Chapter 13
Water Acquisition by Roots From the Subsoil: Impact of Physical Constraints on the Dynamics of Water Capture

Wendy H. Vance and Stephen P. Milroy

Abstract Physical subsoil constraints, such as high soil strength, low porosity or unfavourable pore characteristics, impair crop water use, either through effects on water availability or the ability of the crop to access the water. By reducing the capacity of the soil to store water or by impeding infiltration or drainage, physical subsoil constraints can alter the availability of water to the crop. By delaying root exploration, reducing ultimate rooting depth or reducing the efficiency with which water is extracted from a soil zone, they can reduce the crop's ability to access water present. The resultant impact on crop water use is modulated by factors including the amount and distribution of rainfall, the soil's water holding capacity and the depth and severity of the constraint. While the processes by which subsoil constraints influence crop water uptake are generally well-understood, important aspects still need clarification or quantification. There are still many questions regarding processes of water transfer from the bulk soil to the roots' vascular elements. New knowledge will need to be effectively linked with our understanding of water uptake at the scale of the crop or soil profile. There is also a need to improve knowledge of the influence of agronomic management on pore size distribution, continuity and stability in terms of their influence on root system development. Finally, simulation studies that evaluate the interaction of access to water with differing soil types and climatic zones will provide important extrapolation to allow the agronomic importance of subsoil constraints to be quantified in the context of inter-annual variation in rainfall distribution.

W. H. Vance (✉)
Centre for Sustainable Farming Systems, Food Futures Institute, Murdoch University, Murdoch, WA, Australia
e-mail: W.Vance@murdoch.edu.au

S. P. Milroy
Centre for Crop and Food Innovation, Food Futures Institute, Murdoch University, Murdoch, WA, Australia
e-mail: S.Milroy@murdoch.edu.au

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13.1 Introduction

The availability of an appropriate supply of water is fundamental to crop productivity. On the one hand, subsoil constraints impact the amount and dynamics of water available to plants and, on the other hand, constrain the capacity of the plant to access the water that is there. In the context of optimum plant growth, physical subsoil constraints are those which impede water movement or root growth into or within subsoil layers, thus constraining access to both water and nutrients. The definition of the subsoil varies; usage differs between regions, soil types and disciplines. Here we adopt the functional definition of Oliveira and Bell (2022) given in Chap. 1: the subsoil is the zone below the topsoil (up to 0.2 m depth) where cultivation, fertiliser placement and soil sampling do not normally occur.

Water moves along the soil-plant-atmosphere continuum due to differences in water potential. Firstly, transpiration is driven by the difference in water vapour pressure in the atmosphere compared to that inside the leaves; the water loss generates a lower water potential in the leaf. This then drives water movement through the plant from the roots (Lambers et al. 2008). Similarly, depletion of soil water due to uptake by the roots generates a gradient in soil water potential that drives the movement of water from the bulk soil to the plant roots (Bengough 2003). Soil structure, porosity, pore size distribution and pore continuity can all affect both the storage of water in the soil and the movement of water from the bulk soil to the roots. Further, roots have to be able to adequately explore the soil volume and maintain effective contact with the soil matrix to enable water uptake by the root. Any changes in soil condition that alter these traits have a fundamental impact on the crop water use and hence crop performance (Tinker 1976; Hamblin 1986; Ritchie 1981; Bengough 2003; Jin et al. 2013; Ahmed et al. 2018).

The impact of subsoil impediments and their alleviation on water uptake and hence yield of crops have been extensively studied. For example, Schneider et al. (2017) conducted a meta-analysis of 1530 yield comparisons across 67 experimental sites, where some form of deep cultivation had been applied. The strongest drivers of yield benefit were as follows: the presence of soil layers which restricted root growth, the surface soil texture and limited water availability. These factors interacted so that the benefit of disrupting a root-restricting layer was generally greater under conditions with limited water availability. This analysis emphasizes the importance of restricted access to water as a process through which subsoil constraints limit yield.

The main components influencing water supply and demand by a crop are outlined in Fig. 13.1. These interact over time to determine the water balance of the crop and the significance of the water balance for final crop performance. In this chapter, we will use a field-based definition of the plant-available water-holding

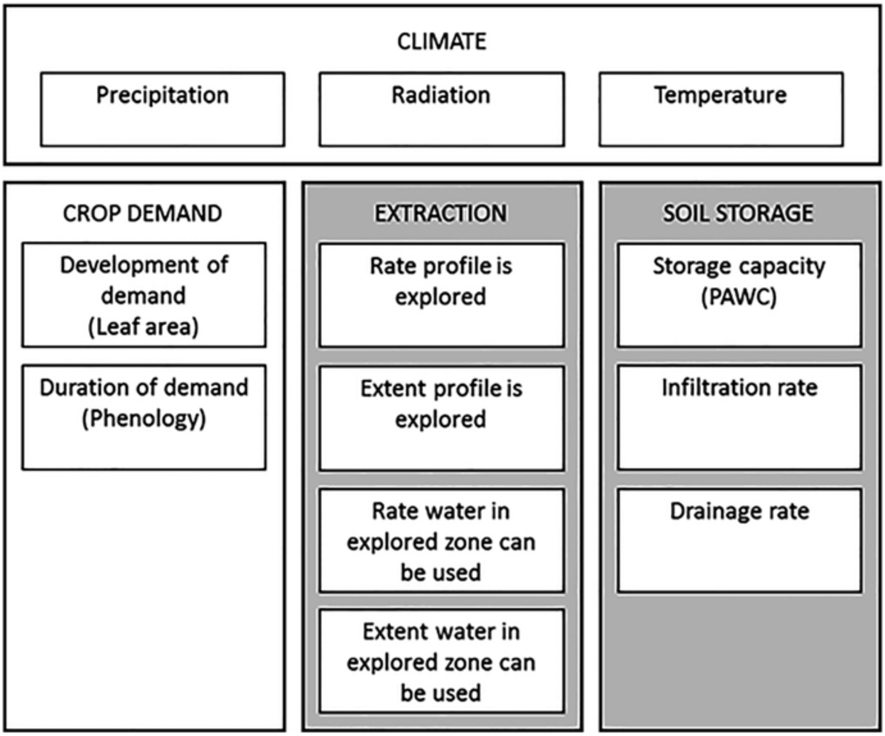

Fig. 13.1 Components contributing to the water supply and demand of a crop. Components grouped in shaded boxes may be influenced by subsoil constraints

capacity (PAWC) of a soil (Dalgliesh and Foale 2005). The PAWC is that water held between the drained upper limit (DUL) and the crop lower limit (CLL). The DUL is the water content when wet soil has drained under gravity to a relatively stable state. The CLL is the water content beyond which the crop is unable to extract further water (Dalgliesh and Foale 2005). The DUL is a function of soil characteristics only, whereas the CLL is determined by the interaction of crop and soil traits (Hochman et al. 2001; Dalgiesh and Foale 2005). Subsoil constraints may alter a number of characteristics that impact on either DUL or CLL and hence PAWC. Extraction of water by the crop root system will be considered in terms of the conceptual framework presented by Meinke et al. (1993) based on the work of Passioura (1983) and Monteith (1986). The exploration of the soil profile is described by the rate of vertical root descent and the maximum rooting depth achieved (Fig. 13.2). Once roots enter a given soil layer, water extraction can be described by an exponential decline with time from the DUL to the CLL for that layer (Fig. 13.3). Each of these processes can be modified by subsoil constraints or their amendment. There are a diverse range of potential interventions which aim to improve water acquisition by plants and which can be particularly valuable in the case of subsoil constraints. These interventions aim to improve soil structure,

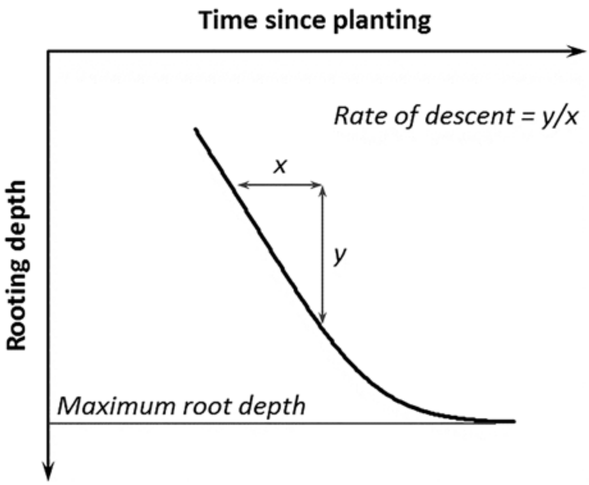

Fig. 13.2 Increase in rooting depth of an annual crop with time since planting. The increase in rooting depth often slows or stops around the time of flowering or the start of seed filling

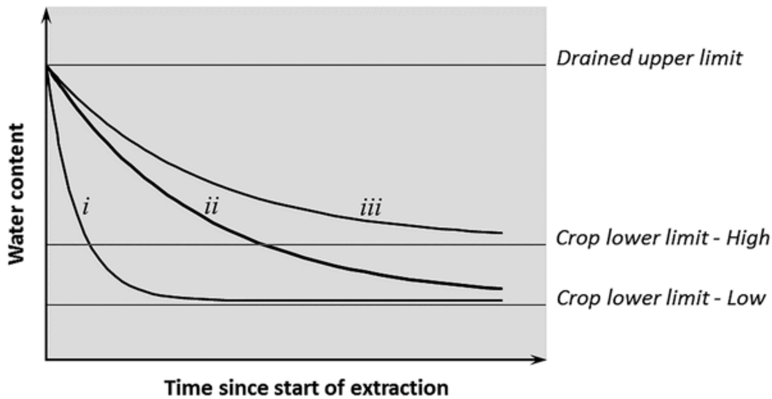

Fig. 13.3 Extraction of water from a layer in a profile after that layer is accessed: (*i*) high rate of extraction and low lower limit, (*ii*) low rate of extraction and low lower limit and (*iii*) low rate of extraction and high (less dry) lower limit

increase root elongation into the subsoil, increase plant-available water or improve access to the water present. Management tools may either involve direct interventions or agronomic management approaches to change the physical structure of the soil, or they may utilize better adapted plant genotypes to improve crop performance under constrained conditions (Table 13.1). Important aspects of the impact of physical subsoil constraints on root system development and function have been discussed in Chap. 6 (Oliveira and Fernandes 2022) and Chap. 8 (Scanlan et al. 2022). For completeness, some of these ideas will be briefly mentioned first.

Table 13.1 Interventions to improve water acquisition by plants in soil with physical subsoils constraints

Physical interventions: to change the physical structure or the soil			
Intervention	**Mechanism**	**Impact**	**References**
Subsoil cultivation	Removal of plough pan or hard layer impeding vertical root exploration. Improved infiltration	Earlier root exploration of deeper layers. Increased plant-available water-holding capacity. Increased available water	Hamza and Anderson (2003, 2008), Sadras et al. (2005), Mohanty et al. (2007), Barraclough and Weir (1988), Tardieu (1994)
Subsoil cultivation	Removal of impeding layer increases root length density in lower layers	Improved root proliferation at depth	Munkholm et al. (2008), Chen et al. (2014)
Compaction	Imposed compaction, reduce excessive drainage	Increased availability of water	Singh et al. (2014)
Agronomic interventions: to improve root elongation into subsoil			
Crop rotation: biological subsoiling	Large rooted species penetrate hard layers	Increased root length density at depth	Guaman et al. (2016)
Crop rotation: primer plants	Species with vigorous root systems penetrate deeper into subsoil	Increased stability and continuity of biopores. Improved root proliferation in subsoil	Yunusa and Newton (2003)
Amelioration	Subsoil manuring: organic matter amendment to subsoil clay layer	Improved soil physical properties and increased root growth in layer	Gill et al. (2009), Sale et al. (2018)
Amelioration	Deep placement of lime or gypsum	Improved soil aggregate structure or stability	Baldock et al. (1994), Vance et al. (1998)
Plant genotype differences: strategies for root growth and water uptake			
Root growth	Preferential root growth into pores and cracks	Root elongation deeper into profile	Volkmar (1996), Hatano et al. (1988), White and Kirkegaard (2010)
Root types	Root types that penetrate pores and make contact with pore walls	Improved exploration of profile. Reduce resistance at soil-root interface	Athmann et al. (2013)
Anchorage	Root hairs provide anchorage to allow penetration of soil matrix	Improved root exploration through pores and within soil matrix	Bengough et al. (2011), Jin et al. (2013)
Hydraulic redistribution	Redistribution of water in soil matrix *via* roots due to water potential gradients	Water within soil matrix is potentially more available	Prieto et al. (2012)

(continued)

Table 13.1 (continued)

Physical interventions: to change the physical structure or the soil			
Intervention	**Mechanism**	**Impact**	**References**
Root-soil contact	Root hairs behind root tips increase surface area Mucilage production increases water content of the rhizosheath	Increased rate of water absorption May increase hydraulic conductivity at root-soil interface during drying	Carminati et al. (2010), Carminati et al. (2017a, b); Ahmed et al. (2018)
Penetration ability	Differences in root penetration through hard soils, re-entry to soil matrix from pores	Root elongation deeper into profile	Materechera et al. (1991), Clark et al. (2003), Hirth et al. (2005), Botright Acuña et al. (2007), Bengough et al. (2011)
Root system architecture	Optimises distribution between surface and subsurface	Increased root length and density in subsoil	Palta et al. (2011), Wasson et al. (2012), Lynch and Wojciechowski (2015)

13.2 Conditions for Optimum Root Growth and Function

For optimum crop performance, the key soil physical properties, temperature, water status, aeration and soil mechanical resistance (soil strength), must not limit root growth or function (Letey 1958; Boone 1988; McKenzie et al. 2011). These primary factors affect root growth directly (Letey 1958), but they are interrelated and interact to a significant degree (Miller 1986; Zou et al. 2000; Iijima and Kato 2007; Bengough et al. 2011). Soil texture, bulk density, structure and structural stability and porosity characteristics have an indirect effect on root growth *via* their influence on the primary factors (Letey 1958; MacEwan et al. 2010). In this section, we will briefly outline the empirically derived parameters that define suitable conditions for root growth.

13.2.1 Temperature

Like most plant functions, root growth responds strongly to temperature. Thus, soil temperature, which varies with time of year, with time of day, with depth in the soil and with management, is a fundamental governor of root system development (Boone 1988; McMichael and Burke 1996). Root growth can occur over a relatively broad range of soil temperatures. However, each species has an optimum range, with the rate of root extension and development being reduced progressively by temperatures either above or below this range (Kaspar and Bland 1992; McMichael and Burke 1996; Misra 1999; Gregory 2007). This has a direct impact on the ability of the plant to explore the soil profile and hence access soil resources.

13.2.2 Aeration

In general terms, soil aeration needs are met when the soil porosity is adequate to admit a supply of oxygen that meets the needs of the root system for maintenance, growth and function. However, for a given soil in a given condition, soil aeration is the direct complement to water status. The more pore space that is occupied by water, the less can be occupied by air. The aeration requirement varies between species and with the ability of the plant to supply oxygen to the active roots *via* internal means (e.g. by the development of aerenchyma). However, to ensure plant development is not penalized, the soil should have an air-filled porosity of 10–15% with at least 10% of the gas in the pore space being oxygen (Dexter 1988; da Silva et al. 1994; Bengough 2003; McKenzie et al. 2011). The critical air-filled porosity also depends on the gas diffusion rates in the particular soil with well-structured soils being better able to supply oxygen to the root compared to apedal soils (MacEwan et al. 2010 modified from Pierce et al. 1983). The air-filled porosity that limits root growth also varies with texture, ranging from 14–20% for sandy soils to 10–13% with increasing clay percentage (MacEwan et al. 2010). Finally, for aeration requirements to be met, there is also a need for continuity of transmission pores (i.e. pores >30 μm equivalent diameter) to allow gas exchange with the atmosphere.

13.2.3 Water Status

Soil water status impairs root growth and function in two principal ways: poor aeration in wet soils and increased soil strength in dry soils. As indicated in the previous paragraph, high soil moisture status can result in poor soil aeration when too much of the pore space becomes filled with water, particularly in soils with low porosity or impaired pore continuity. On the other hand, as the soil dries, the greatest impact on root elongation is through the increased soil strength. This is discussed in the following paragraph. Further, as the root and soil dry, shrinkage may result in reduced contact between the root and soil contributing to increased hydraulic resistance at the interface and inhibition of the function of the root in water uptake. However, the significance of this for hydraulic resistance is still unclear (Ahmed et al. 2018). Root hairs and mucilage may play an important role in maintaining connectivity (Carminati et al. 2017a, b). Finally, for a water supply that does not restrict root growth, the pore size distribution should be made up of greater than 15% macropores (i.e. transmission pores >30 μm equivalent diameter) and greater than 20% mesopores (0.2–30 μm equivalent diameter) (Cockroft and Olsson 1997). The hydraulic conductivity of the bulk soil *per se* rarely restricts water supply to a level that would impair growth (Dexter 1988).

13.2.4 Mechanical Resistance

Soil mechanical resistance is a critical characteristic governing the rate of root growth. A penetrometer resistance of 2 MPa is a useful representation of the soil strength above which root elongation will be impeded (da Silva et al. 1994; Clark et al. 2003). In reality, root growth elongation slows as resistance increases beyond a species-specific threshold until the resistance is great enough to stop further elongation (McKenzie et al. 2011). The resistances at which elongation begins to slow and at which growth stops vary among species. While species differ in their ability to exert axial root growth pressure, differences are more clearly related to root diameter (Boone 1988; Materechera et al. 1991; Misra 1997; Clark et al. 2003).

Soil mechanical resistance can vary with a number of characteristics, including texture and compaction (Kirkegaard et al. 1992; Iijima and Kato 2007). Importantly it also varies substantially with soil water content because soil strength increases exponentially as the soil dries (Stirzaker et al. 1996; Iijima and Kato 2007; Bengough et al. 2011). However, Bengough and co-workers (2011) highlight that even in wet soils, with matric potentials as high as −100 to −200 kPa, mechanical resistance can still be high enough to decrease root elongation rates by 50%.

When any of the above requirements are not met, there will be poor root system growth and development and therefore a reduced capacity of the crop to access soil resources. While soil physical properties may limit root growth either in the topsoil or the subsoil, these constraints have been identified as particularly problematic for root growth in subsoils (Adcock et al. 2007; MacEwan et al. 2010; McDonald et al. 2013; Lynch and Wojciechowski 2015), especially when the topsoil contains insufficient water and nutrients (Wong and Asseng 2007).

13.3 Soil Water Availability

Inhospitable subsoils commonly combine a number of constraints that can reduce water infiltration and drainage rates as well as the soil's water storage capacity due to lower total porosity, an altered pore size distribution and reduced pore continuity (Stirzaker et al. 1996; Bengough 2003; Gregory 2007; MacEwan et al. 2010; Lipiec et al. 2012; Gao et al. 2016; Pires et al. 2017). The net result is a change in the amount of water available for use by the crop and potentially a change in the timing of when it is available.

Compaction is frequently found to reduce water movement into the subsoil. Mossadeghi-Bjorklund et al. (2016) showed a significant reduction in hydraulic conductivity in the 0.3–0.5 m depth layer as a result of an imposed compaction treatment. This was associated with a reduction in the density of macropores, and there was also evidence that the compaction may have disrupted macropore continuity. Conversely, Hamza and Anderson (2003, 2008) achieved dramatic increases in infiltration rates due to subsoil cultivation across a number of soils with compacted subsoil, although the conductivity of the subsoil was not measured. The outcome was an increased soil water content in the top 500 mm of the soil. Mohanty et al. (2007) also found a significant benefit in terms of water storage in response to subsoil cultivation on a Vertisol, although the increase was small.

While the usual impact of compaction on water dynamics is negative due to the retarded water movement into the soil resulting in lower water availability, this is not always the case. Thus, Singh et al. (2014) reported that on a highly permeable soil, imposing a compaction treatment reduced excessive drainage. This improved water retention as well as reducing nitrate losses via leaching.

Water movement in texture contrast soils can present particular problems. The saturated hydraulic conductivity of the subsoils may be less than 1–2 mm day^{-1} (Belford et al. 1992; Dracup et al. 1992; Eastham and Gregory 2000). The low rate of water movement through the subsoil results in water accumulating in the more permeable layers above, leading to temporary perched water tables with the potential to cause waterlogging (Dracup et al. 1992; Zhang et al. 2004). In the Mediterranean-type climate of Western Australia, this typically occurs during winter when rainfall often exceeds the potential evapotranspiration rate. Because crop evapotranspiration (ET) is close to the potential at this time, the differences in soil water status have little direct influence on crop water use (Eastham and Gregory 2000). However, the outcome is likely to vary, depending on the dynamics of water availability versus the pattern of crop demand with development, as well as any secondary effects due to the impact of waterlogging on the crop, such as root system damage or impaired nutrient uptake.

Not only can subsoil constraints alter water supply by influencing infiltration and drainage, they have also been shown to alter the plant-available water-holding capacity (PAWC) of certain layers and thus the PAWC of the whole soil profile. Lipiec and co-workers (2012) showed that compaction led to less water being held in the plant-available range within the subsoil. Water in micropores of less than 0.5 μm radius is held at low potential (very negative) and so is unavailable to the plant. Compaction reduced the total porosity in subsurface aggregates and decreased the volume of pores with 1–3 μm radius but increased the volume of pores with a radius less than 0.3 μm. The overall result was a reduction in the volume of pores holding water in the available range (ca. −10 to −1500 kPa). Similarly, Babalola and Lal (1977a) found that the PAWC of a gravel layer was reduced with increased gravel percentage. They found lower total porosity and differences in pore size distribution, which may have contributed to the differences in PAWC.

The benefit of removing a compaction layer has also been demonstrated at the crop scale. Sadras et al. (2005) found that deep cultivation reduced the lower limit of extraction measured for some soil layers under a wheat crop but had little influence on the drained upper limit, thus increasing the PAWC. That is, the amount of water available to the crop was increased. As these experiments focused at the crop level, the mechanisms underlying the change were not explored. It is therefore unclear to what extent the effects were due to alterations in water holding characteristics of the soil or to the effectiveness of root exploration within the layer.

Thus, overall, there is evidence that subsoil constraints can influence the storage of water in the profile through changes in infiltration rate, drainage rate and PAWC. However, the significance of such changes for crop performance will depend on the rainfall pattern and the dynamics of crop water demand.

13.4 Rate at Which Roots Explore the Soil Profile

Regardless of whether plant roots are in the subsoils or surface, they need to overcome the resistance forces of the soil to penetrate the soil matrix (Bengough et al. 2011; Jin et al. 2013). Soil mechanical resistance is often greater in the subsoil than in the soil surface due to overburden pressure, the presence of fewer roots and less fauna to create biopores, the potential presence of gravel layers and the lack of disturbance by tillage (Unger 1979; Jin et al. 2013; Gao et al. 2016).

The pressure required for a plant root to penetrate the soil is the sum of the radial pressure required to expand a cavity and the axial pressure to overcome the frictional resistance at the soil-root surface along the root (Bengough et al. 2011; Jin et al. 2013). The root-soil friction is reduced by the sloughing off of border cells and the production of mucilage at the root tips (Iijima et al. 2004; Gregory 2007). To allow the tip to advance against mechanical impedance, root hairs behind the root tip play an important role in providing anchorage. This is also important for allowing the root to bend and change directions or to grow across an existing crack in the soil and re-enter the soil matrix (Bengough et al. 2011; Jin et al. 2013).

There are a number of soil factors whose influence on root growth is via their contribution to soil mechanical resistance. Taylor and Ratliff (1969) generated variation in resistance through differences in soil water potential and bulk density. They were able to derive a single relationship between resistance and root elongation rate of peanut across both sources of variation, emphasizing that the importance of the component variables was their contribution to mechanical resistance. The response curve suggested that a penetrometer resistance of 2.0 MPa would reduce the root extension rate by 50%.

The maximum rate at which roots penetrate downward into the soil (Fig. 13.2) is to some degree characteristic of a species (Dardanelli et al. 1997). For wheat, field measurements indicate a rate of descent of around 1.2–1.3 mm $°C^{-1}$ day^{-1} (mm per degree-day) across sands and structured clay, and for winter and spring, genotypes (Kirkegaard and Lilley 2007; Thorup-Kristensen et al. 2009). For soybean and maize, a rate of 2.0 mm $°C^{-1}$ day^{-1} has been derived (Ordonez et al. 2018). Physical subsoil constraints, such as compaction or high gravel percentage, impede the descent of the roots and hence delay the time at which crops can access water held at different depths in the soil profile.

At the crop level, while high mechanical resistance due to compacted or gravel layers may retard the descent of the roots into the soil, the passage of roots through soil biopores and cracks means that the impact is not as great as might be calculated based on uniformly strong soil (Stirzaker et al. 1996). White and Kirkegaard (2010) found that in a well-structured, high-strength soil, 85–100% of wheat roots in subsurface layers were in pores and cracks, with multiple roots occupying single voids. However, only 5% of pores were occupied by roots, which may reflect a lack of pore continuity, precluding roots from using a proportion of pores for vertical exploration. Under controlled conditions, Hatano and co-workers (1988) demonstrated the importance of macropores for root growth by showing a correlation between the spatial distribution of pores and the distribution of maize roots across a number of soil types. Importantly, the data showed that the proportion of roots penetrating macropores, rather than the soil matrix, was higher in the soils with higher bulk density and lower water content, that is, in stronger soils. Volkmar (1996) also demonstrated the increased dependence of root penetration on macropores as soils became drier. Interestingly, Stirzaker et al. (1996) demonstrated that the frequency of roots in pores of strong soil was three to four times higher than might have been expected based on probability.

While there is good evidence for the greater importance of soil pores for root extension in strong soils, the impact that this has on access to soil resources is likely to differ among species. For example, Athmann et al. (2013) found that the mode of contact between a root and the pore wall appears to differ between species. Barley with its fibrous root system and oilseed rape with its taproot system exhibited different strategies. In barley, seminal roots made contact with the pore wall, growing few laterals but having many long root hairs. In oilseed rape, on the other hand, roots grew vertically down the centre of the pores, the root hairs were shorter and contact with the pore wall was made by the lateral roots. There is little information available on how other root system characteristics influence the ability of a plant to utilize pores in strong soil. It could be suggested that variation among species (or among genotypes within a species) in terms of the number of primary axes, the degree of branching and the root width could influence the ability of roots to grow into available pores and hence access resources in zones of high soil strength.

Both soil compaction and gravel content impede the descent of the rooting front through the impact of high mechanical resistance on the elongation of individual roots (Babalola and Lal 1977a, b; Taylor and Brar 1991; Popova et al. 2016). Field experiments assessing the benefits of deep cultivation can provide useful comparisons, demonstrating the impact of mechanical resistance in retarding the exploration of the profile. In an early study, Barraclough and Weir (1988) examined the response of winter wheat to subsoil cultivation to remove a layer of high mechanical resistance. The 'plough pan' lay beneath the zone of cultivation with a peak penetrometer resistance at approximately 0.35 m. Four months after sowing, roots had reached 1.2 m in the treatment that received subsoil cultivation but only 0.40 m where the plough pan had remained. After this, however, vertical root penetration in the untreated soil was rapid. Tardieu (1994) cited earlier work in which it was found that the vertical penetration of maize roots through a clay loam soil was seriously retarded by an imposed compaction treatment until the drying profile began to develop cracks which allowed extension of roots through the layer of high mechanical resistance. In both examples, root exploration of deeper layers was delayed until the constraint of the layer with high mechanical resistance was overcome. However, such responses can show marked inter-annual variation. Rengasamy and Reid (1993a, b) showed that subsoil cultivation at 0.3 m could dramatically improve the vertical penetration rate of faba bean roots on a compacted silt loam. However, in the first year, roots in the compacted treatment had reached ca. 0.35 m by flowering, whereas where subsoil cultivation was used, roots had reached ca. 0.55 m, but in the second year, there was no difference in rooting depth until the beginning of pod filling.

The delay in vertical root exploration is strongly associated with access to soil resources. Radford et al. (2001) presented a good example of the impact of compaction on retardation of the depth of soil water extraction. Comparing three intentionally compacted treatments to the control, they demonstrated that the most severe compaction treatment delayed the time at which the crop accessed water at a depth of 1.0 m by as much as 50 days. In terms of the depth of profile that could be utilized by the crop at a given time, at 50 days after sowing (DAS), the crop on the compacted treatments was extracting to between 0.4 and 0.6 m, while on the non-compacted treatments, extraction had reached around 0.9 m. The most severely compacted treatment did not access water from 0.9 m until 100 DAS, at which time the non-compacted control was extracting from a depth of around 1.3 m.

The delayed exploration of the soil due to subsoil constraints means that a smaller proportion of the water in the profile is available to the plant at any given time. Thus, there is a reduced capacity to continue optimal crop growth if the soil water is not replenished by irrigation or rainfall. The significance of this for yield will therefore depend to a very great degree on the pattern of water inputs relative to the temporal development of crop demand and the PAWC of the soil.

13.5 Maximum Depth of Soil Exploration

Under unconstrained conditions, the maximum depth of soil exploration by the crop is determined by the rate of vertical root growth and the duration of root growth (Fig. 13.2). In annual crops, root growth, and hence vertical exploration, typically ceases sometime around the time of flowering or the start of seed filling (Dardanelli et al. 1997). A summary of typical roots depths for annual and perennial crops is reported by Costa and Coutinho (2022). As well as impeding the rate of exploration of the soil profile, subsoil constraints can limit the maximum depth of soil to which roots explore and hence from which water can be extracted. There are two ways in which this occurs: the constraint in a layer may be of sufficient magnitude to render it impenetrable to roots, thus dictating the maximum rooting depth, or the descent of roots may be delayed by constraints to such a degree that the soil is not fully explored before ontogenetic factors effectively stop root growth.

Soil strata of particularly high mechanical resistance, whether due to compaction, high gravel content, cemented gravels or in some cases high clay subsoils, can present an absolute limit to root exploration (e.g. Dracup et al. 1992; Wong et al. 2009; Khan et al. 2016). In such cases, the maximum amount of water available to a crop is limited to that stored above the impenetrable layer. The impact that this has on water use and crop performance depends on the interaction of the depth of the constraint, soil water holding capacity above the constraint, the pattern of rainfall and crop management (Wong and Asseng 2006, 2007). The depth at which an impenetrable layer lies can vary markedly even within a field (Wong et al. 2008), which has consequences for the amount of water available to the crop, and hence crop yield, as well as the risk of drainage and leaching of nutrients (Wong et al. 2006). In rainfed systems, the spatial variability in yield induced by impenetrable barriers is usually most marked in wet years. In dry seasons, crop growth across the site is more likely to be limited uniformly by water deficit, but in wet seasons, the profile is more likely be filled and the water accessible to the crop at any given position in the field becomes a reflection of the depth of the impenetrable layer (Wong and Asseng 2006). Simulation analysis of the interaction of seasonal rainfall and agronomic inputs allows management to be varied spatially to reflect crop yield potential, as well as drainage and leaching risks (Wong and Asseng 2006). It can also provide important information to support the decision of whether correction of the subsoil condition is warranted.

In other situations, the depth of soil water extraction may be limited not by an absolute barrier but due to the rate of root descent being reduced. If root descent has been retarded sufficiently, ontogenetic limitations on the duration of significant root growth may mean exploration ceases before the roots have exploited the depth which a non-constrained root system might achieve. In the study of Radford et al. (2001), described earlier, although the rate of descent of the extraction front was delayed by the treatment with an intermediate degree of compaction, it ultimately reached the same depth as that in the non-compacted treatment. In the most severely compacted treatment, the rate of descent early in development was retarded to such an extent that although the subsequent rate of exploration was not different from that in the moderate compaction treatments, the ultimate depth of extraction was some 0.3 m shallower than the non-constrained treatment.

13.6 Efficiency of Extraction From a Soil Layer

Once a soil layer has been accessed by the root system, the rate at which water is removed and the amount of water that can be removed (Fig. 13.3) are influenced by both plant traits and soil properties (Meinke et al. 1993; Dardanelli et al. 1997). Subsoil constraints can reduce the efficiency with which water is extracted by the crop from any given soil volume in terms of either the rate of extraction or the proportion of the soil water ultimately accessed by the crop. In addition to soil-based mechanisms, such as changes to water potential, content and movement, there are three groups of plant-based mechanisms by which this can occur: changes in the amount and disposition of roots within a layer, effects at the root/soil interface and alterations to morphology, anatomy and chemistry of individual roots.

Since soil mechanical resistance reduces root elongation rate, the amount of roots in a layer of high resistance is typically less than if that layer had had lower resistance. Root length density (RLD) of potato has been shown to differ dramatically between plots of contrasting soil resistance (Parker et al. 1989). Thus, crops such as potato, broccoli and lettuce have been shown to be highly responsive to treatments to remove layers with high mechanical resistance such as plough pans (Montagu et al. 1998; Guaman et al. 2016). The results of Guaman et al. (2016) are of particular interest. Inter-row subsoil cultivation reduced the soil penetration resistance between 0 and 0.6 m in a soil with a strong plough pan, resulting in a 70% increase in the RLD in these layers. However, ‘biological subsoiling’ (the use of rotation crops to correct the plough pan) did not reduce the observed penetration resistance, but the RLD was still improved by the same amount. Further, a combination of the two treatments resulted in a 120% increase in RLD relative to the control.

Importantly, the removal of a layer with high mechanical resistance often results in greater root density in layers deeper in the soil. Differences in resistances in soil layers, around 0.3 m, have been shown to alter the RLD of wheat throughout the profile (Munkholm et al. 2008; Chen et al. 2014). However, in the work of Vocanson et al. (2006), the extent of such benefits appeared to differ with weather and genotype. Interpreting the mechanisms underlying field experiments such as these is somewhat difficult due to possible feedforward effects: That is, removing compaction improves root proliferation which provides access to a greater amount of soil resources, thus improving crop growth, which in turn leads to more root proliferation. There would be a particular value in combining field-based studies with more mechanistic exploration of the factors contributing to the responses.

Within a given layer, the impact of mechanical resistance on water extraction is greater than might be expected on the basis of the difference in average RLD. This relates again to the importance of macropores and soil structure for root growth. Root distribution within a soil layer is not uniform. Examining a range of structured soil types under controlled traffic, Logsdon and Allmaras (1991) found significant clumping of maize and soybean roots in all layers and under all tillage methods. In this example, the roots were not constrained to biopores or significant cracks. The non-uniform and non-random distribution of roots in soils means that more of the soil volume is a greater distance from the nearest root than would otherwise be the case (Tardieu 1988; Logsdon and Allmaras 1991). This means that on the basis of geometry alone, water is less readily extracted from the soil (De Willigen 1987). As a result, residual water remains in unexplored parts of the soil matrix (Pardo et al. 2000; Amato and Ritchie 2002). Thus, the extraction of water from the soil is slower and not all water is extracted from the soil matrix (Passioura 1991). In high strength soil, the dependence of roots on soil pores is greater (Hatano et al. 1988; Volkmar 1996) because of the greater difficulty of penetrating the bulk soil. At the same time, the number of pores is lower and distribution less uniform (Hatano et al. 1988; Kim et al. 2010; Berisso et al. 2012). As a result, the non-uniformity of root distribution can be expected to be higher and the rate and extent of water extraction to be lower.

White and Kirkegaard (2010), working with a well-structured, high-strength soil, found that virtually all roots below a depth of 0.6 m occupied pores or cracks.

However, in this case, distribution did not differ significantly from random. An estimation of the potential rate of water extraction suggested that the density and distribution of roots was not likely to limit water uptake. This was not consistent with the significant proportion of residual water left by an adjacent crop even though it was growing under water limitation (Kirkegaard et al. 2007). The authors suggested that the discrepancy may have been due to limitations to hydraulic conductivity at the soil-root interface. Mechanisms that govern the rate of water transfer from the soil to the root require significant further research. In reviewing hydraulic processes in plant water uptake and their significance for the yield of water-limited grain crops, Ahmed and co-workers (2018) emphasized the need to better understand the transfer of water between the bulk soil and the root vascular tissue as well as the significance of the underlying processes at the plant and crop level. In particular, they stressed our limited knowledge of the role of mucilage, root hairs, soil-root contact and aquaporins. Both root hairs and root exudates are significant in overcoming high hydraulic resistance at the soil-root interface. Mucilage appears to play an important role in maintaining contact between the soil and the root as soil water declines and roots shrink (Ahmed et al. 2014; Carminati et al. 2017a). Similarly, it has been demonstrated that the presence of root hairs results in a smaller drop in water potential across the soil-root interface as the soil dries (Carminati et al. 2017b). In high-strength soils, the importance of these mechanisms is likely to be accentuated, because contact between the root and the soil matrix may be either particularly high or low. In the study of White and Kirkegaard (2010), mentioned earlier, most roots in the subsoil of a well-structured, high-strength soil were in pores and contacted the soil primarily via root hairs. By contrast, roots in cracks were adpressed to the soil surface and had few root hairs. Indeed, the density of root hairs could be related to the proportion of the root surface that was in contact with the soil. If high soil strength limits root hair elongation (Haling et al. 2014), their function in overcoming limited contact between the root and the soil may be reduced. The results of Haling et al. (2014) are consistent with the limited penetration of the pore wall observed by White and Kirkegaard (2010). Thus, the need for research into mechanisms influencing the rate of water transfer across the soil-root interface is of particular significance to the question of the influence subsoil constraints on crop water supply.

13.7 Consequences for Seasonal Crop Water Use

The magnitude of the impact of a subsoil constraint on crop water use, and hence yield, is modulated by many factors, including the amount and distribution of rainfall, the PAWC of the soil and the depth and severity of the constraint. The world's major food crops, rice, wheat, maize and potato, are each grown across a wide range of climatic zones. For example, in Australia alone, wheat is grown in subtropical climates on predominantly stored soil water, in temperate climates with equi-seasonal rainfall and in Mediterranean-type climates with winter dominant rainfall

(Fig. 13.4.). In addition to climatic type, inter-annual variation also needs to be considered.

The influence of the pattern of rainfall relative to the time course of crop demand in modulating the significance of a subsoil constraint is demonstrated in the results of Rengasamy and Reid (1993b). Subsoil cultivation to remove compaction increased total crop ET of faba bean in one case but not in the other two. In one case, adequate rainfall late in the season met crop demand for water, and so no stress appears to have been encountered. In another, it appears that soil water was fully depleted in both the compacted and deep cultivated soils. These three possible outcomes were conceptualized as generalized cases by Ahmed et al. (2018).

The impact of a subsoil constraint on water supply and crop performance is also dependent on soil type. Sadras et al. (2005) found contrasting responses to the removal of subsoil compaction in different positions in the landscape (lower versus higher positions) that differed in soil type. They used deep cultivation to remove a compaction layer in a landscape with sandy-loam soil on low-lying land and sandy ridges. The treatments had little effect on water use (ET) of a wheat crop on the sandy-loam soils but increased ET by 30–40% on the sandy soil with transpiration increasing by up to 90%. The responses in crop growth were consistent with measured transpiration.

The complexity of the interaction between factors that alter the impact of subsoil constraints has been explored using dynamic simulation models of crop growth and yield. Wong and Asseng (2007) used a model to estimate the yield benefit to wheat crops from correcting subsoil constraints in sandy soils in a Mediterranean-type environment. They found that in lower rainfall regions or dry seasons, the benefit of correcting a constraint was small, as root and crop growth were limited by the depth of soil wetting before the constraint was reached. In wetter years and regions, the

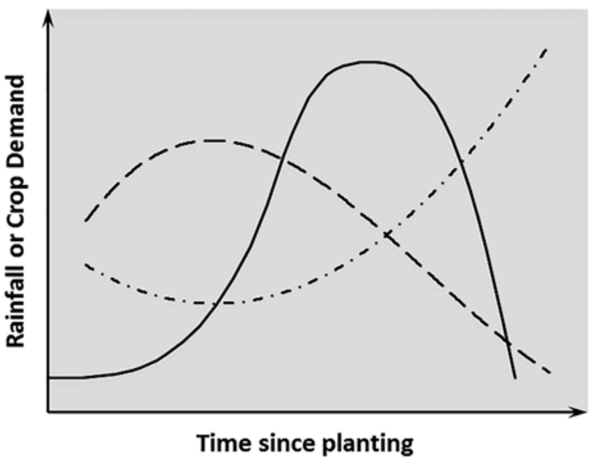

Fig. 13.4 Increase and then decline in water demand by an annual crop (solid line) compared to generalized rainfall patterns for a Mediterranean-type climate (dashed line) and a subtropical climate (dot-dash line)

benefit was greater, because the constraint stopped the roots from accessing the water that would otherwise have been available for growth. They also found a greater average response on coarse texture soil, because the wetting front reached greater depths for a given amount of rainfall and the roots needed to penetrate deeper to access the same amount of water. Such analyses are important to support the decision to make investment in correcting a subsoil constraint. Lilley and Kirkegaard (2007) used the same model to examine the benefit to wheat of access to water located deep in the rooting zone. Working in a somewhat wetter, less strongly Mediterranean environment with heavier soils, they drew similar conclusions to Wong and Asseng (2007). They also found that the yield benefit of access to water deep in the profile was significantly altered by the amount of water available at sowing. This points to the possible impact of agronomic decisions such as crop sequence (via the extent to which the previous crop depleted the soil water reserve) and summer fallow management on the benefit arising from correcting a subsoil constraint and raises the general question of the interaction between subsoil constraints and any agronomic practices that alter water availability or demand.

For cereal crops grown on stored soil moisture and with limited in-season rainfall, it is important to ensure adequate water supply remains to allow good grain size as a component of yield (Cornish and Lymbery 1987; Richards and Passioura 1989; Passioura 2006). Pre-anthesis water use supports the development of potential yield in terms of canopy development, the number of ears per unit area and the number of kernels per ear. Post-anthesis water use supports the filling of the reproductive sink. Thus, while the impact of subsoil constraints on total crop ET will be of primary importance, it is conceivable that delaying the timing of water use by the crop may also influence yield, yield components and quality. However, there is limited field-based information on such effects by subsoil constraints.

In summary, the influence of subsoil constraints on crop water use is known to be influenced by the amount and distribution of rainfall, soil type and the depth of the constraint. Given the complexity of the interactions and the importance of the timing of water supply to yield development in many crops, there is a need to develop a broader picture of the likely impact of subsoil constraints under different conditions. Simulation modelling will be a useful tool in this regard to allow likely benefits to be evaluated for different soil types, in different rainfall environments and in the context of inter-annual variation in rainfall and temperature.

13.8 Future Research Needs

While there is a significant amount of understanding about the mechanisms by which subsoil constraints influence the uptake of water by crops, there are still important aspects that need clarification or quantification. Three key areas are outlined here.

13.8.1 Soil-Root Interface

Ahmed et al. (2018) outlined a suite of questions that still need to be resolved regarding the mechanisms of water transfer from the bulk soil to the roots' vascular elements. In addition, our understanding of the movement of water across the soil-root interface is not well integrated with our understanding of water uptake at the scale of the crop and soil profile. Linking these different process levels, and, in particular, defining how the processes at the interface are influenced by subsoil constraints, may contribute important information to our understanding of how crops respond to declining water availability under adverse soil conditions. The extent to which processes at the soil-root interface differ among species and the consequences of this for crop performance have also received little attention.

13.8.2 Crop Management and Soil Pores

Given the apparent importance of soil pores for the development and function of crop root systems, there is a need to strengthen our knowledge of the influence of crop management practices on pore size distribution, pore continuity and pore stability. This should not only focus on the influence of different cultivation methods and traffic management but should also encompass the interaction with crop rotation, cover management and soil chemical amendment, which may influence the rate of development and persistence of pores of different sizes.

13.8.3 Quantifying Importance

At the whole crop level, subsoil constraints modify the availability of water both spatially and temporally. At the same time, they also influence the capacity of the crop to access that water, again, both in space and time. There are few studies which attempt to explore both sets of processes under the same conditions and so identify their relative importance and the extent to which they interact. The impact of these processes on the total amount of water used by a crop and the pattern of usage over the crop cycle will determine the magnitude of the impact on crop performance. Simulation studies, such as those of Wong and Asseng (2007) or Lilley and Kirkegaard (2007) that have evaluated the influence of access to water in the context of differing cropping systems, management, soil types and climatic zones, provide an important extrapolation to allow the agronomic importance of these processes to be seen in the context of inter-annual variation in rainfall. There would be particular value in applying this approach specifically to subsoil constraints, if the appropriate processes could be robustly captured in simulation routines. This is not facile. A substantial amount of research would need to be conducted to adequately quantify responses in the component process and allow for calibration and validation. Integration and analysis at this level is fundamental to allow the extensive knowledge of the influence of soil constraints on soil and plant processes to be used to inform agronomic decision-making.

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