Bio Factsheet

Number 82

Transport in Flowering Plants

This Factsheet covers the relevant AS syllabus content of the major examination boards. By studying this Factsheet candidates will gain a knowledge and understanding of:
- **the need for transport systems in flowering plants.**
- **the distribution of xylem and phloem in root, stem and leaf.**
- **the structure of xylem and phloem in relation to their functions.**
- **the uptake of water and the transpiration stream.**
- **the effect of changing environmental factors on transpiration.**
- **the mass-flow model to explain translocation, including the 'energy-requiring' nature of the process.**
- **the experimental evidence supporting the mass-flow model.**

Transport systems in terms of size and surface area to volume ratio.
Substances such as glucose molecules and nitrate ions move naturally from a region of higher concentration to one of lower concentration by diffusion. Water diffuses through a selectively permeable membrane from a region of higher water potential to one of lower water potential, a process known as osmosis. These vital processes are essential but adequate only for the transport of molecules and ions over short distances within a living system. Diffusion by itself is not sufficient; it is often too slow, possibly in the wrong direction and inadequate over longer distances. The evolution of flowering plants has seen the development of efficient transport systems which have enabled plants to colonise the land, to increase their size and to develop an erect habit. Xylem and phloem enable the movement of water, organic molecules and ions over long distances.

Distribution of xylem and phloem in root, stem and leaf.
Xylem tissue transports water and dissolved mineral salts absorbed from the soil by the root system. It conducts the dilute solution up the stem and into the leaves. Phloem tissue transports organic substances up **and** down a plant, taking the molecules from where they are made (leaves) to areas where they are used (growing points/flowers) or stored (roots, seeds, fruits).

> ***Remember** - transport of water and ions in the xylem is usually referred to as **conduction**. Transport of organic materials in the phloem is usually referred to as **translocation**.*

The distribution of xylem and phloem tissues in the root, stem and leaf of a dicotyledonous plant is shown in Fig 1, 2 and 3. Xylem and phloem collectively make up the vascular tissue of the plant.

Fig 1. Transverse section of dicotyledonous root

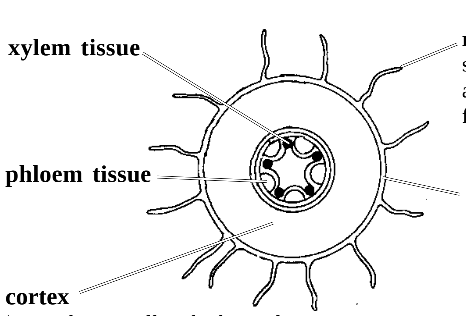


Fig 2. Transverse section of dicotyledonous stem

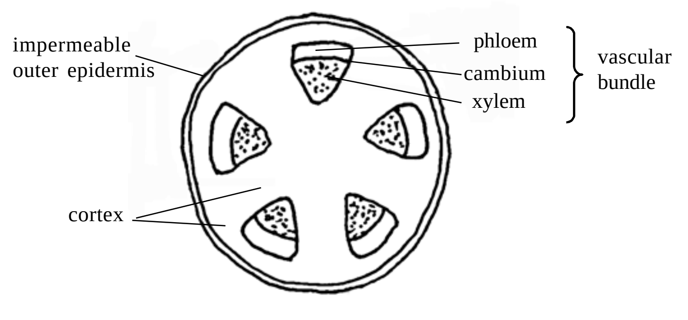
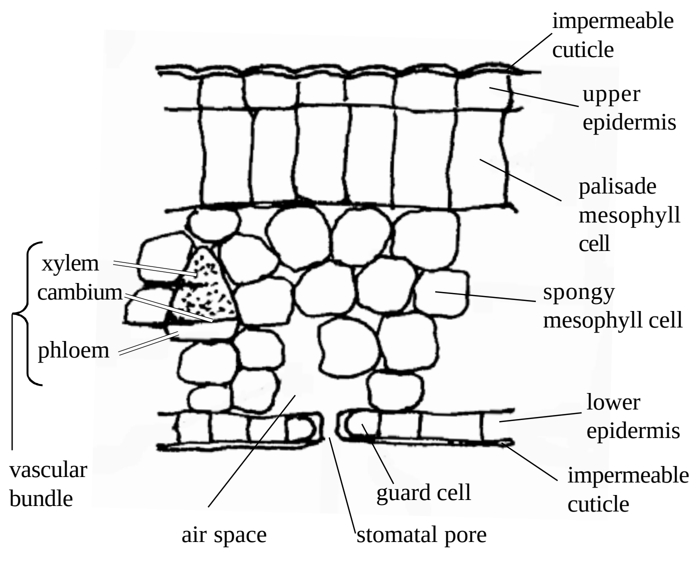


Fig 3. Vertical section of dicotyledonous leaf

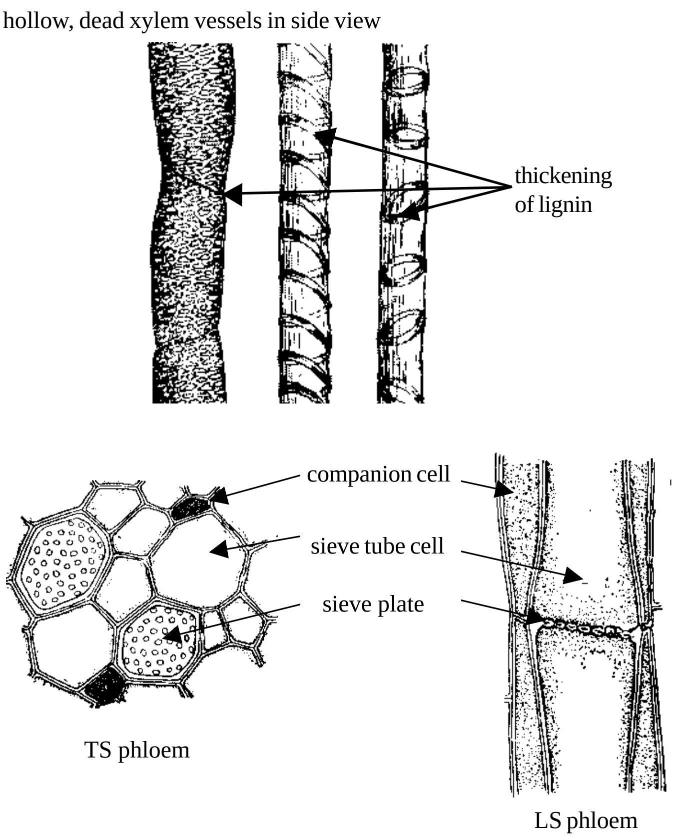


The structure of xylem and phloem cells related to their functions.
Xylem: There are two types of xylem cells involved in the transport of water, **tracheids** and **vessel elements**.
Both types of cell have cell walls thickened with lignin. Lignin strengthens the wall enabling it to provide support. It also waterproofs the cell so that it can conduct water. However, the impermeable lignin isolates the protoplast and as a result, mature xylem cells are dead and hollow. Lignin is laid down in the wall in a variety of patterns. For example, the conducting units may show annular, spiral or reticulate thickening.

Tracheids are long, thin cells with tapered ends. Xylem vessel elements are usually wider than tracheids and have thinner walls. Vessels are arranged in chains. The end wall of each vessel element is perforated, often missing altogether. This arrangement of elongated cells enables continuous flow of water from one element to the next in the series. Lateral movement of water is possible, both types of xylem cells having pits. Pits occur where the secondary wall layer containing lignin is missing, water passing readily through the primary cellulose wall. Water can therefore pass from one xylem tracheid or vessel element to an adjacent one.

Phloem: The cells involved in translocation form continuous tubes called **sieve tubes**. Each sieve tube is made from a chain of **sieve tube elements**. The end walls of phloem sieve tube elements have holes in them enabling one element to communicate with the next in line. This allows the continuity essential for the translocation of organic molecules through the sieve tube. The perforate end walls of a sieve tube element are called **sieve plates**. Phloem sieve tube elements, in contrast to xylem vessel elements, are alive when they are mature and functionally active. However, they differ from many mature, live plant cells, by lacking a nucleus, ribosomes and a Golgi body. Adjacent to each sieve tube element there is at least one companion cell. **Companion cells** possess a full compliment of organelles including those lacking in sieve tube elements. **Plasmodesmata** are numerous here, enabling the cytoplasm of a companion cell to communicate with the cytoplasm of its neighbouring sieve tube element. The organelles of a companion cell are thought to service both the needs of the companion cell and those of the sieve tube element alongside. The structure of xylem and phloem tissue is shown in Fig 4. (See Factsheet No. 19 Plant Tissues)

Fig 4. Structure of xylem and phloem



> ***Exam hint*** *– remember that lignin gives strengthening properties, making xylem a skeletal, supporting tissue as well as a water-conducting tissue. Exam questions often ask about the dual role of xylem.*

Uptake of water and the transpiration stream.

The term **water potential** is used to describe the tendency for water molecules to move within and between cells. A net movement of water will occur from one region to another as a result of a difference in water potential. Where a water potential gradient exists, the net movement of water is determined by the direction of the gradient. Water will tend to move from a region of higher water potential to one where it is lower. When the water potentials of two regions are the same, equilibrium exists, the concentration gradient is zero and therefore the net movement is zero.

> ***Remember*** *- Water will still move in both directions at equilibrium but since the rate of movement in each direction is the same, movement appears to have stopped altogether.*

Pure water has the maximum water potential. The presence of solute molecules lowers water potential. Maximum water potential has been defined as having a value of zero. This means that all solutions must have a water potential which is negative. (See Factsheet 54 Water potential (Sep 1999))

Some of the epidermal cells in younger roots are modified in a way that increases the root surface area in contact with the soil and the soil solution found in it. These cells have their outer wall extended to form a thin-walled tubular structure that penetrates the spaces between adjacent soil particles. Such cells are called **root hair cells**. Root hairs have very thin, cellulose walls that are readily permeable to water and dissolved mineral ions. The cell sap of root hairs and the water found between soil particles contain dissolved solutes, but the cells have a lower water potential than the solution outside in the soil. The plasmalemma, just inside the cell wall, is selectively permeable. Osmosis takes place and water passes down the water potential gradient from the soil solution into the root hair cell vacuole. The plasmalemma includes transporter proteins in its structure enabling, at the same time, the uptake of ions by facilitated diffusion and, when the uptake is against a concentration gradient, active transport.

Water entering a root hair cell vacuole raises its water potential relative to other cells internal to it and consequently, provided the root hair cell continues to take water from the soil, water will pass osmotically into the next adjacent cell vacuole and so on across the root cortex. This is called the **vacuolar** pathway. Some water crossing the cortex may pass from cell to cell through plasmodesmata via the cytoplasm, without entering the vacuole. Water crossing the cortex by this route is said to follow the **symplast** pathway. The walls of epidermal cells of young roots and the cortical cells of all roots are made from porous cellulose. Intercellular spaces also occur in the cortex. Consequently some water may be absorbed by the root hair wall from the soil and travel from cell to cell across the root cortex by capillarity through the air spaces and porous cell walls. Water crossing by this route is said to follow the **apoplast** pathway.

Before water can reach the xylem tissue in the centre of the root it must cross the endodermis. This is a continuous cylinder of cells which surrounds the central vascular tissue. Each endodermal cell has a layer of suberin (a fatty substance) impregnated in its four radial walls. This is the Casparian strip forming a continuous waterproof barrier, blocking the apoplast route. To progress further, water must cross the plasmalemma of the endodermal cells into the cytoplasm or vacuole before it can enter the xylem vessels.

> ***Exam hint -*** *Make sure that you understand the significance of the casparian strip. This forces water to move through the vacuole or symplast pathways. Movement through these routes is controlled by the selectively permeable membranes of the endodermal cells. The casparian strip therefore allows these cells to precisely control which ions enter the xylem*

A plant must exchange gases with the atmosphere around it in order to photosynthesise maximally. Most gases are exchanged in flowering plants via the leaves. Stomata, when open, allow carbon dioxide to enter and excess oxygen to exit the leaves. Water escapes at the same time. This loss of water from the shoot system of a plant is called **transpiration**. Transpiration creates a water potential gradient between the leaves and the root system, lower in the leaves and higher in the roots. This potential difference helps to bring water up the xylem from the roots to the leaves and out into the air. The following sequence of events summarises the events taking place to generate this upward movement.

1. Air flow around a leaf takes humid air away from open stomata replacing it with drier air.
2. A water diffusion gradient exists between the damp air in leaf air spaces and the relatively drier air outside. Consequently water diffuses out of a leaf into the air increasing the diffusion gradient between the damp spongy mesophyll cells and the air in the leaf spaces. As a result water diffuses from the mesophyll cells into the air spaces.
3. Loss of water from the mesophyll cells lowers their water potential relative to the xylem in an adjacent vein in the leaf. Thus water will diffuse from the xylem in the leaf into the mesophyll cells.
4. This lowers the water potential of the leaf xylem, relative to that in the stem and in turn that in the root.
5. Consequently water moves up the stem from the roots into the leaf and out into the atmosphere.

Attracting **cohesive** forces exist between water molecules so that a continuous column of water is maintained from the xylem in the root, through the stem and into a vein of a leaf. As water evaporates from the damp surface of a mesophyll cell, more is dragged up to replace it. This generates a force that is sometimes described as **shoot tension** and forms the basis for the cohesion tension theory to explain the movement of water through a plant. **Adhesive** forces also attract water molecules to the walls of the xylem vessels, also helping to maintain an unbroken column of water.

The force involved in the movement of water from the soil to the leaves of a flowering plant is therefore likely to have at least two components (i) an upward push (root pressure) and (ii) an upward pull (shoot tension). Fig 5 illustrates the transport of water through the plant.

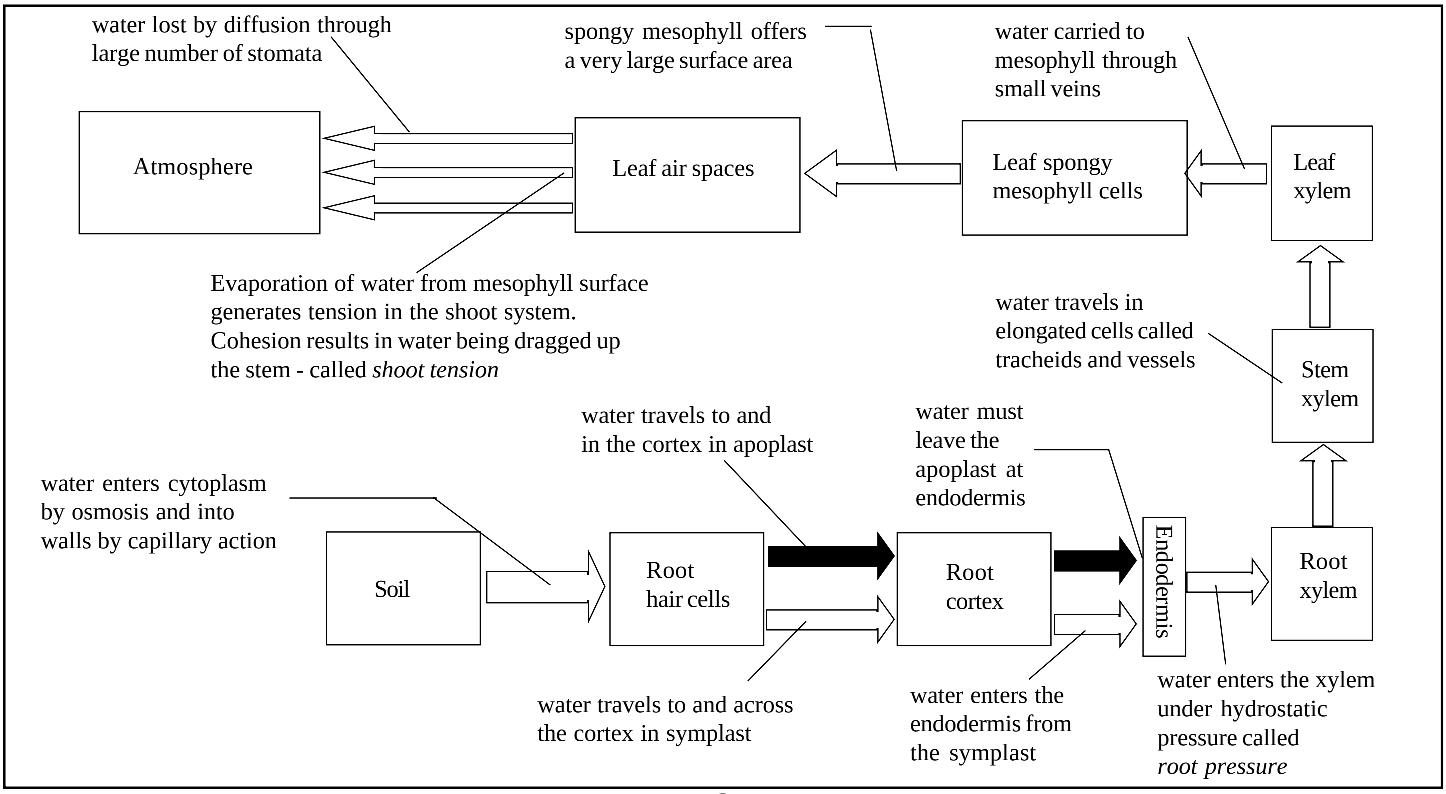
Transpiration and the effect of changing environmental factors.
Stomatal transpiration occurs when water evaporating from the mesophyll cell surfaces of a leaf diffuses, via open stomata, into the air around a leaf. Any environmental factor that affects rate of evaporation and diffusion must affect the rate of transpiration. Factors will include the relative humidity and temperature of the air and air movement. Increasing atmospheric relative humidity reduces the diffusion gradient between leaf and the air external to it, therefore the rate of transpiration will fall. Increasing air temperature will lead to more rapid evaporation and diffusion rate with consequential increase in the rate of transpiration. In windy conditions the moist air outside stomatal pores will be blown away maintaining a steep water diffusion gradient and therefore wind action will encourage greater loss by transpiration. Light also affects transpiration, but indirectly, the stomata of most plants being open during daylight hours and closed at night.

The cuticle of a plant is not totally impermeable to water and some can even escape through closed stomata. This loss is called cuticular transpiration, accounting for a limited amount of water only.

Translocation and the pressure-flow model.

Translocation moves food around a plant in a variety of directions. However, whatever the direction, movement always occurs from a sugar **'source'** to a sugar **'sink'**. A source can be any tissue or organ that is making sugar available to the plant. Examples of sources will include leaves where sugar is being manufactured or storage organs such as tubers or rhizomes where stored starch is being hydrolysed by enzymes. A sugar sink will be any tissue or organ that is actively using or accepting sugar. Prime examples of sinks are growing roots, shoot tips, flowers, seeds and any other organs storing food. This means of course that perennating organs including tubers and rhizomes will be sinks at certain times of the year and sources at other times. Phloem sap contains a variety of solutes, including amino acids, hormones, mineral ions, sugars and water. **Sucrose** concentration may be as much as 30% by weight.

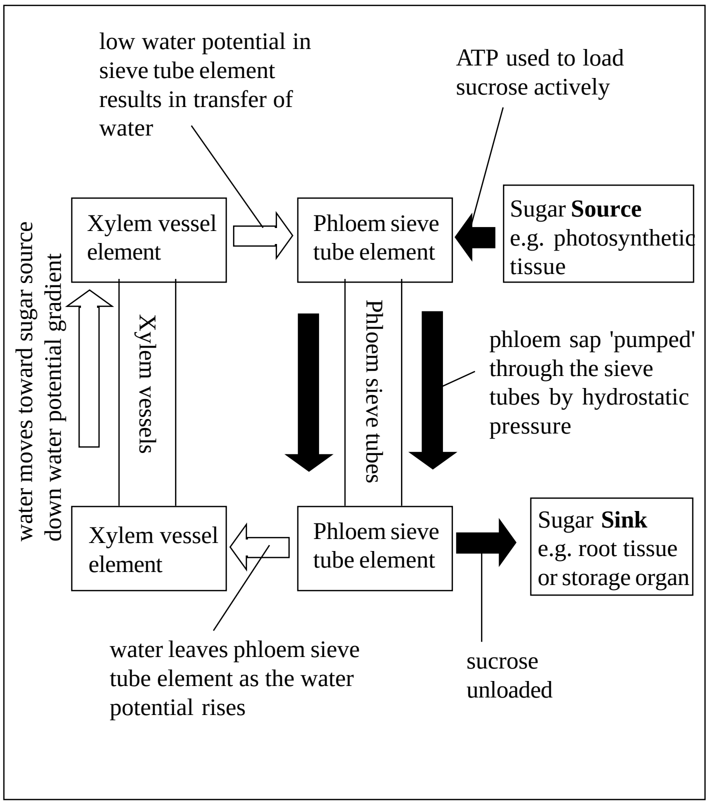
Fig 5. Water uptake and transport through the plant.



Sugar manufactured in photosynthesising mesophyll cells is loaded into phloem sieve tube elements. This involves moving sucrose through a series of plasmodesmata, linking cells between the mesophyll cells and the sieve tube elements. Many plants show sucrose concentrations in their sieve tube elements that are two to three times the concentration seen in mesophyll cells, suggesting that **active transport** is employed to enhance the loading of sucrose. One type of membrane protein hydrolyses ATP which in turn enables another membrane protein to transport sucrose across the membrane and into the sieve tube element.

Plant physiologists still have a lot to discover about the way phloem works as a tissue in moving organic substances around the plant body. However, one model which is currently more acceptable than others is the **pressure-flow model** which is illustrated in Fig 6.

Fig 6. Pressure-flow model to explain translocation



Loading sucrose from a 'source'into a sieve tube dramatically lowers the sieve tube's water potential at that location. Conversely, removal of sucrose from the sieve tube by a 'sink' raises its water potential. Consequently there will be a dramatic uptake of water by the sieve tube osmotically at the 'source-end' and loss from it at the 'sink-end'. This generates a gradient of hydrostatic pressure great enough to drive the phloem sap through the sieve tube from the 'source' to the 'sink'. Continuous removal of sucrose by diffusion or active transport for use by the 'sink' and replenishment by the 'source' maintains the pressure gradient needed to maintain this system of pressure-flow or mass flow. Water is recycled passing into xylem tissue from the sieve tube elements in the region of higher water potential adjacent to the 'sink', at the same time lowering the hydrostatic pressure of the sieve tube. Water, having moved up the plant, will leave the xylem, eventually passing into the sieve tube elements by osmosis, in the vicinity of the 'source' thus maintaining the necessary, raised hydrostatic pressure.

Experimental evidence to determine the route of movement of organic molecules in plants.

Evidence for the involvement of phloem in translocation comes from investigations including ringing experiments, the use of radioactive tracer elements and the use of excised aphid stylets (modified mouthparts).

- Phloem tissue lies just beneath the bark of a tree. When a strip of bark is removed, the phloem in that region is removed with it exposing the xylem. If the strip is continuous around the stem, phloem continuity above and below the 'ring' is lost. Downward movement of organic material including sucrose is therefore prevented, such solutes accumulating 'upstream' of the damage. This leads in the short term to enhanced growth and enlargement above the ring and long term, if the tissue below is non-photosynthetic, to the death of that tissue and probably the whole plant.
- $^{14}CO_2$ can be supplied to a plant. Photosynthesis fixes this into glucose that will be radioactive. Sucrose derived from this glucose will also be radioactive. Such labelled molecules can be traced and their progress through the phloem can be monitored.
- Aphids have mouthparts that are modified to form stylets. The insect employs these to locate and penetrate a single phloem sieve tube. As a result they are force-fed, the pressure-flow pumping the sucrose-rich sap into their bodies. Physiologists take advantage of these 'taps' by excising (cutting) the anaesthetised insect from its mouthparts. An excised stylet continues to 'bleed' sap for several hours after the insect's body has been removed. This allows the contents and the flow pressure of the sap to be monitored.

Practice Questions

1. The table shows some of the characteristics of two types of plant cell.

	Cell X	Cell Y
Structure	Hollow and dead when mature. Ends of cells overlapping. Have bordered pits.	Hollow and dead when mature. Form long cylinder as end cell walls break down
Length	Up to 10 mm	Stacked end to end, units stretch up to 1 metre
Width	10 - 15 µm	40 - 80 µm

(a) Identify cells X and Y. 2
(b) Suggest why flowering plants possess large amount of tissue formed from cell Y rather than from cell X. 4
(c) (i) Name the tissue in flowering plants where sugars and amino acids are transported. 1
(ii) Name the two main types of cell found in that tissue. 2
(iii) What is meant by the term 'mass flow'? 2

Total 11

2. One model used to explain how plants translocate organic solutes is called the pressure-flow model.
(a) This model uses the terms sugar 'source' and sugar 'sink'. Explain what these terms mean in the context of this model. 2
(b) Explain the mechanism suggested in this model to account for movement of solutes during translocation. 8

Total 10

3. (a) Define the term 'transpiration' 2
(b) Distinguish between each of the following pairs of terms:
(i) symplast and apoplast; 3
(ii) root pressure and shoot tension. 3
(c) Complete the table to show the likely effect of environmental factors on the rate of transpiration. 3

Environmental factor	Rate of transpiration
(i) Increase in air temperature	(i)
(ii) Increase in relative humidity of the air	(ii)
(iii) Increase in air movement around the leaves	(iii)

Total 11

Answers

Semi colons indicate marking points.

1. (a) X = tracheid; Y= vessel; 2

(b) large leaf surface area and many stomata;
results in much water loss by transpiration;
this must be replaced from transpiration stream;
vessels can transport greater volumes/faster than tracheids; 4

(c) (i) phloem; 1
(ii) sieve tube; companion cell; 2
(iii) the bulk transport of materials from one point to another;
as a result of pressure difference between the two points; 2

Total 11

2. (a) 'source' is any tissue or organ where sugar synthesis exceeds sugar consumption or storage/converse 'sink';
photosynthetic leaves are sources/storage roots/corms/bulbs/fruits are sinks; 2

(b) sucrose loaded into sieve tube element;
specific membrane proteins hydrolyse ATP to ADP;
energy made available to carrier protein which transports sucrose across the membrane;
water potential of sieve tube element drops dramatically so water enters osmotically;
the removal of sucrose at 'sink' results in increased water potential in sieve tube element;
ref to hydrostatic pressure gradient;
'loaded' phloem sap moves from source to sink;
water enters xylem at sink;
returned from xylem to phloem at source;
max 8

Total 10

3. (a) loss of water by evaporation from a plant;
in particular from the leaves/via stomata/lenticels; 2

(b) (i) in symplast water moves across cell membranes; and through cytoplasm; whereas in apoplast water moves through cell walls; and intercellular spaces; max 3
(ii) root pressure provides upward push; osmotic in origin; *whereas* shoot tension provides upward pull; generated by evaporation of water; and cohesive forces; max 3

(c) (i) increase; 1
(ii) decrease; 1
(iii) increase; 1

Total 11

Acknowledgements;
This Factsheet was researched and written by David Baylis
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