Chapter 2

Subsoil Constraints and Water

> **Key**
>
> - Water is the principal factor limiting crop production in rainfed farming systems in southern Australia.
> - The Plant Available Water Capacity (PAWC) is the maximum amount of water a soil can store that a plant can use.
> - PAWC depends on a combination of soil properties and crop variety.
> - Subsoil constraints reduce the amount of water available to the crop.
> - Subsoil constraints can often be detected in the paddock through the presence of unused water in the subsoil immediately following harvest.

The key challenge for most dryland graingrowers in Australia is to achieve 'more crop per drop' of rain (Passioura 2006). Moisture stress limits grain production throughout large sections of Australia's dryland farming systems. Even in regions where temporary water logging frequently occurs, most grain crops can experience water deficits at some point in the season severe enough to reduce grain yields. Consequently having a basic understanding of soil water is fundamental to good agronomic management of crops.

Of the rain that falls, some will contribute to runoff, some will evaporate directly from the soil surface and the remainder will infiltrate into the soil; and under wetter conditions some of the latter may drain below the root zone if the soil profile is already saturated. In order to maximise grain yields (and profitability), both the amount of rainfall that is stored as soil water in the soil within the crop root zone and the use of this water by the crop to produce grain needs to be maximised.

Subsoil constraints generally reduce crop yields through limiting the ability of a crop to access and efficiently use all of the soil water potentially available to a crop. A basic understanding of how to measure soil water and its availability to crops can assist in identifying whether subsoil constraints are present. These measurements can also be used to assess how successful any resulting changes in management have been in overcoming these constraints.

1. Rainfall Use Efficiency (RUE)

Also referred to by some as Water Use Efficiency (WUE), RUE is a useful on-farm measure of the efficiency with which rainfall and/or soil water is converted into grain yield. In its simplest form, rainfall use efficiency is simply the amount of grain produced (kg/ha) for every mm of rain that falls on a paddock. It is calculated as:

$$\boxed{\begin{array}{c}\text{Grain}\\\text{yield}\\\text{(kg/ha)}\end{array}} \Big/ \boxed{\begin{array}{c}\text{In-crop}\\\text{rainfall}\\\text{(mm)}\end{array}} = \boxed{\begin{array}{c}\text{R.U.E.}\\\text{(kg grain/mm rain/ha)}\end{array}}$$

Equation 2.1: Calculating rainfall use efficiency (RUE) for a paddock.

Many approaches have been developed over the years to calculate rainfall or water use efficiency, ranging from 'back of the envelope' type approaches such as the very popular French and Schultz calculation (French and Schultz 1984), to more complicated computer based simulation models. In the French and Schultz approach, as in most others, account is made of the amount of rainfall that is inevitably lost to evaporation directly from the soil surface and not used directly (transpired) by plants. French and Schultz set this value to 110 mm for medium to high rainfall zones in southern Australia, although this can vary widely depending on soil type, crop type, plant vigour and environmental factors, including rainfall pattern (Figure 2.1).

Farmers can use RUE to compare the actual yield achieved with the yield potential of their paddock based on seasonal rainfall, although there are some limitations.

For example, rainfall falling just before grain maturity will contribute very little to crop water use or grain production, and biological and abiotic factors such as disease and nutrient deficiencies can reduce RUE. As a general rule however, once allowance is made for evaporation, farmers should aim for a benchmark of 21 kg/ha of cereal grain produced for every additional mm of rain received during the growing season.

RUE may also be an important indicator of the presence of subsoil constraints. In fact the importance of subsoil constraints to crop production was first recognised in studies that attempted to maximise RUE by applying the best agronomic management (adequate nutrients, controlling weeds and diseases). This showed that even when all these limitations were accounted for, RUE values equivalent to only 50 to 75% of the yield potential were recorded, indicating that some other factor/s, later identified as subsoil constraints, were reducing yields.

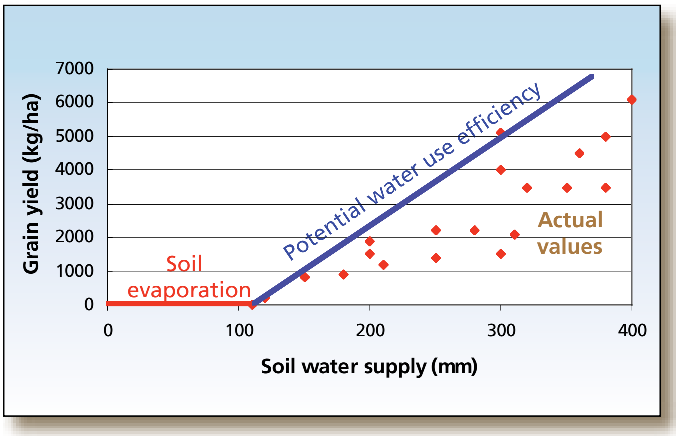

Figure 2.1: Diagram of rainfall use efficiency concept.

2. Plant Available Water Capacity

An important allied concept to RUE or WUE is **Plant Available Water Capacity** (PAWC) (Figure 2.2). PAWC is the maximum amount of water stored in the soil that a plant can ***potentially*** extract. Technically it is defined as the difference between the Upper Storage Limit (USL), or the maximum amount of water a soil can hold after it has become saturated and drainage has ceased, and the Lower Storage Limit (LSL). The LSL of the soil is determined by measuring the soil water content (%) at a water potential (suction) of –1500 kPa (–15 bars) in a laboratory on soils taken from each soil layer. The value of –15 bar is a used to approximate the maximum suction that an 'average' plant root can exert on the soil. However, in reality, plant species differ significantly in their ability to extract water from the soil. The LSL value of –1500 kPa has been determined through repeated experimentation as the water potential at which plants would undergo permanent (as opposed to temporary) wilting because the soil could not supply sufficient water to meet the loss of water through transpiration. The USL is also commonly referred to as **Field Capacity** and the LSL is also known as the **Permanent Wilting Point** (PWP). The USL is normally defined as the soil water content at a suction pressure of –10 (or sometimes –30) kPa. Similarly, the value of –10 (or –30) kPa for Field Capacity was determined through experimentation but does vary significantly with that measured in the field. PAWC should be measured over the effective (or potential) rooting depth of the crop and this depth should always be quoted with the value.

The term **Plant (or Crop) Lower Limit** (PLL) is often used interchangeably but confusingly with LSL by different groups but it is important to recognise that the LSL and PLL represent two different quantities of water. The PLL is a measure of the water remaining in the soil after a crop has used as much as it could possibly extract. Consequently, the PLL is a variable value and changes with crop type, season, and nutrition etc. Importantly PLL is strongly influenced by subsoil constraints. PLL can only be measured retrospectively ie. at or after grain maturity, whereas the LSL is a physical property of a given soil measured in the laboratory, and is therefore fixed. In some cases, such as when a crop receives heavy rainfall late in the season, measuring PLL is not applicable since the crop will not have the opportunity (time) to utilise all the soil water before maturity. Most, but not all, grain crops would be at PLL at maturity, but very few ever reach LSL. In some cases, eg due to near surface evaporation, soil water content can be lower than both the PLL and LSL.

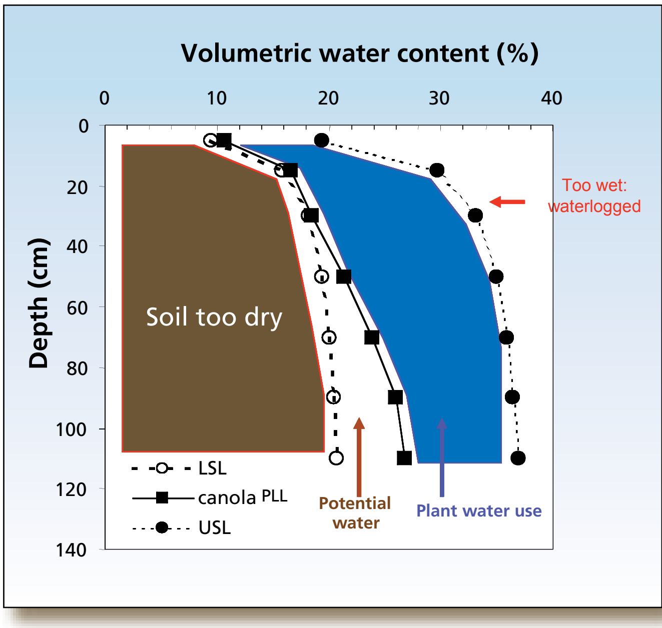

Figure 2.2: Diagrammatic representation of water use by canola growing on a Calcarosol from Birchip, Victoria. The diagram shows the total actual amount of water that can be used by the plant (PAWC) referred to as 'plant water use' on the graph. The soil water listed as 'potential water' is the quantity of water unavailable to crops due to subsoil constraints. The sum of 'plant water use' plus 'potential water' equates to the $PAWC_E$.

Knowledge of PAWC when combined with historical estimates of PAW and WUE, can allow yield potential to be estimated, which in turn can be used to assess the financial viability of different options to manage subsoil constraints.

Measuring Soil Water

Various terms are used to indicate the amount of water present in the soil. These terms reflect the specific quantity of water they describe and the manner in which they are calculated.

1. **Gravimetric soil water content:** Soil water content is expressed as a proportion or percentage of the dry weight of soil, and is measured as the change in weight of soil after oven drying at 105°C as a proportion or percentage of the dry weight. It is calculated as:

   Gravimetric Water (%) = (Wet soil weight (g) – Dry soil weight (g)) / Dry soil weight (g) × 100

   or

   Gravimetric Water (g/g) = (Wet soil weight (g) – Dry soil weight (g)) / Dry soil weight (g)

2. **Volumetric soil water content:** The mass or volume of soil water contained in a given volume of soil. It is defined as volumetric because it is a quantity per unit volume (e.g. g/cm^3 or cm^3/cm^3 or mm per length of soil depth). It is measured from a known volume of soil or calculated from representative bulk density measuements. Conversions between g and mm assumes that 1 cm^3 of water is 1 g in mass. It is popularly calculated as the gravimetric water content multiplied by the bulk density for a volume of soil (for example that contained in a 10 cm layer). **Bulk density** (see glossary) is a measure of the weight of dry soil (g) in a volume of soil (cm^3). It typically ranges from 0.9 up to 1.7 g/cm^3 for different soils, and it tends to be higher in sands and compacted soils than in clays. Volumetric water is calculated as:

   Volumetric water (g/cm^3) = gravimetric water (g/g) × bulk density (g/cm^3)

   or

   Volumetric water (mm) = gravimetric water (g/g) × bulk density (g/cm^3) × soil depth (mm)

3. **Plant Available Water Capacity (PAWC):** A measure of the maximum quantity (volume) of water stored in a soil (once a profile has been fully wetted up or 'recharged') that is ***potentially available*** for use by plants provided that there are no constraints to water use. Values are calculated for the potential crop rooting depth. This depth is approximately 120 cm for many cereal crops in the region. It is calculated as the difference between the volumetric Lower Storage Limit (LSL) and the volumetric Upper Storage Limit (USL) for each soil layer (see Glossary and following pages) expressed as mm of water. It is calculated as:

   PAWC (mm) = [USL – LSL] × soil depth (mm) for each layer to a set depth eg. 120 cm

4. **Effective Plant Available Water Capacity ($PAWC_E$):** This is a measure of the maximum quantity of soil water actually available to a plant (after a profile has been fully recharged) **once other factors such as subsoil constraints are considered.** It is therefore similar to the PAWC but it is calculated using PLL (Plant Lower Limit) rather than LSL. The actual quantity of $PAWC_E$ is always less than or equal to PAWC: it is never greater than PAWC. $PAWC_E$ is dependent on the response of the plant itself, especially rooting depth and the physiological capacity of the roots to remove water from the soil. $PAWC_E$ therefore varies with each crop, season etc. It is expressed in terms of mm of water and calculated as:

   $PAWC_E$ (mm) = [USL - PLL] × soil depth (mm) for each layer to a set depth eg.120 cm

5. **Plant Available Water (PAW):** This is a measure of the quantity of soil water available to a plant at any one point in time to the potential rooting depth. PAW is frequently measured near the time of sowing because it provides a valuable early indication of yield potential that can be used to make better management decisions. PAW is expressed as mm of water and can be calculated as:

   PAW (mm) = [Volumetric water – PLL] × soil depth (mm) to a set depth (normally 120 cm)

6. **Water Use (WU):** This is the cumulative amount of water used by a crop over time (normally the growing season) and therefore requires soil water (volumetric) to be measured at least 2 points in time ie. Time 1 (e.g. sowing) and Time 2 (e.g. grain maturity). The calculation of Water Use includes evaporation, transpiration and run-on/run-off and drainage but for annual crops these are typically assumed to be zero with the major components of water use being crop transpiration and soil evaporation. The calculation is similar to WUE but the units are expressed as an amount of water (mm), not an amount of grain per unit of water used. It is calculated as:

   Water use (mm) = Volumetric water (Time 2) + rainfall/irrigation – Volumetric Water (Time 1)

Please see the following section for an explanation of PLL. Please also refer to the excellent publication by Dalgleish and Foale (1998) which provides a detailed description of plant water use and soil water measurement.

Factors affecting PAWC

The amount of water held in a soil (and therefore PAWC) is determined by both the soil texture (ratio of sand, silt and clay) and the structure of the soil (which influences the number and size of pores between soil particles). Soils retain water because water molecules are attracted to each other and to the soil particles and organic matter. Two important factors which affect the relative amount of water that a soil can hold are:

- **Pore volume and pore size distribution.** Water is held in the pore space of soils by capillary forces or tension (negative pressure). Soils with a lot of small pores (such as clay soils) hold water at a greater tension compared to soils with large pores. Plants therefore have to apply a much greater suction to extract the water from clay soils as it progressively dries than sands. The forces required to extract water from these small pores are so high that at relatively high gravimetric soil water contents (around 20 – 30 %) plant roots can no longer extract water from clay soils.
- **Particle size distribution.** Water is attracted to soil particles and will form a film on their surfaces. Soils formed from finer particles (such as clays) can hold more water compared to soils formed from larger particles (sand), because clays have a much higher total surface area than sands for the same volume of soil.

As a result, soils with high clay contents eg. Vertosols, are able to store more water than soils with a higher sand content (eg. Calcarosol) because the USL occurs at a higher gravimetric soil water content (Figure 2.3). Although water can be more difficult to extract from a clay soil due to the smaller pore size (ie. they also have a higher value for the LSL), the overall effect is that normally a greater amount of water is 'available' to plants (Figure 2.4), except for some poorly structured clay soils.

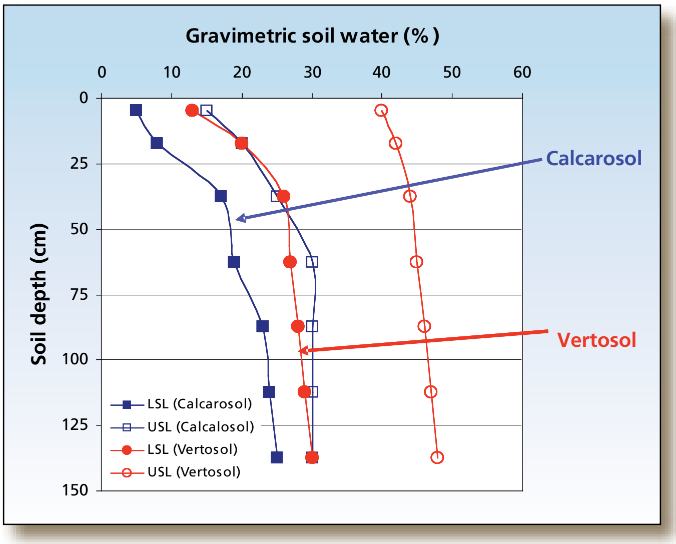

Figure 2.3: Comparison of the Upper Storage Limit (USL) and Lower Storage Limit (LSL) for two contrasting soils in Victoria: a Vertosol from Dooen and a Calcarosol from Walpeup. The figure highlights the greater amount of water (rainfall) needed by the heavy clay Dooen (15 to 20% in the topsoil) to get to the level where the plant can start accessing water compared to the sandy Walpeup soil (< 10%). Data source: O'Leary et al. (1997).

Plant water use and subsoil constraints

Although PAWC is determined by soil physical factors, plants are rarely able to fully exploit this potential, and it is the PLL that is usually measured in the field. The total amount of water extracted from soil by a plant depends on rooting depth, root length and/or root length density and the physiological capacity of the roots themselves to extract water from the soil. Subsoil constraints can affect all of these.

The maximum rooting depth of a plant is determined by a combination of its genetics and the environment in

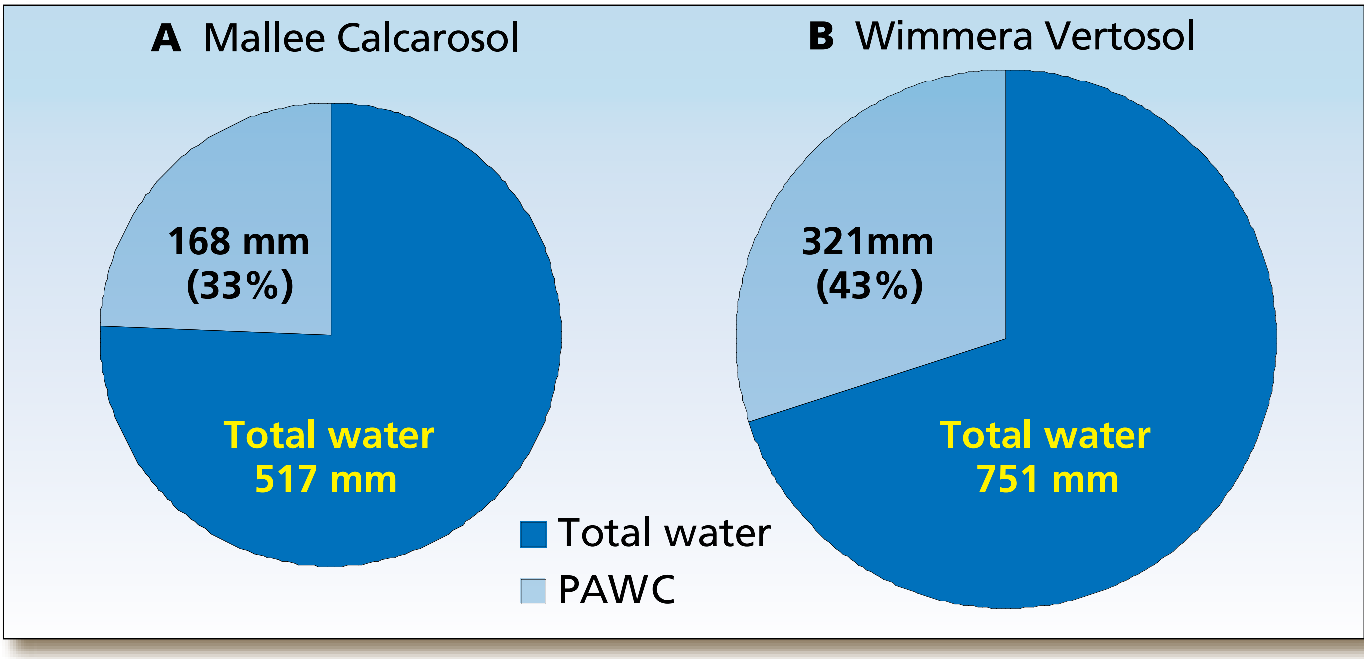

Figure 2.4: Comparison of total soil water storage and plant available water capacity (PAWC) for (A) Mallee Calcarosol and (B) Wimmera Vertosol, assuming a rooting depth of 150 cm.

which roots grow. Rooting depth will therefore vary with crop type and variety. Many pulse crops for example, such as faba beans or lentils, have a maximum rooting depth of only 60 – 80 cm, whereas cereals such as wheat can send roots to 120 –140 cm in heavy clay soils, *providing there are no subsoil constraints.* Consequently, the soil PAWC for wheat can potentially be nearly double that of lentil in the same soil.

Subsoil constraints can act to reduce the effective rooting depth below the genetic potential, for example through toxicity (eg. by acidity or boron) slowing or preventing root growth, by osmotic potential – whereby salts reduce the rate and eventually the amount of water that can be absorbed by the plant – or by soil compaction and high soil strength preventing physical penetration by the roots.

Plants with a greater root density (ie. cm of root length/ cm^3 of soil) will potentially have a greater capacity to extract water than those with a lower root density. Root length density tends to be higher in perennial species (eg. lucerne) than annual species due to the greater longevity of the perennial (Figure 2.5). This higher rooting density, combined with greater depth of rooting helps explain the observation of many growers that the soil profile is generally much drier following several years of lucerne compared to several crops of wheat or pulses.

Plants also vary in the physiological capacity of their roots to extract water from soil (ie. they exert different suctions), although the extent of this variation is generally not large. However some chemical properties of the soil eg. salinity, can dramatically affect root physiology and thus water extraction.

Comparing theoretical WUE (using PAWC) to actual, or measuring the change in soil water content at different depths over a cropping season (by visual inspection or quantitative measurement) can provide a valuable indication of the presence of subsoil constraints. New technologies, such as Electro-Magnetic Induction (EM) Mapping, are enabling changes in soil moisture to be mapped across paddocks at reasonable cost. These maps can be compared with biomass or (header) yield maps to locate areas of a paddock where subsoil constraints are likely. Field inspection and soil analysis at these sites is then necessary to determine which constraints are present, and their relative severity so that an appropriate management options can be selected.

The pattern of soil water extraction and rooting depth of a particular crop is one of the most useful indicators of whether subsoil constraints are impacting on it. The larger the difference between the LSL and PLL, the more severe are the likely impacts of subsoil constraints. For example, in 1998, wheat at Birchip extracted little soil water below 40 cm, despite experiencing a Decile 4 rainfall season (see Figure 2.6). In contrast barley which tends to have better salinity tolerance than wheat, was able to utilise more soil water throughout the profile in the same plots in the following year ie. soil water was reduced to near the LSL by the barley but not wheat. It is easy to over-estimate the amount of soil water present, especially if heavy rain falls near harvest or during the subsequent autumn period as a significant proportion of this water can be lost to evaporation. A lack of soil water in the subsoil after harvest is not absolute proof that subsoil constraints are absent as many soil profiles, especially those with large PAWC eg. Vertosols, require very large amounts of good soaking rain (> 200 mm) to fully recharge the profile.

Conclusions

Knowledge of what is happening to the soil water under a crop is an essential prerequisite for the recognition and management of subsoil constraints for all grain crops. Measurement and subsequent benchmarking of water use efficiency by a crop is a prerequisite for identifying the presence of subsoil constraints. Assumptions about how much soil water is present at any one time are no substitute for observation or measurement in the paddock.

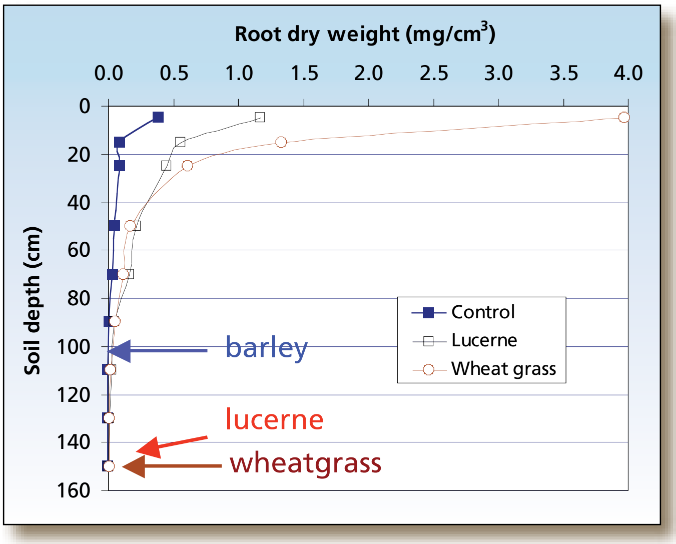

Figure 2.5: Comparison of root distribution of control (barley), lucerne and crested wheatgrass growing on a Sodosol at Birchip. Arrows represent maximum rooting depth of barley, lucerne and wheatgrass.

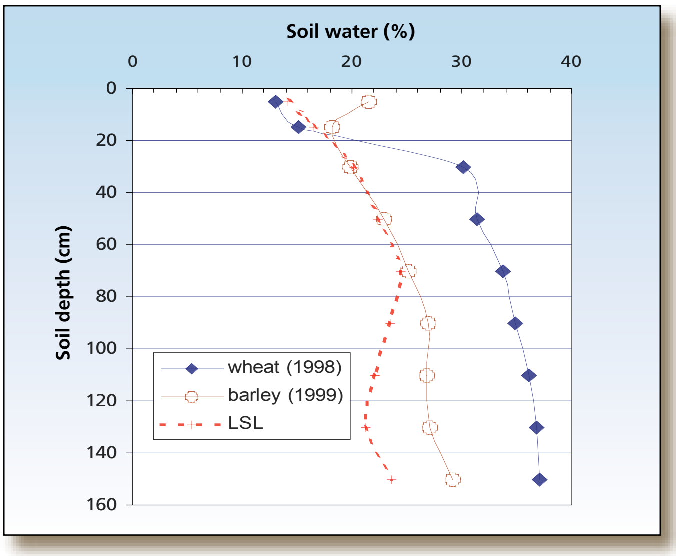

Figure 2.6: Comparison of water extraction patterns of wheat (in 1998) and barley (1999) compared to the Lower Storage Limit (LSL) on a Sodosol at Birchip.

References and further reading

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