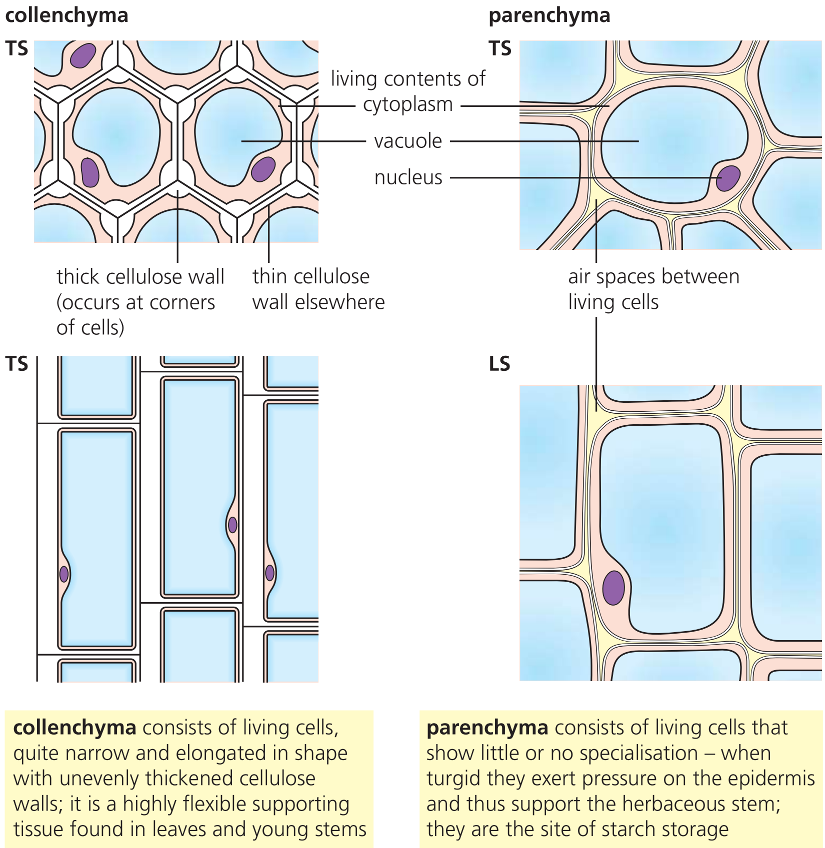


Figure 7.7 The structure of parenchyma, collenchyma and fibres

Observing and recording plant structure using low-power plan diagrams

You will be examining prepared slides of sections through plant organs in the laboratory, using the light microscope. The name given to the detailed study of the structure of living tissues is **Histology**. Slides of thin sections were commonly used to discover the structure of multicellular organisms. You may notice that the material they show has been selectively stained to highlight structures.

With guidance, the different tissues a slide shows can be identified and their precise distribution represented in a **plan diagram** (also called a tissue map). This will show their relative positions to scale. Individual cells are not shown. Then the size of the specimen can be calculated and the magnification represented by a scale bar.

Figure 7.1 has the necessary information to create a plan diagram of part of a plant stem. However, it is important you create your own plan diagrams by examining prepared slides, using an eyepiece graticule (page 9) to show tissues in correct proportions. Follow the guidance on recording observations in drawings on page 8.

Figure 7.2 has the necessary information to create a plan diagram of part of a plant leaf. However, it is important you create your own plan diagrams by examining prepared slides, using an eyepiece graticule to show tissues in correct proportions.

Figure 7.3 has the necessary information to create a plan diagram of part of a plant root. However, it is important you create your own plan diagrams by examining prepared slides, using an eyepiece graticule to show tissues in correct proportions.

Question

3 Draw and label a plan diagram of a representative part of the section of the stem in Figure 7.1 to accurately record the distribution of the tissues.
Using the magnification data given, add an appropriate scale bar line to your drawing.

7.2 Transport mechanisms

Movement of xylem sap and phloem sap is by mass flow. Movement in the xylem is passive as it is driven by evaporation from the leaves; plants use energy to move substances in the phloem.

Xylem sap moves in one direction from the roots to the rest of the plant. The phloem sap in a phloem sieve tube moves in one direction from the location where it is made to the location where it is used or stored. At any one time phloem sap can be moving in different directions in different sieve tubes.

By the end of this section you should be able to:

a) explain the movement of water between plant cells, and between them and their environment, in terms of water potential
b) explain how hydrogen bonding of water molecules is involved with movement in the xylem by cohesion-tension in transpiration pull and adhesion to cellulose cell walls
c) describe the pathways and explain the mechanisms by which water and mineral ions are transported from soil to xylem and from roots to leaves
d) define the term transpiration and explain that it is an inevitable consequence of gas exchange in plants
e) investigate experimentally and explain the factors that affect transpiration rate using simple potometers, leaf impressions, epidermal peels, and grids for determining surface area
f) make annotated drawings, using prepared slides of cross-sections, to show how leaves of xerophytic plants are adapted to reduce water loss by transpiration
g) state that assimilates, such as sucrose and amino acids, move between sources (e.g. leaves and storage organs) and sinks (e.g. buds, flowers, fruits, roots and storage organs) in phloem sieve tubes
h) explain how sucrose is loaded into phloem sieve tubes by companion cells using proton pumping and the co-transporter mechanism in their cell surface membranes
i) explain mass flow in phloem sap down a hydrostatic pressure gradient from source to sink

The movement of water through the plant

We have seen that:

- xylem is the water conducting tissue, found in the vascular bundles of the stem and leaves, and in the central stele of the root
- the main tap root and lateral roots grow through the soil, continuously making contact with fresh soil
- the thin layer of dilute soil solution found around soil particles is where the plant obtains the huge volume of water it requires
- minerals salts as ions are also absorbed from the soil solution.

Contact between root and soil is also vastly increased by structures called **root hairs**. The root hairs are formed at a short distance behind the growing tip of each root. They are extensions of individual epidermal cells and are relatively short-lived (Figure 7.8). Elsewhere the outer cells of the root have walls that are waxy and therefore waterproof. Consequently, it is only in the region that the root hairs occur that the root is able to absorb water and ions.

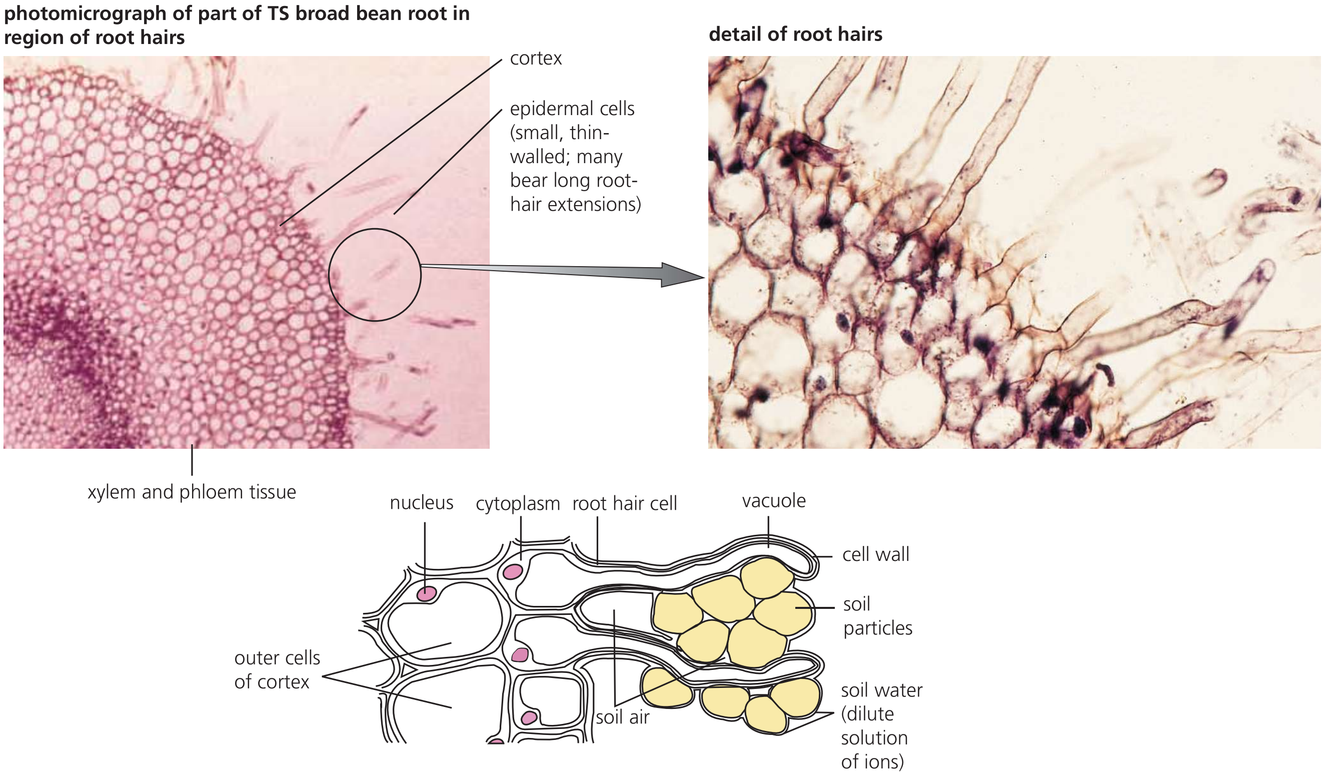


Figure 7.8 Root hairs – the site of absorption and uptake

Uptake of water – the roles of the root hairs

Root hairs are the point of entry of water on its passage through the green plant.

soil → root → stem → leaf → air

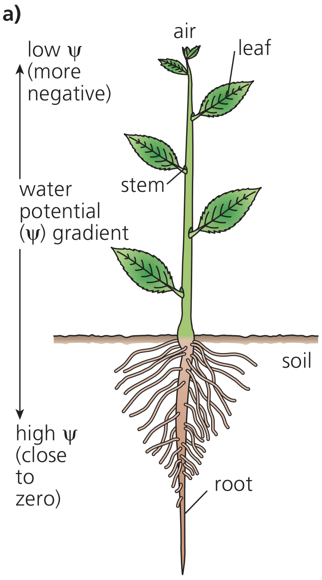
The very large numbers of delicate root hairs form behind each root tip (Figure 7.3). These are in close contact with the soil solution which has a very high water potential. (Remember, **water potential**, the name we give to the tendency of water molecules to enter or leave solutions, was introduced in Topic 4, page 83.) At the same time the cells of the root cortex have a water potential much lower than that of the soil solution. Water enters the root from the soil solution, passing down a water potential gradient (Figure 7.9a).

Another process occurring in the root hairs is the active **uptake of soluble ions** from the soil solution. These ions include nitrate ions, magnesium ions and several others, all essential to the metabolism of the plant. Once absorbed, the ions are transported across the cortex of the root. They converge on the central stele and there they are actively secreted into the water column flowing up the xylem. The continuing movement of ions across the cortex of the root is partly responsible for the gradient in water potential between soil solution and the cells of the stele. We return to the issue of ion uptake later in this topic.

Question

4 What features of root hairs facilitate absorption from the soil?

a)



From root hairs to xylem – apoplast and symplast

Look at Figure 7.9b. It shows the two pathways that water can take through plant tissues.

The alternative **pathways of water movement** shown are:

- the **apoplast**. This is the interconnected 'free spaces' that occur between the cellulose fibres in the plant cell walls. These free spaces make up about 50 per cent of the volume of the cell wall. The apoplast also includes the water-filled spaces of dead cells and of the xylem vessels. Note that this route entirely avoids the living contents of cells. We shall see that most of the water passing through plant tissue travels by this pathway, most of the time – a case of transport by mass flow.
- the **symplast**. This is the living contents of cells. Water enters cells through the cell surface membrane by osmosis and diffuses through the cytoplasm of cells and the cytoplasmic connections between cells (called **plasmodesmata**). You will remember that the cells are packed with many organelles. These tend to slow the flow of water, so this pathway is not the major one for water movement.

So, most water travels across the root via the apoplast pathways, until that is, the endodermis, is reached.

b)

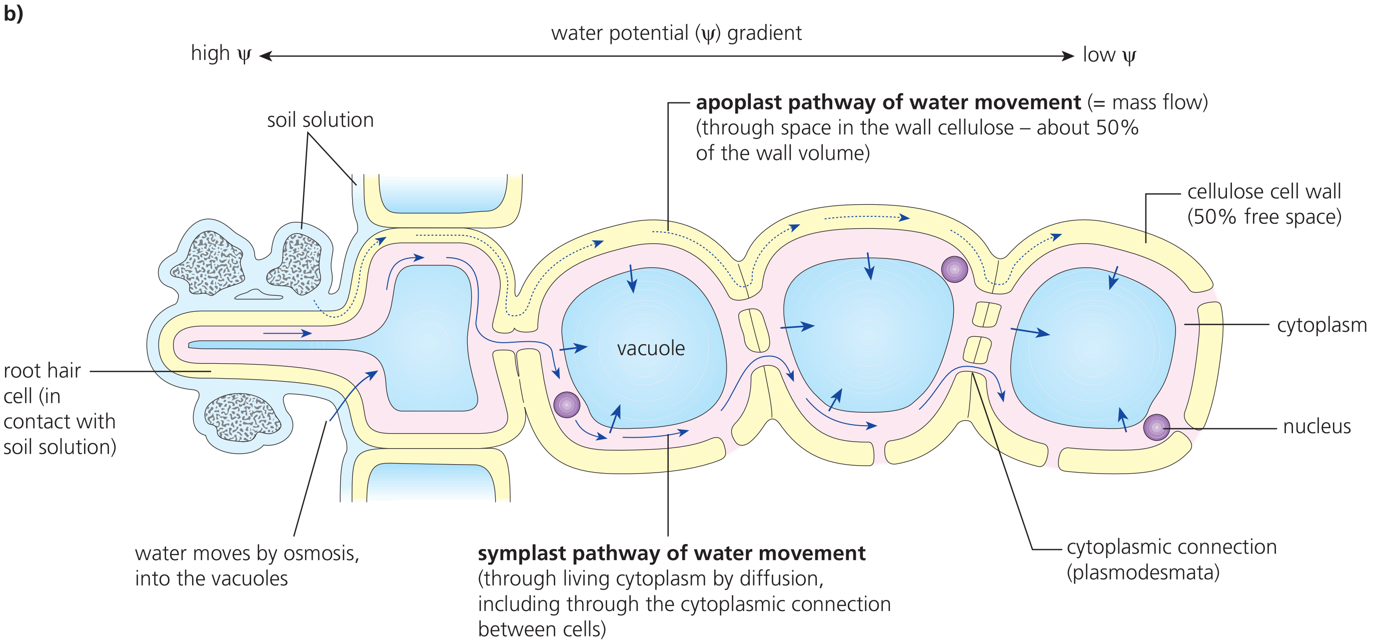


Figure 7.9 Water movement – force and pathways
a) The water potential (ψ) gradient of the whole plant
b) The water potential (ψ) gradient across cells of the root cortex

The role of the endodermis

This is a single layer of cells that surrounds the central stele of the root. These cells have a waxy strip in their radial walls, known as the **Casparian strip**. The wax is so strongly attached to the cellulose that it stops the movement of water by the apoplast pathway – but only temporarily. All water passes into the cytoplasm of the endodermis cells and then travels by the symplast pathway. You can see the position of the Casparian strip and its effect on water movement in Figure 7.10.

After that, water can and mostly does return to the apoplast pathway and travels the remaining short distance to reach the xylem vessels. This movement, too, is down a water potential gradient. However, the next steps – entry into the xylem and movement of water up to the leaves – depend on events in the leaves. Next, we need to investigate the process of loss of water vapour from the cells of the leaves.

Question

5 What is the consequence of the Casparian strip for the apoplast pathway of water movement?

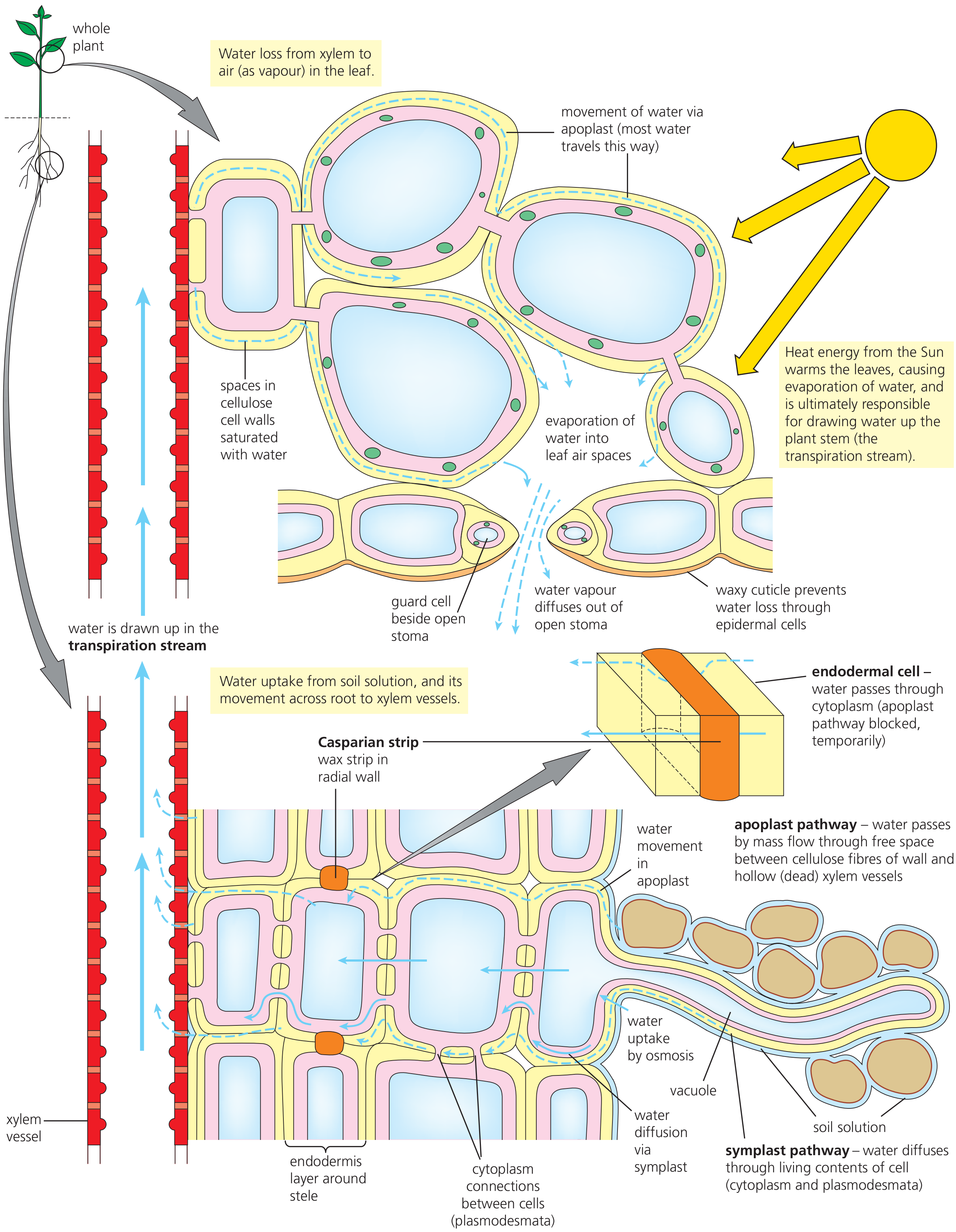


Figure 7.10 Water uptake and loss by the green plant

Transpiration: the process through which water vapour is lost from the aerial parts of plants. It occurs as the result of evaporation of water at the surface of mesophyll cells into the airspaces within the leaf, followed by diffusion of water vapour out of the leaf, mainly through stomata, down a water potential gradient from the surface of spongy mesophyll cells via airspaces in the leaf to the atmosphere.

Transpiration and the role of stomata

Transpiration is the name given to the loss of water vapour from the aerial parts of plants. The mesophyll cells in the leaf are moist and their walls contain water between all the cellulose fibres there. Consequently, there is a film of water around the outside of the cell walls, too. So water is freely available to evaporate from the cell walls and it does so. The air inside the leaf is usually saturated with water vapour.

Stomata are pores in the epidermis of leaves. Each stoma consists of two elongated **guard cells**. These are attached to the surrounding epidermal cells and joined together at each end but they are free to separate to form a pore between them (Figure 7.11). The epidermal cell besides a guard cell is called a subsidiary cell.

The water vapour that accumulates in the air spaces between the mesophyll cells diffuses out through the pores of open stomata, provided there is a concentration gradient between the leaf spaces and the air outside the leaf. This difference in concentration of water vapour between the leaf and the external atmosphere is highest in hot, dry, windy weather. Transpiration is greatest in these conditions, as we shall shortly demonstrate. The site of transpiration is shown in Figure 7.12.

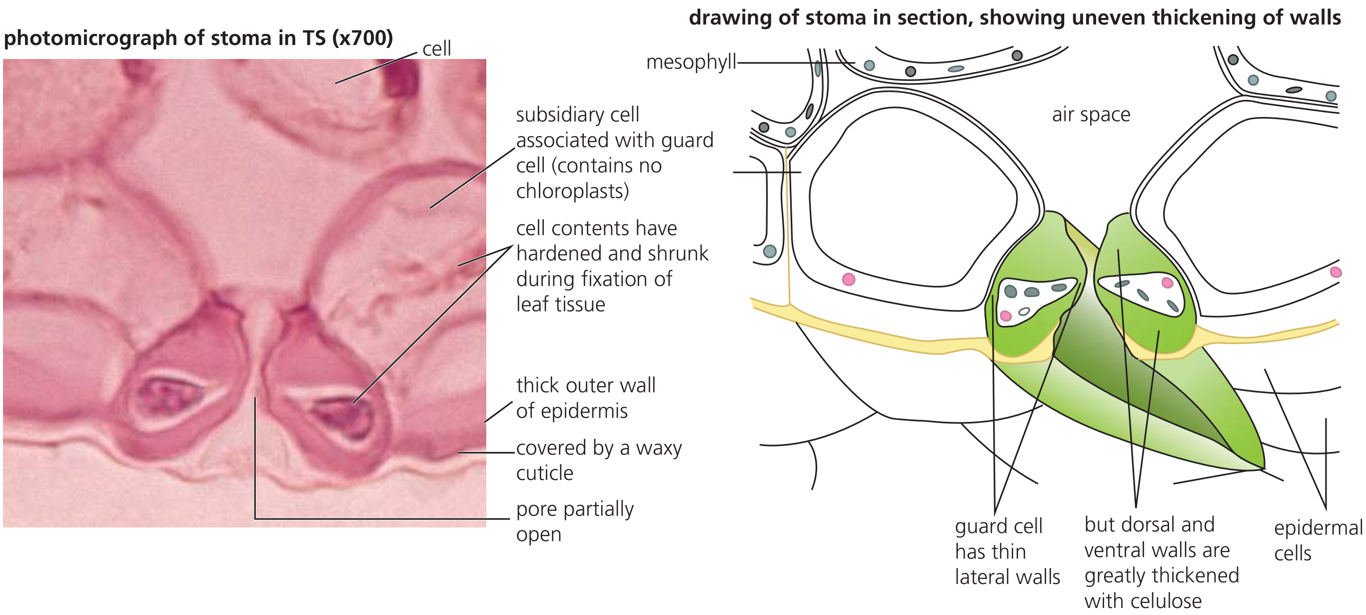


Figure 7.11 The structure of stomata

Stomatal aperture and water loss – an experimental approach

Water vapour diffusing out of a leaf through open stomata can be detected by cobalt chloride paper (blue when dry, pink when it absorbs water). The time this takes to happen will indicate the number of open stomata (Figure 7.13). This experiment can be adapted to compare water vapour loss from the leaves of different plants.

The results can be related to stomatal frequency in the same plant leaves by spreading a film of nail varnish on the leaf surfaces. When the film has dried it can be peeled off with fine forceps, placed on a microscope slide with a drop of water and a cover slip added. The number of open stomata observed in the microscope field of view can be counted. The mean of five counts for each leaf will provide a significant result.

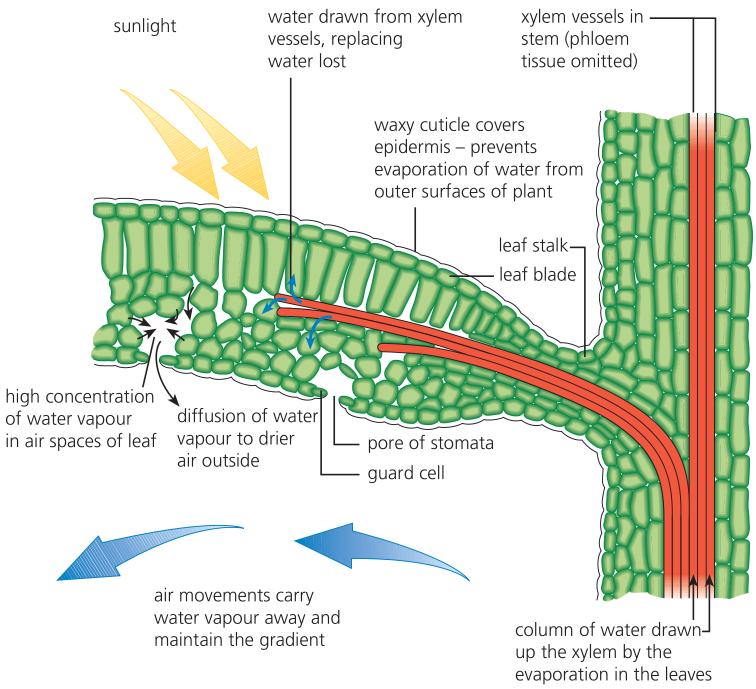


Figure 7.12 The site of transpiration

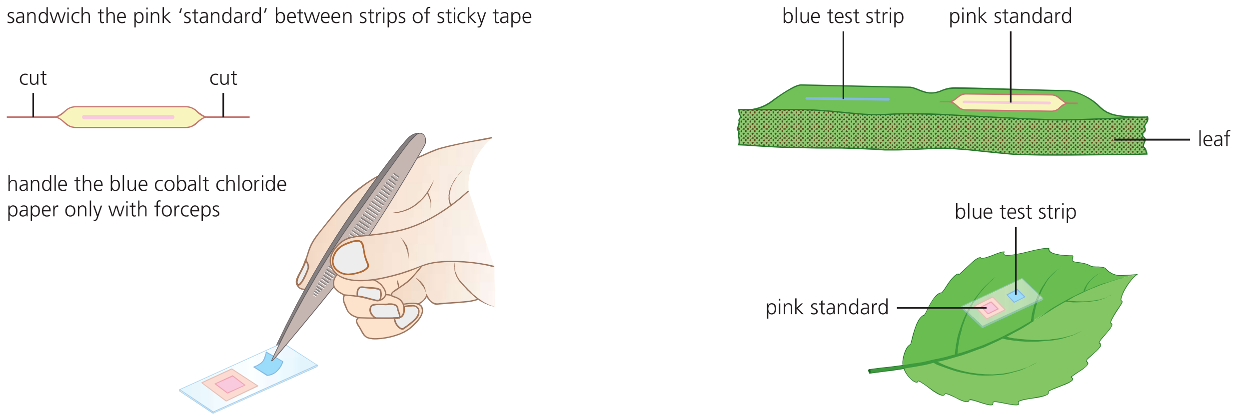


Figure 7.13 Cobalt chloride paper used to measure water vapour loss from a leaf surface

Question

6 Explain precisely why it is that a rise in temperature around a green plant normally leads to an increase in the rate of transpiration.

The transpiration stream

The water that evaporates from the walls of the mesophyll cells of the leaf is continuously replaced. It comes, in part, from the cell cytoplasm (the symplast pathway), but mostly it comes from the water in the spaces in cell walls in nearby cells and then from the xylem vessels in the network of vascular bundles nearby (the apoplast pathway).

These xylem vessels are full of water. As water leaves the xylem vessels in the leaf a tension is set up on the entire water column in the xylem tissue of the plant. This tension is transmitted down the stem to the roots because of the **cohesion** of water molecules. Cohesion is the force by which individual molecules stick together. Water molecules stick together as a result of hydrogen bonding. These bonds continually break and reform with other adjacent water molecules, but at any one moment a large number are held together by their hydrogen bonds, and so are strongly attracted to each other.

Adhesion is the force by which individual molecules cling to surrounding material and surfaces. Materials with an affinity for water are described as **hydrophilic** (see 'The solvent properties of water' on page 53). Water adheres strongly to most surfaces and can be drawn up in long columns, through narrow tubes like the xylem vessels of plant stems, without danger of the water column

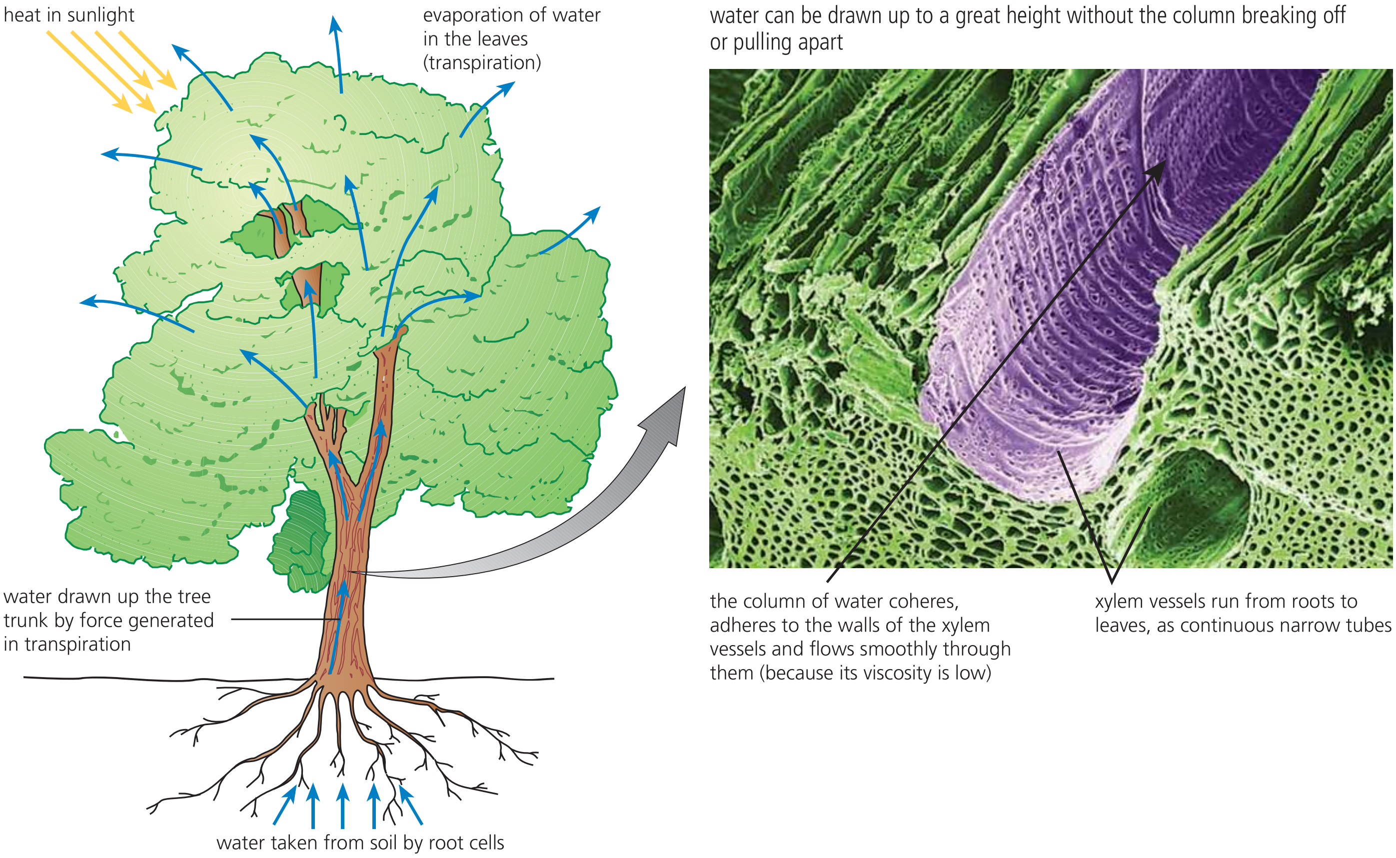


Figure 7.14 Water is drawn up a tree trunk

breaking (Figure 7.14). Compared with other liquids, water has extremely strong adhesive and cohesive properties that prevent it breaking under tension.

Consequently, under tension the water column does not break or pull away from the sides of the xylem vessels. The result is that water is drawn (literally *pulled*) up the stem. So water flow in the xylem is always upwards. We call this flow of water the **transpiration stream** and the explanation of water transport up the stem, the **cohesion–tension theory**.

The tension on the water column in xylem is demonstrated experimentally when a xylem vessel is pierced by a fine needle. Immediately, a bubble of air enters the column (and will interrupt water flow). If the contents of the xylem vessel had been under pressure, then a jet of water would have been released from the broken vessel.

Further evidence of the cohesion–tension theory comes from measurement of the diameter of a tree trunk over a 24-hour period. In a large tree there is an easily detectable shrinkage in the diameter of the trunk during the day. This is explored in the data handling activity on the CD. Under tension, xylem vessels get narrower in diameter, although their collapse is prevented by the lignified thickening of their walls. Notice that these are on the inside of the xylem vessels (Figure 7.15).

The diameter of a tree trunk recovers during the night when transpiration virtually stops and water uptake replaces the earlier losses of water vapour from the aerial parts of the plant.

Figure 7.15 Xylems vessel with internal rings of lignin thickening their lateral walls

Investigating transpiration

The conditions that affect transpiration may be studied using a **potometer**. You will find that these are also the conditions which effect evaporation of water from any moist surface. They include the humidity of the air, temperature and air movements. In Figure 7.16 the ways in which these factors may be investigated is suggested.

Actually, the potometer measures water uptake by the shoot. In the potometer the shoot has an unlimited supply of water. By contrast, in the intact plant the supply of water from the roots may slow down (as in drought conditions, for example), so the water supply is also a factor in the rate of transpiration in the intact plant. This point will help you answer Question 7.

Table 7.1 Factors that influence transpiration and how to investigate them

The factors that influence transpiration:	How to investigate factor using the potometer:
humidity – at low humidity more water evaporates	compare transpiration by shoot contained in polythene bag with that by shoot in moving air
temperature – heat energy drives evaporation from surface of mesophyll cells	compare transpiration at different air temperatures
air movement – wind carries away saturated air from around leaves, maintaining a concentration gradient between leaf interior and air outside stomata	compare transpiration at different fan speeds
water supply – if leaves become flaccid the stomata close	(not applicable – potometer supplies unlimited water to shoot)

Question

7 Explain the significance of the fact that in large trees there is an easily detectable shrinkage in the diameter of the trunk during the daytime in hot weather that recovers in the night.

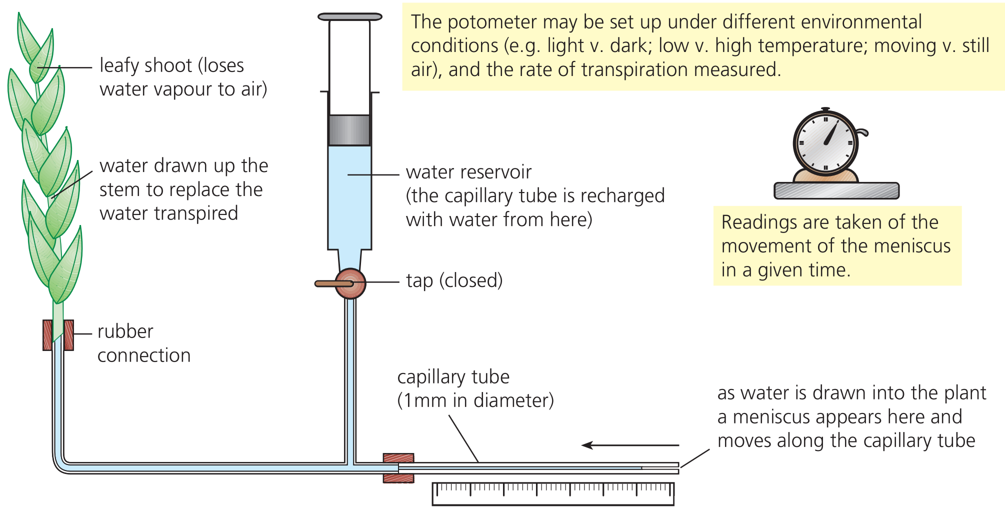


Figure 7.16 Investigating transpiration using a potometer

Does transpiration have a role?

We have seen that transpiration is a direct result of plant structure, plant nutrition and the mechanism of gas exchange in leaves, rather than being a valuable process. In effect, the living plant is a 'wick' that steadily dries the soil around it.

However, transpiration confers advantages, too.

- Evaporation of water from the cells of the leaf in the light has a strong cooling effect (page 52).
- The stream of water travelling up from the roots passively carries the dissolved ions that have been actively absorbed from the soil solution in the root hairs. These are required in the leaves and growing points of the plant (see below).
- All the cells of a plant receive water by lateral movements of water down a water potential gradient from xylem vessels, via pits in their walls. This allows living cells to be fully hydrated. It is the turgor pressure of these cells that provides support to the whole leaf, enabling the leaf blade to receive maximum exposure to light. In fact, the entire aerial system of non-woody plants is supported by this turgor pressure (Figure 4.17, page 88).

So, transpiration does have significant roles in the life of the plant.

Xerophytes: plants of permanently dry and arid conditions

Most native plants of temperate and tropical zones and many crop plants grow best in habitats with plenty of rain and well-drained soils. These sorts of plants are known as **mesophytes**. It is the structure of these plants that has been described in this topic so far. Typically, their leaves are exposed to moderately dry air. Much water is lost from their leaves, particularly in drier periods. This is especially the case in the early part of the day. Later, if excessive loss of water continues, it is prevented by the responses of the stomata – they close (Figure 7.11). After that, the water lost can be replaced by the water uptake that continues, day and night.

On the other hand, some plants are well able to survive and often grow well in habitats where water is permanently scarce. These plants are known as **xerophytes**. They show features that directly or indirectly help to reduce the water loss due to transpiration to a minimum. The adaptations they have that enable them to survive where water is short are referred to as **xeromorphic features**. These are summarised in Table 7.2.

Table 7.2 Typical structural features of xerophytes

Structural feature	Effect
Exceptionally thick cuticle to leaf (and stem) epidermis	Prevents water loss through the external wall of the epidermal cells
Layer of hairs on the epidermis	Traps moist air over the leaf and reduces diffusion
Reduction in the number of stomata	Reduces the outlets through which moist air can diffuse
Stomata in pits or groves	Moist air is trapped outside the stomata, reducing diffusion
Leaf rolled or folded when short of water (cells flaccid)	Reduces area from which transpiration can occur
Leaf area severely reduced – possibly to 'needles'	Stems take over a photosynthetic function and support much reduced leaves
Have two types of roots: a) superficial roots b) deep and extensive roots	Obtain water by both: exploiting overnight condensation at soil surface exploiting a deep water table in the soil

Question

8 Suggest why it is that, of all the environmental factors which affect plant growth, the issue of water supply is so critical.

Sorghum, a grain plant that thrives in extremely arid conditions, shows marked adaptations in its leaf structure and root system. Marram grass is a pioneer plant of sand dunes.

Examine Figures 7.17 and 7.18 carefully. Which of the features listed in Table 7.2 does each plant exhibit?

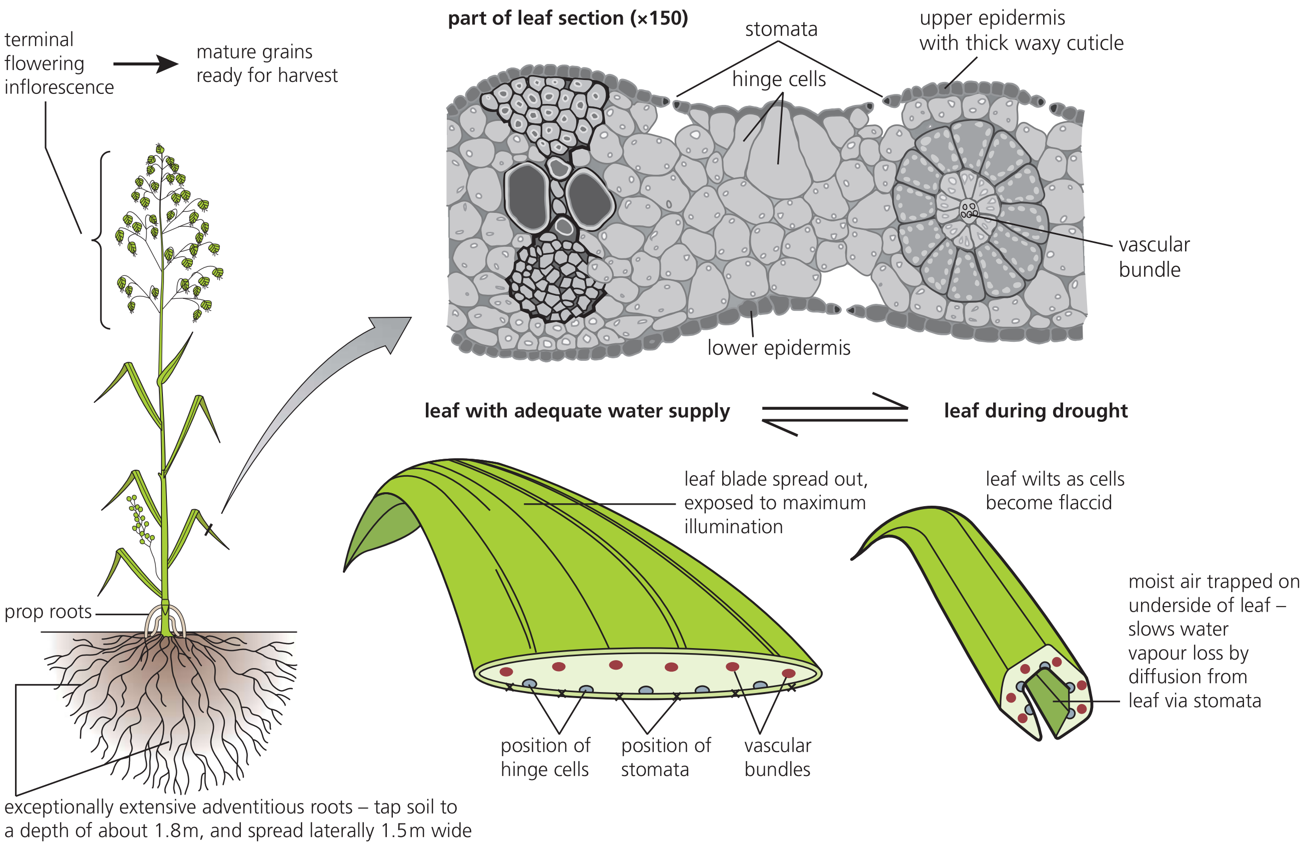


Figure 7.17 *Sorghum*: a drought-resistant tropical plant of economic importance

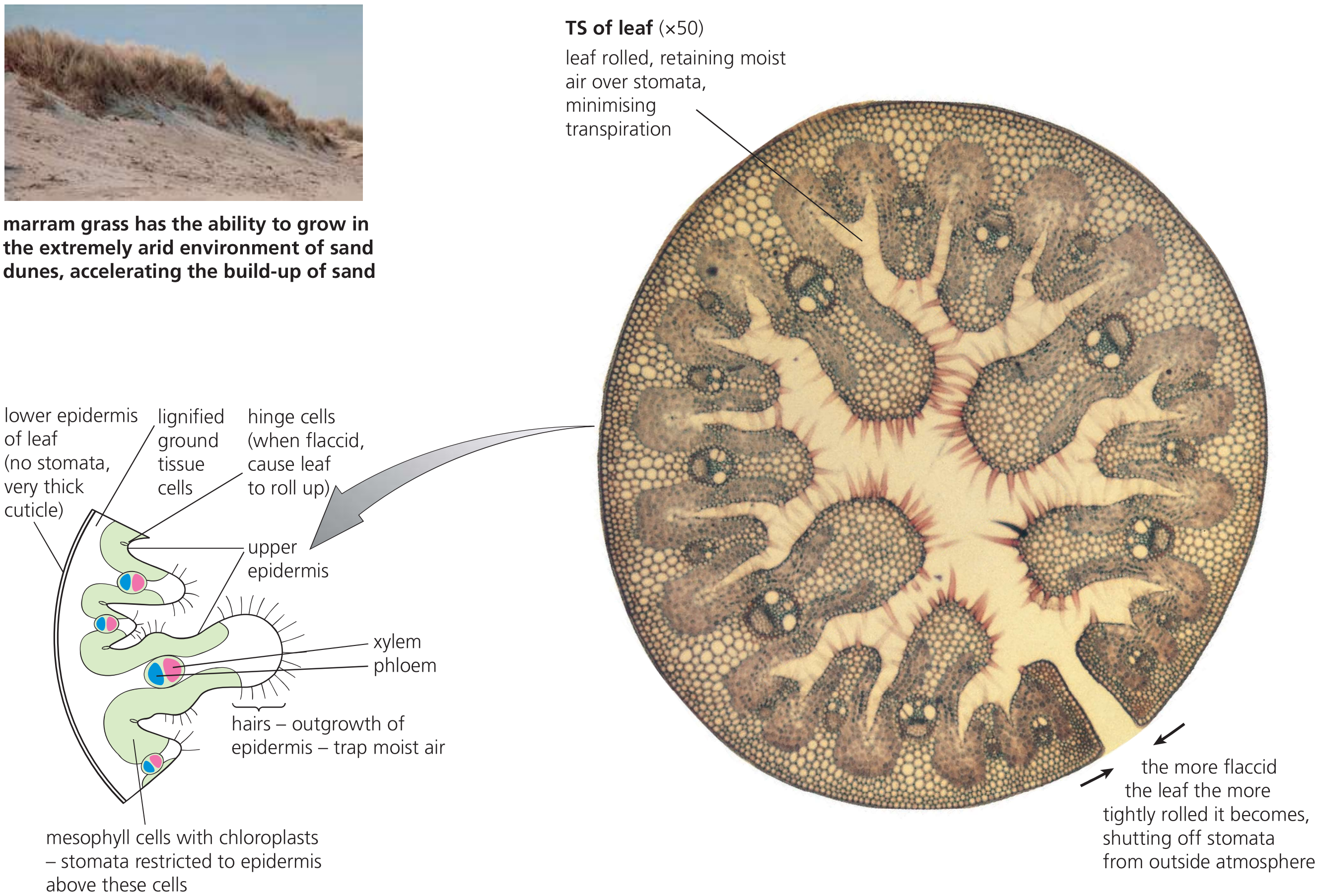


Figure 7.18 Marran grass (*Ammophila*): a part of sand dunes

Question

9 Explain the significance of:

a root hair cells being able to take up nitrate ions from the soil solution even though their concentration in the cell is already higher than in the soil

b plants often failing in soil that is permanently waterlogged. (Think about the importance of oxygen for respiration.)

Inorganic ions and plants

'Minerals' are inorganic elements, some of which are needed by organisms. They include substances like sodium chloride, in which ionic bonding occurs. In ionic bonding one or more electrons is transferred completely from one atom to another, to produce a stable arrangement of electrons. Ionic bonding transforms atoms into stable ions. The example of ionic bonding in sodium chloride is shown in Figure A3 of Appendix 1 (on the CD). Ionic bonding and the formation of ions contrasts with covalent bonding, which is shown in water (Figure 2.27, page 52) and in methane, for example.

Living things need several different inorganic ions but only a handful are needed in relatively large quantities. These are known as the **major mineral elements**. Major mineral elements required by plants include anions, like phosphate ($H_2PO_4^-$), **nitrate (NO^{3-})**, and cations like calcium (Ca^{2+}), and **magnesium (Mg^{2+})**.

The source of mineral ions for plants is the soil solution – the layer of water that occurs around the individual soil particles. Here ions occur in quite low concentrations but plants can take them up through their root hairs. So, water uptake and the absorption of mineral ions occur at the root hairs but they occur by entirely **different mechanisms**.

Ions are taken up **selectively**, by an **active process**, using energy from respiration. This means that the ions that are useful are selected and the ions not required by the plant are ignored. Uptake occurs by means of protein pumps (page 91) in the cell surface membrane of the root cells including root hair cells. Protein pumps are specific for particular ions so, if an ion is required, the particular transport protein is produced by the cells and built into the cell membranes. If the required ion is available in the soil solution, it can be pumped into the cell, despite there being a higher concentration in the cell already.

Extension

Signs and symptoms of mineral deficiency

In the soil, the ions dissolved in the soil solution come from the mineral skeleton of the soil by chemical erosion. They also come from the decay of the dead organic matter that is constantly being added to the soil. Among these are nitrate and magnesium ions, both required for particular biochemical pathways (Table 7.3). Consequently, plants that are deficient in these (and other) essential nutrients normally show characteristic signs and symptoms. Notice that the signs of deficiency of nitrate and magnesium ions are very similar.

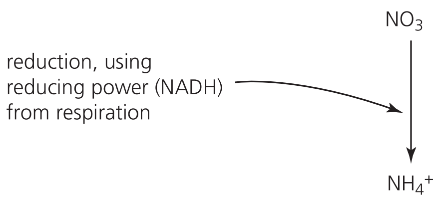
Can you think why this is? Remember, the green colour of plants is due to the presence of chlorophyll. Are nitrate and magnesium ions required for synthesis of new chlorophyll molecules?

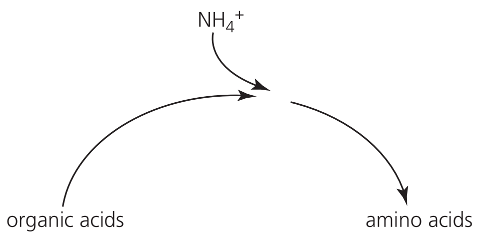
When deficiency symptoms appear in cultivated commercial crops, the mineral nutrients available in the soil may be checked by chemical analysis, to confirm the deficiency. Then, artificial fertiliser can be applied to counter the deficiency and restore normal growth patterns.

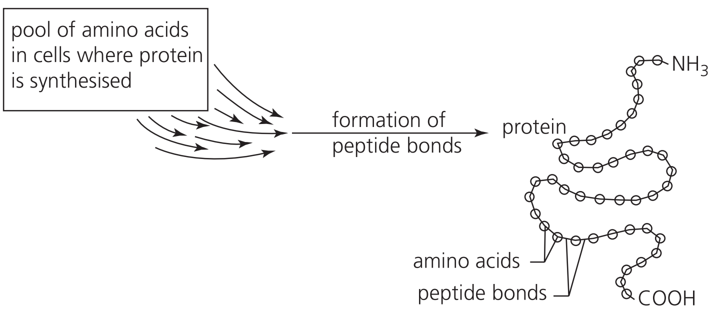
Question

10 Why and how is the supply of essential ions maintained in the soil in agriculture?

Table 7.3 Nitrate and magnesium: symptoms of deficiency and roles in metabolism

<table>
<tr><th>Symptoms of deficiency</th><th>Roles in metabolism</th></tr>
<tr><td>Nitrate deficiency</td><td>Key ingredient in amino acid (and protein) synthesis</td></tr>
<tr><td>upper leaves light green,
lower leaves yellow
</td><td>1 Nitrate ions are reduced to ammonium ions:


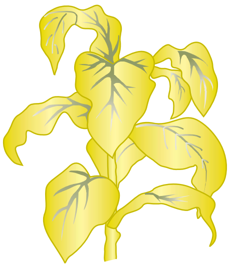
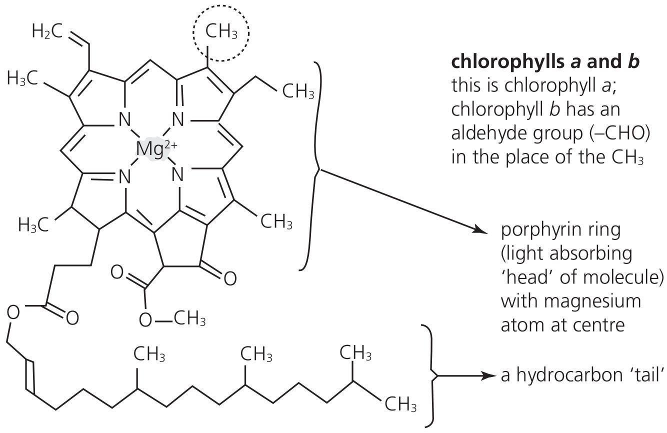
2 Ammonium ions are combined with an organic acid to form the amino acids required for protein synthesis:


3 From the pool of amino acids are formed the polypeptides and proteins the cell requires:


Nucleic acids also contain nitrogen</td></tr>
</table>

(*continued*)

Extension (continued)

Symptoms of deficiency	**Roles in metabolism**
Magnesium deficiency	**Component of chlorophyll**
lower leaves yellow from margins inwards, veins remain green 	

Translocation

Translocation is the process by which manufactured food (sugars and amino acids – sometimes called **assimilates**) are moved around the plant. This occurs in the **phloem tissue** of the vascular bundles (Figure 7.1). The sugars made in the leaves in the light are moved around the plant as sucrose. For example, young leaves export sugars to sites where new stems, new leaves or new roots are being formed. Then, in older plants, sucrose is sent to sites of storage, such as the cortex of roots or stems, and to seeds and fruits.

Meanwhile, nitrates are absorbed from the soil solution by the root hairs. Nitrates are one of the raw materials used in the synthesis of amino acids and also nucleic acids. Amino acid synthesis takes place in the roots. Amino acids are then moved to sites in the plant where protein synthesis is occurring, such as in buds, young leaves, young roots and developing fruits. So you can see that the contents of phloem (known as sap) may vary. Also, it may flow in either direction in the phloem.

Phloem structure – a reminder

Phloem tissue consists of living cells – sieve tube elements and companion cells. Both have cellulose cell walls. These walls do not become lignified. Translocation is dependent on living cells and there is a close relationship between sieve tube elements and their companion cells.

Sieve tubes are built from narrow, elongated cells, connected end to end to form continuous tubes. Their touching end walls are pressed together and become perforated by large pores which remain open. The whole structure, known as **sieve plate**, allows free flow of liquid through the tube system. The cytoplasm of a mature sieve tube element has lost its nucleus, and neither does it have many of the other organelles of a cell. A thin layer of cytoplasm lines the walls.

At least one **companion cell** accompanies each sieve tube element. Sieve tube elements and companion cells are connected by strands of cytoplasm, the plasmodesmata, that pass through gaps in the walls. The contents of the companion cells differ from those of sieve tube elements. They retain their nucleus and the other organelles that are common to cells that are metabolically active – particularly mitochondria and ribosomes. We can assume that companion cells service and maintain the sieve tube elements in various ways.

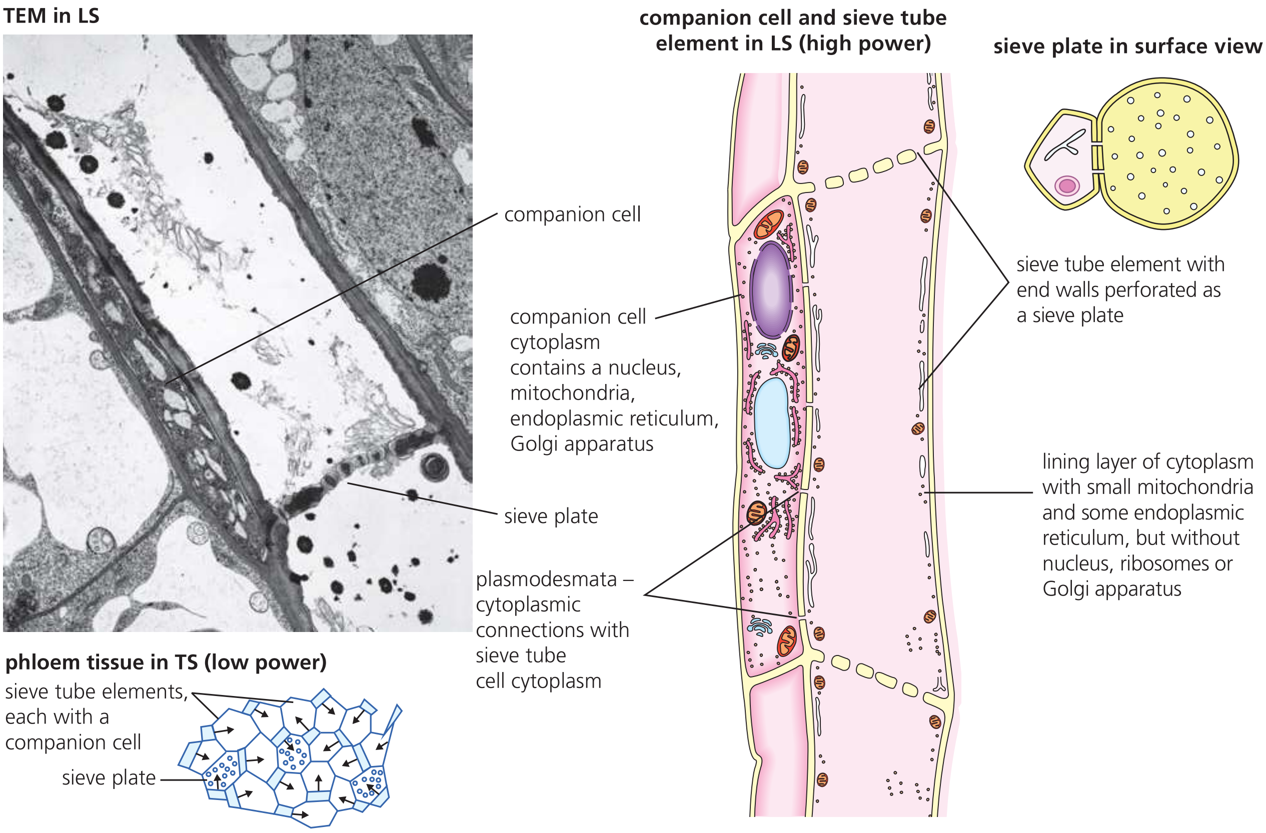


Figure 7.19 The fine structure of phloem

Questions

11 What does the presence of a large number of mitochondria in the companion cells suggest to you about their role in the movement of sap in the phloem?

12 Examine Figure 7.20 carefully.

a What sequence of events would you anticipate in a leaf stalk as the content of a water-jacket is raised to 50°C?

b How would you expect the phloem sap sampled from a sieve tube near leaves in the light and at the base of the same stem to differ?

Phloem transport

Phloem transport occurs by **mass flow** but the pressure difference that drives it is produced by a different mechanism from that in xylem transport. Most significantly, translocation requires living cells (Figure 7.20). Cell respiration is the process by which energy is transferred to drive metabolic reactions and processes. Much of the respiration occurs in the mitochondria. ATP is the molecule produced in mitochondria to transfer energy. We shall see that ATP is involved in the mechanism of phloem transport.

Translocation can be illustrated by the movement of sugar from the leaves. The story starts at the point where sugars are made and accumulate within the mesophyll in the leaf. This is the **source area**.

Sugars are loaded into the phloem sieve tubes through transfer cells (Figure 7.21). From here, sucrose is pumped into the companion cells by the combined action of **primary** and **secondary pumps**. These pumps are special proteins in the cell surface membrane. The primary pumps remove hydrogen ions (protons) *from* the cytoplasm of the companion cell, so setting up a gradient in concentration of hydrogen ions between the exterior and interior of the companion cell. This movement requires ATP. Hydrogen ions then flow back into the companion cell down their concentration gradient. This occurs at specific sites called secondary pumps where their flow is linked to the transport of sucrose molecules in the same direction.

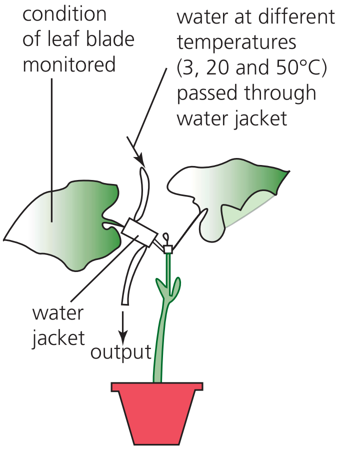
As sucrose solution accumulates in the companion cells it moves on by diffusion into the sieve tubes, passing along the plasmodesmata (Figure 7.19). The accumulation of sugar in the phloem tissue lowers the water potential and water follows the sucrose, diffusing down a water potential gradient. This creates a high hydrostatic pressure in the sieve tubes of the source area.

Meanwhile, in living cells elsewhere in the plant – often, but not necessarily in the roots, sucrose may be converted into insoluble starch deposits. This is a **sink area**. As sucrose flows out of the sieve tubes here, the water potential is raised. Water then diffuses out down a water potential gradient and the hydrostatic pressure is lowered. These processes create the difference in hydrostatic pressures in the source and sink areas that drives mass flow in the phloem.

Figure 7.20 Experiment to show that translocation requires living cells

That translocation requires living cells is shown by investigation of the effect of temperature on phloem transport

Note: in neither experiment did the leaf blade wilt – xylem transport is not heat sensitive at this range of temperatures (because xylem vessels are dead, empty tubes)



(a) at 50°C, translocation of sugar from the leaf blade stopped – this is above the thermal death point of cytoplasm

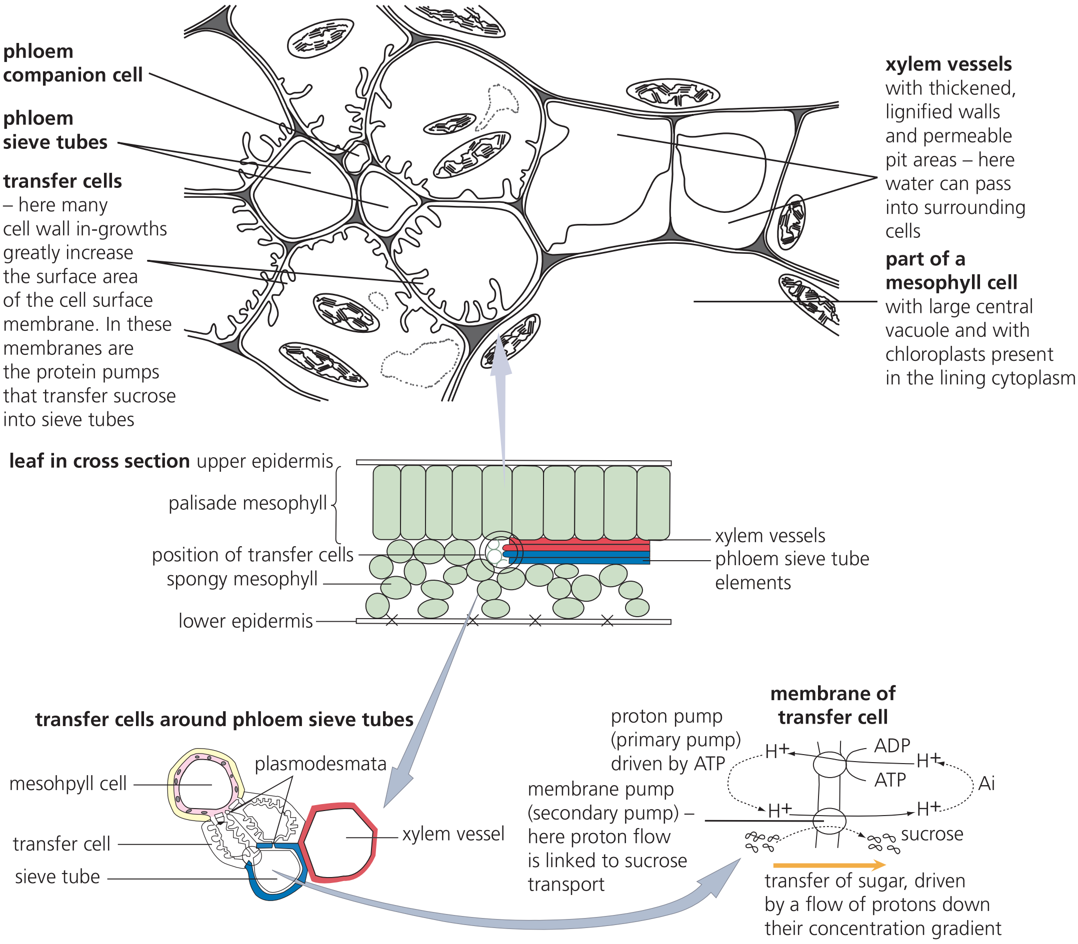
conclusion: living cells are essential for translocation

(b) at 3°C, compared with 20°C translocation of sugar from leaf blade was reduced by almost 10% of leaf dry weight over a given time

conclusion: rate of metabolic activity of phloem cells affects rate of translocation

Figure 7.21 Transfer cells and the loading of sieve tubes

TEM of a leaf vein showing sieve tube elements, transfer cells, xylem vesssels and mesophyll cells (x1500)



The pressure flow hypothesis

The principle of the pressure flow hypothesis is that the sugar solution flows down a hydrostatic pressure gradient. There is a high hydrostatic pressure in sieve elements near mesophyll cells in the light (source area) but low hydrostatic pressure in elements near starch storage cells of the stem or root (sink area). Mass flow is illustrated in Figure 7.22 and the annotations explain the steps.

In this hypothesis, the role of the companion cells (living cells, with a full range of organelles in the cytoplasm) is to maintain conditions in the sieve tube elements favourable to mass flow of solutes. Companion cells use metabolic energy (ATP) to do this.

Question

13 What conditions maintain
- **a** the high water potential of the cell of the root cortex
- **b** the low water potential of the mesophyll cells of a green leaf?

Table 7.4 Evidence for the pressure flow hypothesis

For	Against
The contents of the sieve tubes are under pressure and sugar solution exudes if phloem is cut.	Phloem tissue carries manufactured food to various destinations (in different sieve tubes), rather than to the greatest sink.
Appropriate gradients between 'source' and 'sink' tissue do exist.	Sieve plates are a barrier to mass flow and might be expected to have been 'lost' in the course of evolution if mass flow is the mechanism of transport.

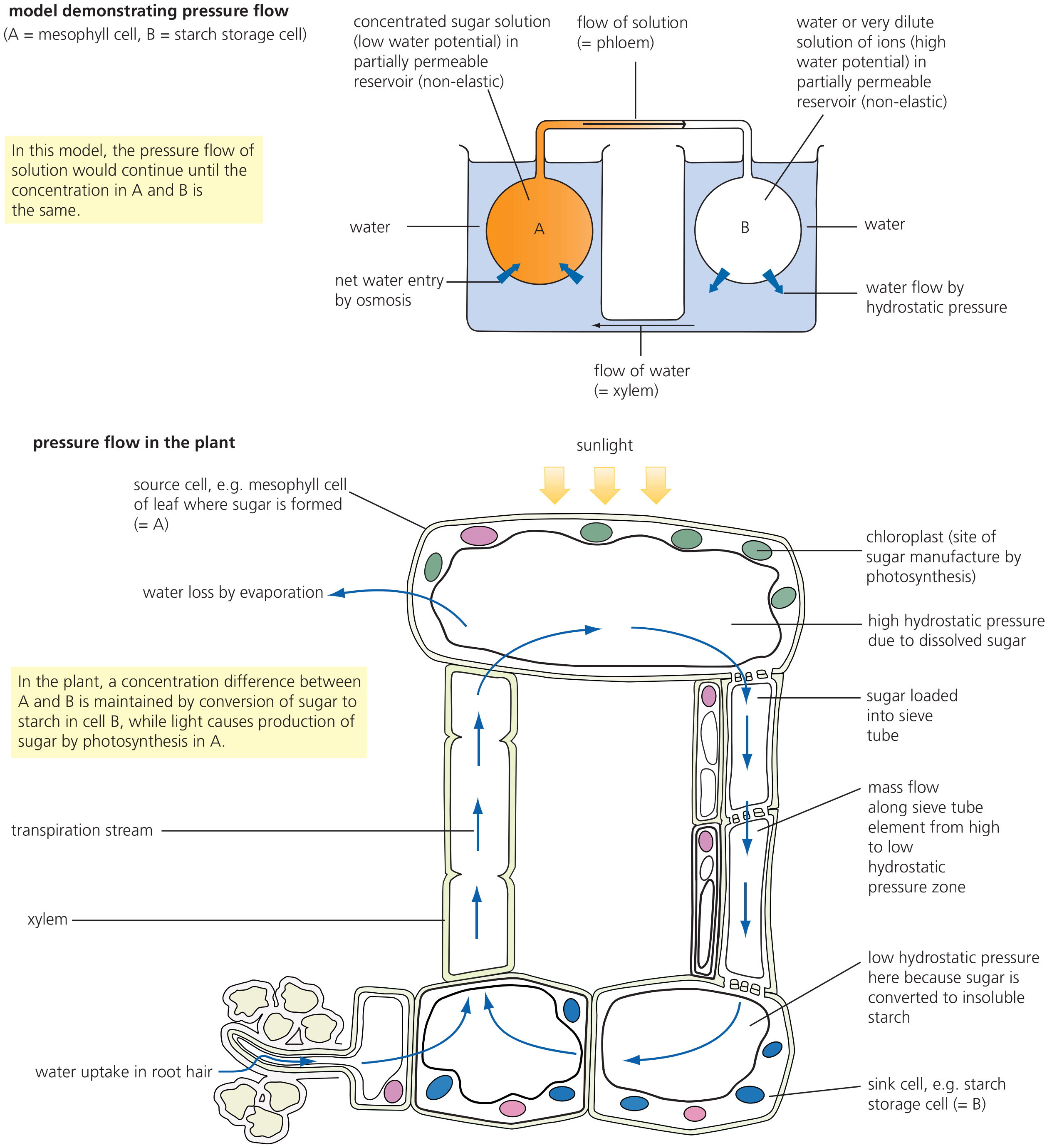


Figure 7.22 The pressure flow hypothesis of phloem transport

Summary

- Internal transport within plants occurs by **mass flow** but there is no pumping organ. Two separate tissues are involved in transport. Water and ions travel in the **xylem**, a system of vessels connected end to end to form non-living tubes. Manufactured foods are carried in a living tissue, the **phloem**, consisting of sieve tubes and companion cells. The xylem and phloem make up the **vascular tissue** that branches throughout the plant body and serves roots, stems, leaves and growing points (buds).
- Water moves from the soil to the aerial system by a **gradient in water potential**. Water is drawn up the stem by a force generated in the leaves by the evaporation of water vapour from the aerial system (**transpiration**).
- Hydrogen bonding between water molecules, and between these molecules and hydrophilic surfaces, is responsible for the **cohesive** and **adhesive** properties of water, and makes possible the upward transport of water in the xylem by cohesion–tension.
- Transport of manufactured food in the phloem is by **active transport** requiring living phloem cells. According to the **mass flow hypothesis**, solutes flow through the phloem from a region of high hydrostatic pressure to a region of low hydrostatic pressure. Hydrostatic pressure is high in cells where sugar is formed, the **source area**, but low in **sink areas**, where sugar is converted to starch.
- Plants that survive permanently arid conditions (xerophytes), including the crop plant *Sorghum* and the sand-dune plant Marram grass, have leaves adapted to reduce water loss by transpiration.

Examination style questions

1 Fig. 1.1 is a drawing of a transverse section of a leaf.

a) i) Use label lines and the letters **X**, **S**, **E** and **D** to indicate the following on a copy of Fig. 1.1:

X a xylem vessel

S a phloem sieve tube

E a lower epidermal cell

D a palisade mesophyll cell [4]

ii) Calculate the magnification of Fig. 1.1. Show your working and express your answer to the nearest whole number. [2]

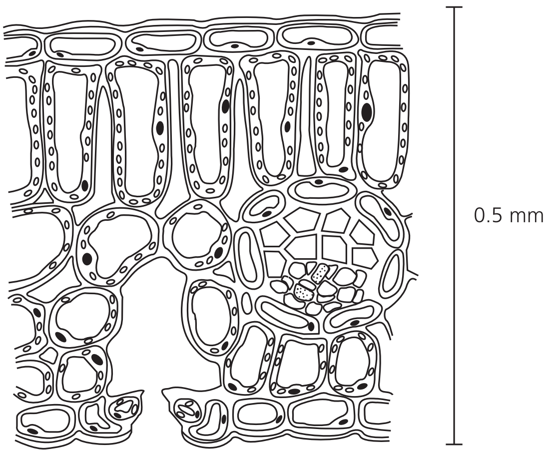


Fig. 1.1

b) Name **two** assimilates that move from the palisade mesophyll cells to the vascular tissue to be exported from the leaf. [2]

c) Explain, using the term **water potential**, how water moves from the vascular tissue to the atmosphere. [4]

[Total: 12]

(Cambridge International AS and A Level Biology 9700, Paper 02 Q2 June 2005)

2 a) Draw and annotate a diagram of a potometer in use in the measurement of transpiration. [8]

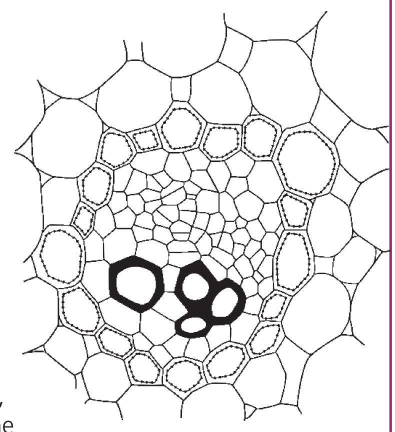
b) Name three external factors that may influence the rate of transpiration in a plant in the light and explain why they have an effect on the rate of loss of water vapour. [6]

c) What is a xerophyte? [1]

d) Tabulate the chief xeromorphic features that *Sorghum* exhibits and explain how and why they are effective. [5]

[Total: 20]

3 The diagram shows a vascular bundle from the stem of *Peperomia dahlstedtii*, a plant from Brazil. The vascular bundles in the stems of *P. dahlstedtii* are unusual because they are surrounded by an endodermis with a Casparian strip.



a) On a copy of the diagram, use label lines and the letters **P**, **Q** and **R** to identify the following in the vascular bundle.

P an endodermal cell with a Casparian strip

Q a cell wall strengthened with lignin

R a tissue that transports assimilates [3]

b) Vascular tissue in roots is surrounded by an endodermis. Describe the function of the endodermis in roots. [3]

c) State and explain two ways in which the **structure** of a phloem sieve tube is adapted for the transport of assimilates. [4]

[Total: 10]

(Cambridge International AS and A Level Biology 9700, Paper 22 Q5 June 2009)