Improving water management in organic crop cultivation

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1 Introduction

1.1 Water on earth and in the atmosphere

The global water cycle gives a simple overview of how water associated with the soil, geological substrata, plants, animals and the atmosphere link to each other. As plants largely, but not uniquely, exploit water in the soil we need to understand how they are able to access this resource and know how large a volume is available. However, soil and plants also lose water to the atmosphere and hence the balance between these three parts of the cycle is critical for identifying whether and how the losses can be replenished, either in the short or long term. Water may seep through soil and into underlying rock strata, which can represent an important mechanism by which nutrients may be lost by leaching from the rooting zone of a crop. In some circumstances, this can be beneficial because it prevents the build-up of salts and the development of salinization. There are times when water needs to be removed from soils through constructed drainage schemes, for example, when there are barriers to natural drainage that cause waterlogging. This can prevent roots from exploring a sufficiently large volume of soil to anchor plants and capture enough mineral nutrients. If soils are not sufficiently permeable, incident rainfall may be so intense that water cannot infiltrate but flows from the field over the soil surface, which can lead to erosion and loss of mineral and organic matter fractions of the soil. We therefore have to consider both the static and dynamic aspects of water availability in the soil.

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1.1.1 Water, weathering and soil formation

The first step in the process of soil formation is the weathering of parent rocks. Water contributes to this process through both physical and chemical actions. The process of physical weathering splits both rocks and minerals but does not change their chemical composition. Water plays a critical role in the splitting of rock by getting into cracks, where it expands on freezing. In arid regions, differential expansion of minerals under the heat of the sun can also split rocks. The fragments formed are transported down from higher elevations into valleys by surface water. Here the fine material can be deposited as the flow of water slows, covering the valley bottoms and effectively levelling the topographical features. After small rocks, large fragments and gravels are deposited, sand particles, which range in size from 20[1] to 2000 μm, settle out. Finer particles, ranging in size from 2 to 20 μm, silt, can also precipitate out. Silt particles tend to have a relatively large surface area-to-volume ratio and hence are easily subject to weathering.

Chemical weathering involves the breakdown of minerals by hydration, hydrolysis and dissolution. The direct effects of water are greatly enhanced by the presence of protons or hydronium ions (H_3O^+) that are derived from organic and inorganic acids. Thus, eventually, even the sparingly soluble silicates are finally broken down. The rate of mineral degradation increases with temperature. Consequently, many tropical soils are strongly developed at greater depths than those in cooler climates but at the same time they may only provide an inadequate supply of essential plant nutrients. In contrast, weathering and soil genesis in colder regions only penetrate to shallow depths of the mineral stratum.

During soil genesis, soil-specific minerals are formed, but at later stages of development these may themselves degrade. Disintegration of solid particles liberates solutes, such as cations, silicic acid, and iron and aluminium compounds. Water transports these solutes together with colloidal solids deeper into the soil or even into the rock strata below. Disintegration, displacement, precipitation and leaching are essential parts of the soil-forming process that depend on water. In temperate-humid regions, for example with limestone parent material, the first step towards soil formation is the decalcification of the rock fragments. Calcium ions leach out and the pH decreases, resulting in the decay of 'primary' minerals and the formation of 'secondary' silicate minerals that belong to the 'clay' fraction. These fine particles are on average smaller than 2 μm. During clay formation the soil colour turns brown, with the colour being dependent on the amount of organic matter and the level of oxidation of iron and manganese oxides. With time, the clay may start to migrate within the soil from near the surface to a lower layer, a soil-forming process called 'lessivage'. Another process, 'podzolization', involves the breakdown of clay by chemical weathering, and the release of sesquioxides of iron and aluminium, which can leach along with soluble humic acids to deeper layers.

In these ways, characteristic soil horizons are formed that are diagnostic of distinct soil types. In arid regions, where soil water is more likely to be lost by evaporation, water flows up towards the soil surface during the more prevalent rain-free periods. As a result, any solutes transported from the subsoil are deposited in the surface layers.

Soil genesis is accompanied by the formation of soil structure, which also is essentially dependent on soil water. Water causes some clay minerals to swell and shrink; furthermore, the soil matrix can become further divided by planes of weakness or fissures. Ice lenses,

1. In many countries, the lower limit for the size of sand is taken as 50 μm.

formed by freezing temperatures, can separate the soil matrix into aggregates of characteristic size and form. Aided by the action of plant roots and mycorrhizal fungi, aggregates made up of sand, silt and clay-sized particles can be formed, which are cemented together by inorganic oxides, amorphous aluminosilicates and organic matter (Goss and Kay, 2005). Both roots and fungal hyphae release organic mucilage that under dry conditions can enhance the stability of soil aggregates (Reid and Goss, 1981, 1982).

1.1.2 Water storage capacity and the availability of water in soil

The space between the solid particles of the soil, both within and between soil aggregates is made up of pores of different effective sizes. It is within this pore space that the storage and movement of water takes place. Just as a sponge, a clod of dry soil will absorb water. Initially, the rate that the water is soaked up may be relatively rapid but it declines with time and will eventually stop. At that point the forces in the soil sample causing the water to enter the pore space within the clod are neutralized. These forces originate on the surfaces of clay particles as 'short range' London–van der Waals forces, the negative electrostatic forces associated with clay minerals and from the adsorbed positively charged counter ions. In addition to these forces, there are capillary forces that are the result of the adhesion of water molecules to the surface of solid soil particles and the cohesive forces between water molecules. In most soils, water wets the surface of particles, which causes the surface of the water within a pore to form a concave meniscus at its boundary with the air. In some dry soils, the nature of the organic matter covering soil particles prevents the surfaces from wetting and the water may form a convex surface, effectively preventing it from entering the pores.

Because of the complexity of soil pores in terms of their structure, particularly the pore necks created where, for example, three touching particles form part of the pore, some air is entrapped as a soil profile wets up during a rainfall event. Prolonged rain will eventually result in the soil becoming saturated with water. When the rain stops, water filling the coarser pores will start to drain from the soil profile and this will continue for some time. The volume of water retained by the soil 'against gravity' after two days of drainage without further rain is commonly referred to as the field capacity. In reality, the soil commonly continues to drain slowly for longer than two days, so the water content at field capacity is really just a convenient concept for calculating water storage capacity. The other important value is the limit of water extraction by plants, the permanent wilting point. At that point, the adhesive forces are too strong for plants to absorb any of the residual water remaining in the soil. The difference between these two water contents, field capacity at the wet end of the scale and permanent wilting point at the dry end, is identified as the soil water content potentially 'available' to plants. Available water content varies with proportions of sand, silt and clay that constitute the soil. These proportions define the textural classes to which soils belong.

The total porosity of the soil is simply the proportion of the volume of voids in the total volume of soil. The sizes, shapes and volumes of individual pores are defined by the spatial distribution of the solid component of the soils and their propensity to form compact or loose aggregates. Small mineral particles, with greater surface electrostatic potentials per unit mass, associate more closely and this causes a greater proportion of the total soil porosity to occur as smaller pores. Thus, the average equivalent diameter of individual pores varies among soils. Smaller pores will retain water more strongly than larger pores; this phenomenon is known as capillarity. The energy by which a capillary can retain water can be simply expressed in terms of hydraulic head as (Or and Wraith, 2000):

$$h(m) = 14.84/r(\mu m) \quad (1)$$

where h is the height that water rises in a capillary with a radius r. Thus, for two soils with equal total porosity, the one with a larger proportion of pores in the small diameter range will retain more water. On the other hand, coarse-textured soils, such as sandy soils, which have most of their pores in the larger size domain (e.g. Unc and Goss, 2006) hold water less strongly than the smaller, capillary, pores. Thus, in general, sands and clay soils have the least available water, with silt and silty-clay loams commonly having the greatest amount of available water (Fig. 1).

1.1.3 Drivers of water movement

In the previous section we described how water moves into dry soil and now we need to consider how the forces at the surface of soil solids combine with others to cause water to move through the soil. We have also discussed the movement of water from upland areas down into the valley. In many parts of the world, where there is a lot of water cascading from one level to another, a part of the energy in the moving water is captured to generate hydroelectric power. The potential of water to do work is greater in the uplands than when it has fallen to the valley and part of that energy released can be used for turning the blades of turbines. In an electrical circuit, the rate at which the charge moves (the unit is coulomb per second) is the current I (unit is ampere) that is related to the potential difference V (unit is volts) between the battery terminals. We can write an equation to describe the movement of the charge:

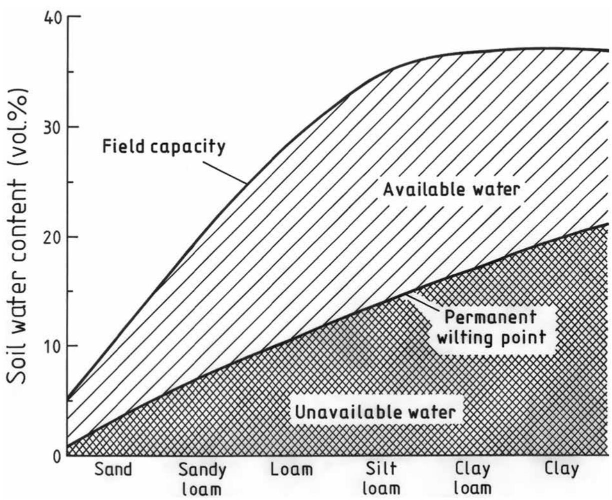

Figure 1 Changes in water content at field capacity and at the permanent wilting point as soil texture becomes finer from sand to clay. The maximum value of available water content occurs at the boundary between silt loam and clay loam texture.

$$I = V/R \quad (2)$$

where R is the resistance (unit is ohm = volt/ampere) in the wiring.

We can write a similar equation for water moving through the soil:

$$q = K(\Delta\phi/\Delta z) \quad (3)$$

where q is the volume of water moving through an area per unit of time (cm^3 H_2O per cm^2 cross-sectional area per unit of time), K is the reciprocal of the hydraulic resistance to flow, the hydraulic conductivity. The difference in water potential between two points in the soil is given by $\Delta\phi$, and this is calculated over a distance of Δz. If we make our calculations on the basis of the weight of water, this results in the unit for ϕ being centimetre, a unit of length. This can greatly simplify the calculations required to determine the flow rate of water, as the unit for K will be cm per unit of time.

As described above, ϕ is the total potential of the water. It is the summation of the matric potential, gravitational potential, the osmotic potential and the pressure potential. The matric potential results from the adsorption of water on the surfaces of mineral and organic materials constituting the solid matrix of the soil, as described above. As the soil dries, matric potential becomes the major component of the total potential. The gravitational potential results from the height of water above a datum position. Osmotic potential results from the presence of solutes dissolved in the water. For osmotic potential to play an important role the presence of a semipermeable membrane to separate two bodies of water is required. In the soil, knowledge of osmotic potential will therefore be important for water to be absorbed by plant roots, as the water has to cross the outer semipermeable membrane enclosing the cytoplasm of cells of the epidermis or the endodermis of a root (for more detail see Section 1.2). An air–water interface also acts as a semipermeable membrane, so under some circumstances the osmotic potential of the soil solution can be important for the loss of water by evaporation. However, even in soils subject to regular applications of soluble fertilizer, the concentration of ions in soil solutions is unlikely to influence the transport of water except in localized regions around fertilizer pellets applied when soils are relatively dry. Pressure potential develops if a water body is being compressed. In soils, the pressure potential is important for movement of water below the surface of the water table.

Equation 3 is known as the Darcy equation and establishes that a flow of water only occurs when there is a difference in its potential ($\Delta\phi$) between locations and the movement is from the point with the higher potential to that with the lower potential. The potential gradient ($\Delta\phi/\Delta z$) is the difference in potential divided by the distance (Δz) between locations, which could be, for example, the distance between two soil layers or soil horizons. If the topsoil is at equilibrium, no water movement takes place. If we measure the gravitational potential, Z, from the soil surface, the value of Z will decrease from Z = 0 cm to Z = −10 cm at a point 10 cm below the surface (Fig. 2). If we assume that ϕ depends only on Z and the matric potential (ψ), if there is no flow, there is no difference in total potential: $\Delta\phi$ = 0 cm. Then ψ at the soil surface (ψ_0) must differ from the value at 10 cm below the surface (ψ_{-10}) by −10 cm, that is, $\psi_{-10} = \psi_0 + 10$ cm (Fig. 2a). If rainfall then occurs, the potential of water at the soil surface will increase. The rainwater will be attracted to the particle surfaces but that also reduces the strength of the attraction forces, which become less negative and hence the matric potential approaches 0. In consequence, the potential gradient will increase from the soil surface to the point 10 cm below. Water will then start to flow downwards from the soil surface. Depending on how dry the soil was at the start of the

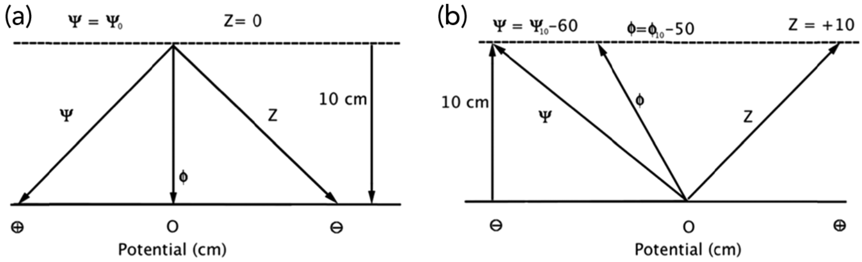

Figure 2 Components of the soil water potential under moist conditions. (a) Equilibrium conditions after rain. (b) Evaporation taking place at the soil surface.

rainstorm, the duration and intensity of the rainfall will determine the depth to which the soil wets. Some time after the end of the storm, the soil above a depth of 10 cm may reach a new equilibrium where no flow is taking place although the matric potential near the surface will again be 10 cm lower than that at the 10-cm depth. If water starts to be lost to the atmosphere by evaporation, the attractive forces at the surface of soil particles start to increase and the matric potential starts to decrease. In consequence, water will move upwards as the total potential gradient increases (becomes more negative) from the 10-cm depth (Fig. 2b).

We can now look at the field capacity and permanent wilting point in terms of matric potential. In soils with a deep unsaturated profile, and thus a thick layer above the watertable, the water held in pores at a matric potential of −330 cm is often taken as the amount at field capacity. This means that the largest water-filled pores are approximately 9 μm in diameter. At the permanent wilting point, the diameter of the largest water-filled pores is about 0.2 μm, so the matric potential is about −15 000 cm. In shallower soils, the water potential at field capacity may be closer to −100 cm, but the potential at the wilting point may be less affected. Although in reality these matric potentials for the maximum and minimum ends of the plant available water in a field soil are only approximate, they are convenient parameters to use for comparing soils in the laboratory.

The growth and productivity of crops can be affected by both the excess and lack of available water.

1.1.4 Subsoil drainage schemes

When climatic conditions are such that rainfall dominates the hydrologic cycle, the soil profile can become saturated and water drains below the depth that plant roots are able to exploit the resource. This allows the water to contribute to groundwater resources. Some soils, particularly those dominated by clay content, drain so slowly that the profile can become waterlogged, and this greatly impairs crop growth and production. Field drainage schemes, which consist of perforated pipe drains that collect the water from the top metre of soil, transport this water off the field to natural watercourses or constructed drainage ditches. The required spacing of the perforated drains depends on the hydraulic conductivity of the subsoil, and in deep clay soils this can require close spacing, which can be prohibitively expensive. If the clay can be moulded, it is possible to create temporary round channels in the soil, 'mole drains', by use of a mole plough. In poorly permeable soils, effective drainage schemes with closely spaced drains can be created by back filling the trench formed when inserting the pipe drains with gravel and then drawing the mole plough through the trenches and perpendicular to them.

Mole drains can function for 3–4 years and allow a spacing of about 2 m. The evidence from fall-sown field crops suggests that the aim of the drainage scheme should be to prevent the top 50 cm of the soil from remaining waterlogged (Belford, 1981) for extended periods. Critical durations for the waterlogging taking place at depths shallower than 50 cm depend on the prevailing temperatures, which control the rate at which the oxygen levels in the soil decline (Cannell et al., 1985). For spring-sown crops, such as pea (*Pisum sativum* L.), even two days of waterlogging can result in significant reduction in shoot growth, pod formation and seed development (Cannell et al., 1979), in part because of the warmer temperatures that prevail after the crop is sown in early spring.

1.1.5 Irrigation systems

To augment the water available through rainfall and snow, it may be necessary to irrigate crops, choosing from a wide variety of schemes.

In *flood irrigation*, water flows into the soil from a supply channel at a sufficient rate to adequately cover the soil. This approach relies on the formation of a flat, even surface with a very small slope to ensure the whole field receives water. The main drawback with such schemes is the large loss of water by evaporation from supply channels and from the flooded soil.

Border strip irrigation involves forming dykes parallel to the slope that enclose strips into which the crop is seeded in rows aligned across the slope. The rows of the crop help to spread the water across the strip.

Furrow irrigation requires the formation of furrows or dykes between individual or groups of crop rows that are sown on ridges or raised beds. The water infiltrates laterally into the ridges or raised beds, which have a greater hydraulic conductivity than the flooded soil in the furrows.

In *basin irrigation* an area is surrounded by a dyke that allows water to pond but prevents it from running off the field. Ponding helps to ensure relatively uniform infiltration into soils that have poor permeability.

Sprinkler irrigation requires more technical equipment and the water is supplied under pressure so that fine droplets can be formed to simulate natural rainfall. Lines of sprinkler jets can move automatically up and down a field to apply a uniform distribution of water. Alternatively, the line of jets can be arranged to form the arm of a centre pivot, uniformly irrigating circular or semicircular areas over which the jets pass.

For crops of greater market value, *drip irrigation* can be used with water being supplied to individual plants through a drip nozzle. By limiting the area of wet soil at the surface, the system reduces the volume of water lost by evaporation before it can be used by the crop and can focus the irrigation on the soil volume containing the plant roots.

Another method for reducing unnecessary losses is to supply the water via subsurface pipes, *sub-irrigation*. Some combined systems have been developed that allow the water intercepted by a drainage scheme to be collected in a holding pond and then to be used to sub-irrigate the crop when the available water declines (Tan et al., 1999; Bonaiti and Borin, 2010).

All of these techniques for irrigation need a clear understanding of the local hydrological cycle as it pertains to the specific crop being produced. That in turn requires a knowledge of the processes involved in water use by each crop.

1.2 The soil–plant–atmosphere continuum

As identified in Section 1.1, there are three interactive components important to the hydrologic cycle: the soil, the plant and the atmosphere. The previous sections have provided an overview of the soil component and now we consider the plant component.

The water potential within plant cells is dependent on the osmotic potential, which is related to the presence of mineral ions and organic compounds, such as sucrose in the vacuole. These solutes are osmotically active and lower the water potential within the plant cell. The reference level for the osmotic potential is pure water with no solutes. Osmotic activity of solutes assumes the presence of cell membranes: the plasmalemma, which separates the protoplasm from the external medium, and the tonoplast between the protoplasm and the vacuole. These cell membranes seem to behave as if impermeable to solutes but permeable to water; however, they are capable of the facilitated transport of ions and other solutes that allow the build-up of a higher solute concentration inside than outside the cell. This difference in concentration facilitates the movement of water across the membrane through special structural units, aquaporins, within it and in consequence lowers the solute concentration inside the cell.

In a fully turgid plant cell, the protoplasm (the cellular content) is replete with water. A turgid cell, together with those in close proximity, gives the tissue some rigidity, which in turn determines the form of herbaceous plants. When the cell cannot absorb more water it is unable to induce water movement towards itself. Under those conditions the total water potential (ϕ) of the cell is zero. The osmotic potential, Ω, that has drawn water into the cell is balanced by the reaction to deformation exerted by the cell walls and surrounding turgid tissue, resisting further expansion that is required to accommodate more uncompressible water. The result is that the cell contents become pressurized. This positive pressure, the turgor pressure, increases the energy level of the water. Expressing turgor pressure in terms of the unit volume of water establishes another component of water potential, the pressure potential, P. It has as a reference level the value for water at atmospheric pressure. In a fully turgid cell at equilibrium, the pressure potential is at a maximum:

$$\phi = \Omega + P \tag{4}$$

When plant cells are subject to extreme drying, some water remains under tension within the microfibrillar structure of the cell walls. This means that we should write Equation 4 as:

$$\phi = \Omega + P + \psi \tag{5}$$

where ψ is the potential resulting from the water attraction to a surface (matric potential), this time the surfaces are within the cell wall. However, when a cell is fully turgid, ψ will be zero. Hence:

$$P = -\Omega \text{ when } \phi = 0 \tag{6}$$

The uptake of water by roots and its movement within the plant do not rely on the expenditure of metabolic energy. The water simply flows from sites of higher potential to sites of lower potential. Water flow within the plant, from the epidermis of the root through the cortex to the xylem in the central stele, and from the stele to various organs of the plant, and finally from the leaves to the atmosphere, is caused by differences in total water potential, just as in the case of water flow through the soil.

Evaporation is important in the transfer of water from the soil and from the plant to the atmosphere. Hence, before continuing with the overview of water moving through the plant, we need to consider the process of evaporation a little further. For evaporation from the soil, water changes its state from a liquid to vapour at or near the soil surface. This change requires the input of energy, most of which comes from the radiant energy of the sun. The water molecules diffuse into the air and away from the soil surface, depending on differences in the vapour pressure. The key values here are the saturated vapour pressure of the air (e_s), which is the maximum value the air can accommodate and which depends on air temperature, and the actual vapour pressure (e). The difference between e_s and e (e_s – e) is known as the saturation deficit. The larger the saturation deficit the more water vapour can be held in the air mass. In addition to diffusion, the transfer of water vapour away from the soil will be much quicker if it takes place as a mass flow, also referred to as convection. Convective vapour movement can result from local heating of the air near the soil surface or can be caused by wind. All of these determinants of evaporation, energy supply, saturation deficit and convection, depend on the climatic factors that create evaporative demand or the potential evaporation. Evaporation from moist soil is influenced to a much greater degree by atmospheric conditions than by the characteristics of the soil surface.

Solar energy reaching the earth's surface, the global or total radiation R_T, arrives as short wave radiation, ranging between 300 and 3000 nm, and may be a little less than half that reaching the outer part of the atmosphere in more humid regions but can reach up to 70% of that value in arid zones with little cloud. The instantaneous value of R_T varies according to the time of day, cloudiness, atmospheric turbidity, season, latitude, slope aspect and altitude. The fraction of R_T reflected from the surface, the fraction r, (the albedo) depends on the colour of the surface and its roughness. Of the radiation that is absorbed, a fraction is re-radiated to the atmosphere in the form of long wave radiation (R_L). The net radiation, R_N, available to keep the air and soil warm and for use by plants in photoassimilation (photosynthesis) is given by:

$$R_N = R_T(1-r) - R_L \quad (7)$$

$$R_N = G + H + LE + A \quad (8)$$

where G is the energy flux used to heat the soil and H is the fraction used to heat the air.

Only a small part of the energy flux is used for photosynthesis, A, and the remainder of the net radiation goes into evaporating water, LE. The term LE, the latent heat flux, is made up of the latent heat of vaporization, L, with a value of 2.45 kJ g^{-1} at 20°C, and the evaporation rate, E g cm^{-2} day^{-1}. The heat of vaporization is required to change liquid water into a gas. The energy flux used for evaporation is only identified if some of it is taken from the evaporating body itself, which will cool down.

Potential evaporation can be calculated from the energy balance equation (Eq. 8) but when taking into account the ease of measurement it is better to combine it with the aerodynamic aspect. Penman (1948) developed such a combination method. The Penman equation for the daily evaporation from a water surface is given by:

$$LE_P = \frac{(\Delta/\gamma)(R_N - G) + LE_a}{\Delta/\gamma + 1} \quad (9)$$

for the potential evaporation rate, E_p (g cm^{-2} day^{-1}), we can write:

$$E_P = \{[(\Delta/\gamma)(R_N - G)/L] + E_a\}/(\Delta/\gamma + 1) \tag{10}$$

where Δ is the slope of the function of saturated vapour pressure versus temperature (mbar °C^{-1}); γ is the psychrometric constant (mbar °C^{-1}); E_a (mm day^{-1}) is a ventilation–humidity term, which takes into consideration the influence of wind speed and the vapour pressure deficit of the air on evaporation; and L, RN and G are as defined for Eq. 8.

As with the process of soil evaporation, three conditions have to be met for evaporation from a plant leaf. Within the leaf, water has to change from the liquid to the vapour phase, an energy-consuming process. Again, the energy comes from the radiant energy of the sun. Secondly, a drop in vapour pressure is necessary to start the diffusion of the water molecules in the vapour phase from the intercellular spaces of a leaf through stomatal pores and out from the confines of the plant. Finally, the water vapour must be removed from the leaf surface to the atmosphere. The latter occurs by diffusion across a thin boundary layer, but that transport is greatly enlarged by the mass flow driven by the wind.

Liquid water is supplied to the leaf through the vascular bundles, which are branched subdivisions of the conducting tissue of the stems and end in the mesophyll as a fine network. Vascular bundles contain the two conducting systems of a plant, the phloem that transports organic and inorganic solutes and the xylem that mainly conducts water and mineral ions. The main conducting units of the xylem in most crop plants are the vessels. As water comes to the end of a vascular bundle in a leaf it moves into the mesophyll cells. In some plants there is a really distinct layer of closely packed columnar cells with many chloroplasts, the palisade layer, and a layer of more loosely packed cells, the spongy mesophyll. In both cases, some water moves through the cells of the mesophyll to the epidermal cells. This outer layer of cells is typically covered with a waxy layer, the cuticle, that is not impervious to water and is responsible for some 3–5% of the total water lost from the leaf. However, the larger proportion of the water in the mesophyll evaporates from the cell walls into the intercellular spaces. The largest of these spaces are associated with structural pores in the epidermal layer, the stomates, and form the substomatal cavity. Stomates provide the main conduits for water vapour to escape from the leaf. Importantly, stomates are the essential openings for carbon dioxide (CO_2) to enter the leaves to be available for photosynthesis. Two specialized cells of the epidermis, the guard cells, form stomatal pores. Because of differential thickening of the cell wall, the guard cells subtend a large pore between them when fully turgid, but as the cells lose turgor pressure the pore size gets smaller. By closing their stomates, plants can greatly reduce their water loss as the supply from the soil declines. However, the closing of stomates also cuts off the supply of CO_2 for photosynthesis.

We can now track the pathway of water through the soil to the root surface, into the root and from there through the stem into the leaves and finally into the atmosphere, the transpiration stream. The component potentials in plant cells vary over a much greater range of values than do those in moist soil. Depending on how turgid the cells are, ϕ for plant cells is much lower (approximately −10 000 cm H_2O) than ϕ for moist soil (ranges between −100 and −1000 cm H_2O). As a consequence of the potential drop between soil and plant, the water will tend to move automatically from the soil towards the root. Once at the root surface it can be absorbed at any point along the root, although the specific water uptake rate, UR, will be greater in the region of the root hair zone, where on the one hand cells are not suberized as a means of impeding radial flow, and on the other hand the surface area of the root hair cell is enhanced by the presence of the hair and by the fact that the root hair can penetrate some distance into the soil away from the drier interface with the root.

Water may be absorbed into root hairs of the epidermal cells or, if the epidermis has been lost, by entering into passage cells of the exodermis as the root ages. In either case, water crosses the semipermeable plasmalemma of the cells and enters the cytoplasm. Once it is within the cytoplasm it can pass from cell to cell by diffusion through the plasmodesmata, which are cytoplasmic connecting strands that link cell through adjoining cell walls. This is the symplastic pathway. Alternatively, water can move through the cell walls and intercellular spaces of the root but not cross a plasmalemma without immediately entering the cells. As a bulk flow, water can be conducted between cells, along neighbouring cell walls or through intercellular air spaces. This route is called the apoplastic pathway. Some water may move across the root via a mixture of the two routes but always crosses the plasmalemma or even the membrane surrounding the internal vacuole of a cell, the tonoplast. This is known as the transmembrane pathway.

Regardless of which of these three pathways carries the water across the root it will eventually arrive at the innermost layer of the cortex, the endodermis, where it has to enter the cell cytoplasm because the apoplastic pathway is impeded by suberization of the cell wall. The flow of water into the xylem of the root from the endodermis is via the transmembrane pathway, where water moves because of the osmotic potential. The vessels of the xylem have no protoplasm and the water enters the apoplastic pathway. In this part of the apoplastic pathway it is the cohesion between water molecules that maintains a constant column of water between the root and the leaves. The evaporation of water driven by the vapour pressure deficit lowers the water potential in the leaves that then drives the water movement through the plant.

It is appropriate at this point to identify how much water is involved in evapotranspiration (ET) from a field over the main growing season. A potential ET of 700 mm per season is fairly typical in Europe and North America. So, from a 1-ha field that ET is equivalent to 7×10^6 L or 7000 t of water. In herbaceous plants, about 80% of the fresh weight is due to water, which is used to provide rigidity to the structure and a relatively small amount, about 1%, is used in photosynthesis. The main role of transpiration and evaporation from the leaf is to keep the leaf temperature from exceeding that which causes the efficiency of the CO_2 fixation process to decline. Evaporation from the soil will cool the soil surface and atmospheric boundary layer above it but will have less benefit for processes in the leaf compared with transpiration.

1.3 The soil water balance

All the water that is lost by evaporation from the soil (E) and is transpired by the plants (T) originates from the precipitation (W) falling on a field. Some precipitation falls onto leaf surfaces and evaporates directly rather than entering the soil; this is referred to as interception (I). Of the water that enters the soil some may drain to below the rooting zone of the crop and be lost (D), in quantities governed by soil hydraulic parameters as described in Sections 1.1.2 and 1.1.3. Some (R) may simply run off over the surface of the soil and enter a watercourse. Depending on the soil water storage capacity, there may be changes in the amount of water (ΔS) in the soil at any time. All these components can be expressed in terms of the equivalent depth (mm) of water

$$W = E + T + I + D + R + \Delta S \quad (11)$$

Determining E and I separately from T is difficult when the crop covers the soil and it is convenient to combine the values into the ET of the plants. From the field water balance, if run-off does not occur, then:

$$ET = W - \Delta S - D \tag{12}$$

In Table 1 the components of the water balance, identified in Eq. 12, are shown for a clay soil under winter wheat. The values were obtained from measurements in the field comparing crops grown following removal of the harvest residues or their incorporation by ploughing. The main difference was the greater water loss to field drains when the residues were incorporated, possibly because of greater conductivity of the topsoil resulting from the associated tillage. The Penman equation used to calculate potential ET assumes loss from a short grass sward and underestimates losses from a relatively tall crop, such as wheat by approximately 15% (Ehlers and Goss, 2016). In the experiment described, the values were between 0 and 21% underestimated.

1.4 Efficiency of water use by crops

The fact that stomates are the point of control for water leaving the plant, and consequently for CO_2 entering, draws attention to the efficiency with which the plant makes use of these two resources. The ratio of the dry matter produced by a crop (DM) to the amount of water used (WU) provides a measure of that efficiency. If we simply consider the amount of water that moves through the plant in transpiration (T), the ratio DM/T is the transpiration efficiency (TE), which can be expressed in units of grams of plant dry matter per litre of water transpired or kg dry matter per m^3 H_2O. However, from a crop management perspective it is easier to determine the ratio of amount of shoot dry matter produced to the total water lost from the field in ET. That is the water use efficiency (WUE). We could also take into account the other ways that the water, which landed on the soil, has been redistributed and left the field without directly involving the plants of the crop.

Table 1 Components of the field water balance of a clay soil under winter wheat. The harvest residues were removed or ploughed under. Measurements of soil water content and soil water potential were made from the end of tiller formation in spring until harvest. The potential evapotranspiration was calculated from an automatic weather station on the site and changes in water storage determined by neutron scattering. Drainage was calculated from downward flows based on soil water potential gradients. The water used by the crop was equated to the evapotranspiration term in the water balance equation

	Harvest residues removed	Harvest residues incorporated
Precipitation (mm)	148	148
Change in soil storage (mm)	−107 ± 10.5	−105 ± 2.2
Drainage	30 ± 1.3	44 ± 2.4
Water used by crop from water balance (mm)	225 ± 11.8	209 ± 4.6
Potential evapotranspiration using the Penman equation (mm)	204	204

Starting with the water use efficiency defined above we can write:

$$WUE = \frac{DM}{ET} \tag{13}$$

Remembering that the transpiration efficiency (TE) is DM/T and therefore DM = TET, we can rewrite Eq. 13 as:

$$WUE = \frac{TET}{ET} = \frac{TET}{E+T} = \frac{TE}{1+E/T} \tag{14}$$

In this equation E/T is the ratio of evaporation from the soil to the transpiration through the plant. We can therefore add the water lost to run-off and drainage into the water balance equation and can describe the water use efficiency for plant production WUE_p:

$$WUE_P = \frac{TE}{1+(E+R+D)/T} \tag{15}$$

and finally, if we consider water that has been used by competing weeds T_{weed} we can write:

$$WUE_P = \frac{TE}{1+(E+R+D+T_{weed})/T} \tag{16}$$

Equation 16 allows different management options to be considered to ensure that the water available to a crop can be used effectively. Ensuring that the maximum amount of water possible can be stored in the soil and not lost in run-off is clearly an important objective as is reducing evaporation when water is scarce.

2 Key aspects of organic farming affecting availability and use of water

The understanding of how water is stored in soil and used by crops allows us to consider how management practices can affect these key aspects.

2.1 Soil management

Clearly, any changes made to the soil can have considerable impact on both the potential for water to enter the soil and to be held available to crops. As indicated in Section 1.1.2 a key aspect in the storage of water is the distribution of pores of different sizes within the soil. These pores can be located within and between the structural units of the soil.

2.1.1 Soil structure

Organic matter is essential for the formation and stabilization of soil aggregates because of its binding and cementing properties. Increasing the organic matter content of soil is generally associated with improved soil structural stability because the aggregates are more resistant to tension-free water, so that pores between and within them are more stable. Fungal hyphae and roots can enhance the creation of soil aggregates by enmeshing soil mineral particles (Miller and Jastrow, 2000). Arbuscular mycorrhizal fungi (AMF) form symbiotic relationships with about 90% of land plants, including most but not all crop plants. The dead hyphae of these fungi, along with decaying root material, can form the core of soil aggregates (Goss and Kay, 2005), but living hyphae produce glycoproteins, glomalin and glomalin-related soil proteins (Wright and Upadhyaya, 1996; Rillig, 2004b), which enhance stability through their cementing properties. 'Sticky' by-products, such as polysaccharides, of the activity of both bacteria and fungi as well as the release of root exudates cement aggregates of soil mineral and organic particles and thus lead to greater aggregate stability. Any management practices that enhance microbial activity and thus the production of polysaccharides tend to give soil greater structural resilience. Importantly, when plants dry the soil during transpiration, the stabilization of soil can increase. However, just adding organic matter to soil is not sufficient to increase stability (Fig. 3a), so there is also an organic matter quality aspect. The increase in aggregate stability reduces their disruption (Fig. 3b) and enhances the infiltration rate (Fig. 3c). After rainfall, the infiltration was found to decline with bigger changes occurring in soil with greater stability (Fig. 3c). A small amount of particle detachment from aggregates, possibly in combination with organic matter, had a large impact on the ability of soil to allow water to infiltrate (Fig. 3d). The greater reduction in infiltration likely resulted from blocked pores, whereas the disruption of the more stable aggregates still permitted good infiltration (Fig. 3d). However, Reinhart et al. (2015) found that the relationship between stability of aggregates and infiltration was not constant and for larger aggregates it could even be negative. The effects of the variation in aggregate stability resulting from the different quality organic material on infiltration are evident from Fig. 4; the results shown in Figs. 3 and 4 are from the same study by Ekwue (1992).

Many comparative assessments of organic farms with conventional operations suggest that the soil organic matter (SOM) content is generally greater under organic agricultural systems, although that does not always have to be the case (Huntley et al., 1997; Trewavas, 2004; Crittenden and de Goede, 2016; see also Watson, Chapter 3). The general benefits to water management of maintaining a large SOM in soil are also evident in terms of water availability. SOM has the net effect of reducing soil bulk density (Hudson, 1994) and attracts water molecules to its surfaces. Even though some of the water associated with organic matter may not be available to plants, Hudson (1994) established that for soils ranging from sands to silty clay loams, the water content at field capacity was increased more by an increase in SOM than it was at the permanent wilting point, thus increasing the available water content. An increase in SOM not only enhances water storage in soil micropores, but the greater development of stable aggregates will also lead to a larger proportion of inter-aggregate spaces, soil mesopores. These pores hold water at relatively large potentials between −2.5 and −300 cm (Regelink et al., 2015) and hence are able to drain water more efficiently (Boyle et al., 1989). The presence of free-draining inter-aggregate spaces and channels formed by soil fauna, such as earthworm, reduces the risk of ponding with all the negative effects on infiltration, soil aeration and related chemical and biological functions.

A decline in aggregate stability can lead to a number of changes in soil structure, including the formation of surface crusts and a dense plough layer which may then be more easily compacted further by heavy machinery. Surface crusts are commonly produced by the energy of raindrops impacting soil surface aggregates and by the slaking and dispersion

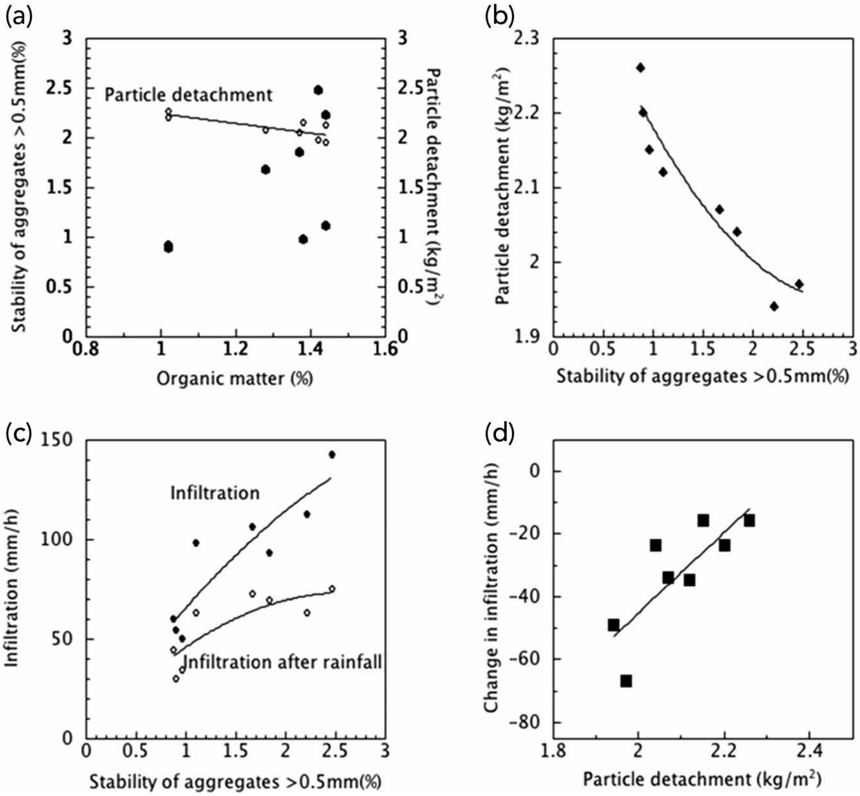

Figure 3 Importance of organic matter for soil structural stability and infiltration. (a) Relationship between soil organic matter and the stability of soil aggregates (closed circles). Although the stability tends to be greater at larger soil organic matter content, the values were not correlated. Nevertheless, the particle detachment (open circles) was inversely related to organic matter content (R2 = 0.89, $p < 0.001$). (b) Particle detachment is strongly related to aggregate stability. (c) Relationship between infiltration into soil and aggregate stability (closed circles) and after rainfall (open circles), the infiltration declined with bigger changes occurring in soil with greater stability. (d) The change in infiltration was inversely related to the amount of particle detachment. Based on Ekwue (1992).

(Folorunso et al., 1992; Carrizo et al., 2015) of soil particles in the presence of tension-free water on the soil surface. Importantly, surface crusts can greatly impair the infiltration of water from rainfall, irrigation or snowmelt, resulting in more loss in run-off from the soil. Surface sealing can have the same effect and can result from the surface application of liquid manure rather than solid manure (Unc and Goss, 2006). Increases in soil density in the plough layer horizon can result as the soil naturally consolidates with changes in soil water content, but it can also result from compaction due to wheeled traffic associated with sowing, pest and weed control, nutrient application and harvesting (Hamza and Anderson, 2005). The treading of soil by grazing animals, as well as when they are herded between paddocks, can result in soil compaction of grassland (Hamza and Anderson, 2005).

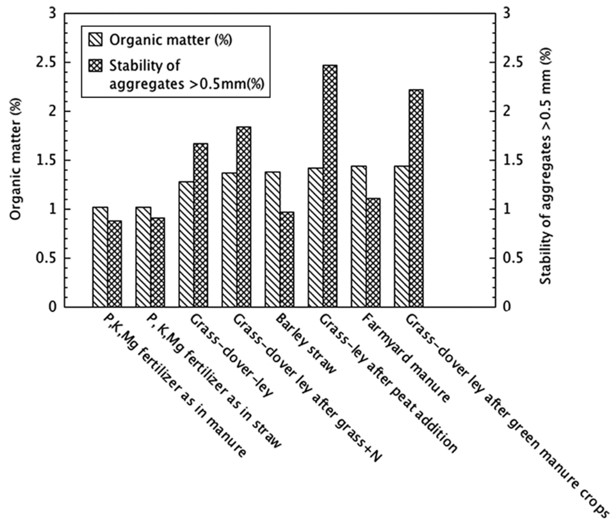

Figure 4 The variation in organic matter and associated stability of soil aggregates resulting from contrasting organic and inorganic amendments applied in agronomic treatments. Based on Ekwue (1992).

2.1.2 Tillage

Tillage systems have been designed to produce a suitable seedbed for crops as well as control weeds and incorporate organic amendments. What has been clear for more than a century (Sturtevant, 1887) is that the use of inversion tillage, for example, mouldboard ploughing, for weed control and seedbed preparation is detrimental to the soil. Much of the negative impact comes from the increased breakdown of SOM and the reduction in beneficial soil organisms, including AMF and earthworms.

In North and South America and the Mediterranean basin, no-till techniques have been developed and refined to plant crops without prior tillage and restricting any soil disturbance to the layer above the depth of seed placement. As no-till soils are cooler and wetter in the early spring season, this can lead to retarded and reduced mineralization and nitrification. Consequently, in Northern Europe emphasis has been more on shallow or reduced tillage practices (e.g. Crittenden et al., 2015). In both cases, the lack of inversion allows retention of harvest residues on the soil surface to protect it from raindrop impact, slaking and dispersion, thereby enhancing infiltration and reducing the risk of both wind and water erosion of the soil.

Although tillage may lead to an immediate increase in total soil porosity in the tilled layer, mainly in form of larger inter-aggregate pores (Lipiec et al., 2006), this is often counterbalanced by more compaction in the subsurface soil layer in comparison with a no-till management (Tebrügge and Düring, 1999). Moreover, tillage-induced soil porosity is not resilient as the plough layer compacts easily during the growth season especially when using heavy machinery. On the other hand, repeated mechanical disturbance and enhanced aeration due to repeated tillage increase the breakdown of SOM and thus breakdown of soil aggregates with the concurrent loss of the biological functions associated with the lost aggregates (Jiang et al., 2011). This can cause soils to consolidate and become compact more readily after tillage (Tebrügge and Düring, 1999), eventually causing them to have a smaller water storage capacity. Moreover, consistent tillage at a given depth can lead to formation of a compact layer, a plough pan, that delays or stops water infiltration into the deeper soil layers, reducing the water storage in the entire soil profile, often leading to water saturation and erosion of the top layer. Nevertheless, by omitting intensive tillage, efficient weed control, especially of perennials, is limited under conditions of organic farming in temperate-humid climates (Zikeli and Gruber, 2017). Future strategies involving the occasional no-till seeding of grain legumes (Massucati and Köpke, 2011) and the use of 'bioherbicides' (Giepen et al., 2014) applied with precision farming measures (Ammann, 2009) may help to overcome these limitations.

Earthworms are commonly classified according to their lifestyle. Epigeic earthworms live close to the surface, where they are important for incorporating surface litter into the soil. In contrast, anecic species live within the soil and characteristically form vertical burrows that are permanent and can be important in the rapid infiltration of water to depth (Ehlers, 1975). The anecic group will collect material from the soil surface, and pull it deep into their burrows before eating it, but they will explore the different layers for nutrients. Endogeic earthworms also tend to live below the surface but their burrows are mainly horizontal within a soil layer and are not permanent. Differences in earthworm numbers and in the predominance of different groups can exist within fields under the same management treatments, largely because of the impacts of tillage (Crittenden and de Goede, 2016). Differences in earthworm populations between management systems also tend to reflect the intensity of tillage (Ehlers, 1975; Barnes and Ellis, 1979; Berry and Karlen, 1993; Crittenden and de Goede, 2016), the length of leys (Scullion et al., 2002; Han et al., 2015) and extent of natural and improved grassland (Fraser et al., 1994). Scullion et al. (2002) found in an extended survey that the most consistent difference between organic and conventional farmland was the biomass of the earthworm population, which was more frequently greater under organic soil management. However, the smaller biomass under conventional management comprised fewer but more mature individuals. No consistent differences between these management systems were found in the deep burrowing anecic worms, which contrasts with the consistently smaller number in ploughed soil compared with no-till land (Ehlers, 1975; Barnes and Ellis, 1979).

One other important tillage practice is the use of equipment to minimize the slope and to guide water to areas where it can be used, thus managing water storage and preventing run-off. Repeated contour tillage enables a semblance of terracing to be developed. Forming laneways that can be put under permanent cover (grassed waterways) can prevent uncontrolled and potentially erosive water loss. On a smaller scale run-off zones can be guided into pits prepared for individual or groups of plants, called the Zaï farming approach.

2.1.3 Nutrient supply

A key aspect of the field water balance is the proportion of water passing to the atmosphere in transpiration relative to that evaporated from the soil surface. In the leaf, there is a balance between the water that passes out through the stomates and the inwards diffusion of CO_2. The factor that influences the relative water loss from the soil through evaporation and transpiration is the proportion of the soil that is shaded by leaves, strictly the area of green leaf covering unit area of soil, the leaf area index (LAI). As a plant canopy develops, the area of ground covered increases with each new leaf but quite quickly the newer leaves shade a part of the older leaves so the LAI increases more slowly. In field crops, once the ground is fully shaded by the leaves, the radiant energy will largely be used in transpiration of water by the plant rather than evaporation from the soil. The rate of development of LAI at the start of the main growing season is therefore important for the effective use of water in the soil. When the LAI has a value of 1, the transpiration rate of the plant is about 40% of its maximum potential.

Depending upon the crop, as LAI reaches a value between 3.5 and 4.5 its transpiration is about 90% of its maximum potential rate. Over this same range of LAI, the net radiation component of soil evaporation may decline by 3–5% of its maximum potential rate, with a further reduction associated with the aerodynamic term (Ritchie, 1972). Both the LAI and the net assimilation rate of the leaves depend on the nutritional status of the plant. Although nutrients can be supplied to conventionally farmed crops as very soluble mineral fertilizers, organic operations depend on materials that need to be mineralized or are only sparingly soluble. In consequence, this could be an important constraint to optimizing production if the start of the growing season is cool and wet. As organic matter releases its nutrients more slowly over the growth season this can limit the development rate of LAI. Improved yields have also been the result of extending the period for which leaves remain green, which may also require enhancing the nutrient supply towards the end of season or preventing early senescence from pest and disease attack.

The selection of crops and the means to protect them against competition, pests and diseases is the purpose of cropping systems.

2.1.4 Crop rotations

Crop rotation is the ordered and planned cycling of crops over time in an arable field; the crops tending to be grown in pure stand with the plant species involved being annuals, biennials or perennials (Ehlers and Goss, 2016). Ideally, the crops selected will make optimum use of the local environmental conditions, taking account of solar radiation, temperature, water supply and soil fertility. Consideration needs to be given to having species that contrast in rooting habit, such as depth and form (tap or fibrous root system). In this way, a crop can take up nutrients that leached below the rooting system of a predecessor. Taproots can generate continuous pores in the soil that can provide pathways for roots of subsequent crops (Cresswell and Kirkegaard, 1995; Han et al., 2016) to access water held in subsoil horizons by avoiding the penetration resistance of the bulk soil (Gaiser et al., 2012). The biopores produced may also allow water to infiltrate rapidly to depth (Cresswell and Kirkegaard, 1995; Kautz, 2014). Fibrous root systems are commonly considered to support soil aggregation and the stabilization of structure, thereby increasing water-holding capacity.

The crops selected may be sequences of plants, all providing saleable components, such as seed, edible leaf, stem fibres and storage roots, or include crops that are grown to enhance or protect the soil. The latter may not be grown 'in season', so that they will not survive over a cold winter, but their shoots will still protect the soil from raindrop impact and the nutrients taken up during their growth period will be recycled. Staple crops, such as wheat, barley, maize, oilseed and grain legumes, may form the main focus of the rotation, but mixtures, such as alfalfa-grass or grass-clover, may also be grown for fodder and support sustainability goals.

In North America and Europe, winter cover crops have been extensively investigated as a means of protecting the soil from the erosive forces of wind and water as well as to increase SOM, thereby enhancing water infiltration and storage. Some of the species used include those that are grown out of season, such as spring oat, but others, such as rye, have to be killed before the next crop can be sown. There is evidence that, with the appropriate selection and prolonged use of winter cover crops, there can be significant increases in SOM, particularly if associated with no-till (Blanco-Canqui et al., 2011, 2015). The greater SOM content can also be associated with improved stability of soil aggregates (Hermawan and Bomke, 1997). Folorunso et al. (1992), working with soils that tended to form a surface crust, observed considerable reductions in the surface strength in the presence of cover crops compared with their absence. Abdollahi and Munkholm (2014) found that the resistance to penetrometer was significantly ($p < 0.05$) smaller between 32 and 38 cm below the soil surface where the brassica cover crop fodder radish (*Raphanus sativus* L. var. *oleiformis*) had grown than where it was not. In their experiment, the compacted zone was associated with a plough pan, considered to have predated the reported experiment (Abdollahi and Munkholm, 2014). In a related experiment, total porosity and air-filled porosity for pores >30 μm diameter at 12 to 16-cm depth in the plough layer horizon were significantly reduced under reduced tillage systems (no-till and harrowing). Irrespective of the tillage treatment, Abdollahi et al. (2014) found that growing a winter cover crop created continuous macropores, which enhanced permeability to air and water and reduced the impedance to root growth. Chen and Weil (2010) investigated root growth of cover crops through compacted soil and found that the best penetration was observed for fodder radish followed by rapeseed, whereas rye was the least effective. In their experiments, Folorunso et al. (1992) found that either the steady-state rate of infiltration or the cumulative total of water infiltrated over 6 h was greater with cover crops than without. The residues from cover crop shoots can provide a mulch to reduce soil evaporation, aid infiltration as well as reducing run-off (Blanco-Canqui et al., 2012) and provide protection from erosive forces (Unger and Vigil, 1998). The plants can also help dry the soil surface layers in spring to aid early planting (Unger and Vigil, 1998).

Cover crops can also help in controlling weeds by competing with their seedlings for light, water and nutrients (Teasdale and Mohler, 2000; Kolodziejek and Patykowski, 2015) or by the release of allelopathic chemicals (Reberg-Horton, 2005; Blanco-Canqui et al., 2015). The physical presence of mulch comprised of cover crop material can adversely affect weed emergence, depending on the proportion of the ground being covered (comparable with LAI) and the solids component of the material (Teasdale and Mohler, 2000).

Pathogen and pest control are important factors in selecting crops and the order in which they are to be grown. Selections can be made to prevent pests and diseases building up in the soil and locality by separating two susceptible crops with one that is not susceptible.

3 Developments in water management in organic agriculture

Many aspects of agricultural production require change if there is to be sufficient food to meet the demands of another almost two billion people by 2050. The land area required for production is declining because of urbanization and land degradation. Salinization, compaction and desertification of soils are increasing and we recognize the damage to the earth that is associated with the clearing of forest. Furthermore, the land that could be brought under production is often marginal for arable agriculture. The conclusion is that the productivity per unit area of land has to increase. At the same time, farms have to grow more produce but without further impacting the wider environment or creating food that is itself of poor or even harmful quality. The build-up of toxic metals in soil and activities that can lead to increased levels of antibiotic resistance genes in soil microbes have to be prevented. Solutions have to be found to prevent invasive species taking over as new weeds and halting the threats to crops or stored produce from migrating insects. But this cannot be at the risk of harmful effects to wildlife or humans. Contamination of water resources with plant nutrients, pharmaceuticals and hormonally active compounds has to stop. More importantly, the concerns over water resources for agricultural production continue to mount as the competition with the supply of potable water for cities becomes more acute.

The required intensification of production must extend to those areas, where at present it is resource limited and levels must be maintained where the impacts of agriculture have contributed to global warming and environmental degradation. Plant breeding is vitally important so that improved water use efficiency can come from enhanced transpiration efficiency as well as from more efficient irrigation, crop protection and weed control. Additionally there is a need to enable plants to be more effective in growing in soils with increasing levels of salinity.

3.1 Managing soil limitations through enhanced soil biodiversity

One of the most exciting developments in the last twenty years has been the ability to identify the different groups of organisms that interact within the rooting zone of plants. The new generation of molecular techniques allows the components of local food webs, previously hidden in the soil, to be identified and quantified. The understanding of the roles that different groups have in the soil is beginning to make possible the identification of practices, which can be adopted in arable agriculture (Goss et al., 2017). Local soil and environmental conditions and plant species will likely influence the range, diversity and functioning of microorganisms across the soil–plant continuum (Tahtamouni et al., 2016). Soil management practices that favour stable microbial ecosystems may be critical for long-term sustainability of agricultural production (Lucero et al., 2014). Landmark papers have identified the critical activities of AMF in natural ecosystems that determine the community dynamics of higher plants (van der Heijden et al., 1998; Helgason et al., 1998; van der Heijden and Horton, 2009). Meanwhile, the contribution that AMF make to enable their host plants respond positively to threats from both biotic and abiotic stresses is becoming clearer, as is the range of abiotic stresses that plants can gain protection against through their symbiotic community. These contributions include resistance to drought (Augé et al., 2001; Augé, 2004), salinity (Liu et al., 2016), toxic metals (Ahmed et al., 2006) and metalloids (Alho et al., 2015), enhanced supplies of nutrients (Al-Karaki and Clark, 1998) and defence against soil-borne pathogens (Akhtar and Siddiqui, 2008). There is also evidence that weed competition can be affected (Qiao et al., 2016). But we also know that there are interactions in the soil between AMF and other organisms, particularly the so-called helper-bacteria, which enhance the potential for AMF to colonize new plants and improve their ability to support the host. A key development has been the recognition that, via the fungal component of a mycorrhiza present in the soil, many host plants can be linked together and communicate with each other. It appears possible that knowledge of one host being attacked is communicated to all linked hosts, which then start the process of initiating production of compounds that can counter the perceived threat.

The practices that provide most support for AMF can be divided into those that make the soil more amenable to their survival and those that provide more mycotrophic hosts (Goss et al., 2017). Reduced non-inversion tillage and no-till cultivation dominate the first category together with the retention of harvest residues. Critical in the second category is the development of rotations that sequence crops, which are members of the grass family (Poacea), with dicots, particularly legumes (Fabaceae), together with using cover crops to prevent soil being devoid of growing plants for extended periods. Non-mycorrhizal break crops in the rotation have to be followed by strongly mycorrhizal plants to maintain the efficiency of the whole system.

4 Conclusion

Improvement in water management in organic production systems requires the adoption of practices that would be considered appropriate for building soil quality with respect to nutrients: build the organic matter levels in the soil and protect it from the effects of erosion and excess wetness. The move away from inversion tillage, always using the mouldboard plough, to shallower soil disturbance, which keeps residues on the surface, balances the adoption of selected rotations that can include cover crops. The evidence points to these practices building SOM; supporting stable, functional, microbial communities and preventing and alleviating compaction and erosion. These approaches help to reduce run-off and support better infiltration and storage of rainwater and irrigation water. The choice of tillage system, crops and cropping sequences can also help in the integration of AMF into the farming system, which can help protect the crops not only from water shortage but also from many other biotic and abiotic stresses.

5 Where to look for further information

The following organizations are involved in research related to soil conditions and plant growth applicable to organic agricultural practices:

ETH Zurich University (https://www.ethz.ch/en/the-eth-zurich/sustainability/research-for-sustainable-development/natural-resources.html)
Rodale Institute (https://rodaleinstitute.org)
The Organic Agriculture Centre of Canada - Dalhousie University (https://www.dal.ca/faculty/agriculture/oacc/en-home.html)
USDA Agricultural Research Service National Laboratory for Agriculture and The Environment (https://www.ars.usda.gov/midwest-area/ames/nlae/)
USDA Natural Resources Conservation Service (https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/water/)

Specific information on water and plant production is contained in Ehlers, W. and Goss, M. (2016). *Water Dynamics in Plant Production*. 2nd Edition. CAB International, Wallingford, UK. This book contains an extensive reference list on water in the soil–plant–atmosphere continuum and also gives an account of the processes of water requirements together with water uptake and use by crop plants.

The potential for supporting the role that mycorrhizal fungi play under modern agricultural practices is evaluated in the *Functional Diversity of Mycorrhiza and Sustainable Agriculture. Management to Overcome Biotic and Abiotic Stresses*, written by Goss, M. J., Carvalho, M. and Brito, I. (2017). Academic Press, Elsevier, San Diego, CA, USA. Further developments will be available through the Institute of Mediterranean Agriculture and Environmental Sciences, University of Évora, Portugal (http://www.icaam.uevora.pt.).

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