Estimating Plant Available Water Capacity
ESTIMATING PLANT AVAILABLE WATER CAPACITY

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Acknowledgements: The authors wish to acknowledge the contributions of the Sustainable Industries Initiative Project Committee, Mike Curll, Dick Browne and Murray Jones. Specific input was received on drafts from Kathy Ophel-Keller, Beth Woods, Greg Butler and Peter Howard. Nicole Birrell was especially helpful in editing the final manuscript. Ian McMaster provided coordination support to the project.


October 2008

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OVERVIEW

The GRDC Project *Training growers to manage soil water* involves research organisations, consultants and farmers across five Australian states (New South Wales, Victoria, Tasmania, South Australia and Western Australia) in training activities associated with the management of soil water and in the characterisation of soils for plant available water capacity (PAWC). This report provides farmers and advisers with practical information, methods and tools for the characterisation of PAWC, with the aim of ensuring consistency across regions.

Why characterise soils?
Characterisation provides a way for the grower, consultant or researcher to gain a better understanding of the size of the soil ‘bucket’ in which the water resources required to grow a particular crop are stored. This information can be used in a number of ways: to add to farmers’ intuitive knowledge (‘gut feel’); to develop better rules-of-thumb for managing resources in a more informed way; and as a critical basic input to simulation modelling using tools such as APSIM and Yield Prophet®, which allow exploration of crop management issues in real time.

What is soil characterisation?
Soil characterisation is the determination of the PAWC of the soil at a particular point in the landscape. Generally the site is selected to represent a much broader section of the landscape that is considered as either being of a similar ‘soil type’ or representing associations of soils with similar characteristics. Characterisation is about defining the ability of a soil to hold water for the use of a particular crop, known as the soil water ‘bucket’. It is different from soil monitoring, which is about measuring the quantity of water in the soil bucket at a certain time.

Information required to characterise a soil for PAWC (Figure 1):
- **drained upper limit (DUL) or field capacity** – the amount of water a soil can hold against gravity;
- **crop lower limit (CLL)** – the amount of water remaining after a particular crop has extracted all the water available to it from the soil; and
- **bulk density (BD)** – the density of the soil, which is required to convert measurements of gravimetric water content to volumetric.

As well as measuring soil physical characteristics, collecting soil chemical data can provide information about the potential for subsoil constraints to affect a soil’s ability to store water, or the plant’s ability to extract water from the soil.

**Working together**
It is recommended that grower groups and/or consultants work together to identify and characterise district/regional soils. The GRDC project can help grower groups and consultants wishing to identify appropriate sites. State-based regional mapping activities may also be useful for identifying appropriate sites. Where practical it is suggested that groups attempt to locate soil characterisation sites next to existing soil description sites, thus adding value to existing information.

**FIGURE 1** A TYPICAL STORAGE PROFILE FOR A HEAVY-TEXTURED SOIL SHOWING THE POTENTIAL WATER STORAGE OF THE SOIL (PAWC) AS DEFINED BY THE DRAINED UPPER LIMIT (DUL), CROP LOWER LIMIT (CLL), SATURATION (SAT) AND TOTAL POROSITY (PO)
How do you characterise soils?

Soil properties can be determined in a number of ways including:
1. Calculation of PAWC from field measurements of DUL, CLL and BD.
2. Laboratory-based generation of a soil moisture characteristic curve, by placing a soil core under constant moisture potentials that equate to DUL (~1.0 m) and lower limit (~150 m).
3. Estimation of PAWC based on knowledge of the water-holding capacity of particular soil textural classes that form the horizons of the soil in question.

This report concentrates on the first of these methods.

What data have already been collected?

More than 500 soils have so far been characterised for PAWC. There are a number of ways of checking data availability for your area. The national database of soil water characteristics, APSoil, can be downloaded at www.apsim.info. Data may also be accessed online through the Australian Soil Resource Information System (ASRIS) website at www.asris.csiro.au/index_ie.html and viewed using Google Earth (http://earth.google.com) with individual site data available for download. The Google Earth data file (*.kml) is available for download from the ASRIS and APSRU websites.

Adding to the database

A major component of the GRDC project Training growers to manage soil water is to coordinate the ongoing collection and databasing of soil water information and to provide it in the public domain as part of the APSoil database. The authors would like to request that researchers and growers undertaking characterisation activities consider including their data in the publicly available database. Contact details of the authors are provided at the front of this report.

Locating the characterisation site in the landscape

The data must enable the characterisation site to be located in the landscape and should include geo-spatial coordinates, information on land ownership and contact details. However, it should be understood that upon publication in the public domain, any data emanating from the project will be identified by GPS coordinates only, no information relating to property name or land ownership will be published.
PART I
CHARACTERISATION FOR DRAINED UPPER LIMIT (DUL) AND BULK DENSITY (BD)

Step 1: Site selection

Sites should be selected to represent the agriculturally important soils of an area. Selecting a representative site can be difficult, particularly in areas with high spatial variability. While there are no easy answers to this challenge it is expected that by combining the local knowledge of growers, consultants and advisers, backed up by spatial tools such as yield and electromagnetic induction (EM) maps, and the support of soils experts, that the problem of soil and site identification can be minimised. In many cases this may mean that it is necessary to characterise a number of sites within a landscape to represent the inherent variability. Soils are highly variable and characterisation of a ‘soil type’ for plant available water capacity (PAWC) will only ever be a good estimation for the particular point and, if the site was selected carefully, a reasonable estimation of the soil that surrounds it.

Select characterisation sites according to the following criteria:

- the soil is of regional importance or of particular interest to a group of growers/consultants;
- likelihood of local logistical support for the activity;
- sufficient land area to enable measurement of drained upper limit (DUL) and crop lower limit (CLL) at the same site;
- a distance of at least two to three tree heights from any tree; and
- opportunity to add to existing data sets.

DUL can be measured either opportunistically or through the establishment of a controlled characterisation site.

Opportunistic

This is the simplest way of determining DUL but it is reliant on the vagaries of the season to ensure that the profile is fully wet (to maximum rooting depth) prior to measurement. A small area of the representative soil (at least 8m x 8m) is identified, then weeded and the crop removed by hand or herbicide. The aim is to allow the soil sufficient time to naturally recharge as the season progresses. When it is considered that recharge is complete, the soil is covered with builder’s plastic (100 micron) and sealed around the edges (with loose soil) to minimise evaporation and to exclude subsequent rainfall (an area of 4 x 4m or 3 x 3m located in the middle of the area is sufficient). The site should be left to drain before sampling for moisture content. Where surface run-off reduces the efficiency of water entry, it is suggested that a layer of organic matter (such as hay) be applied to the soil surface to reduce run-off and evaporation and to enhance infiltration.

Controlled

The establishment of a soil characterisation site (Photos 1 and 2) allows for the controlled application of water and provides confidence that the soil has been fully recharged before sampling. Trickle irrigation is an efficient and cheap method of irrigation as the dripper system can be reused a number of times.

Step 2: Sampling for soil chemistry

Purpose: to determine soil chemical characteristics that may affect PAWC.

Note: Sampling for soil chemistry may occur at any time, but is usually undertaken during site installation or at the time of DUL and BD measurement. Do not take samples from within the irrigated area, that is at DUL measurement, in case changes in soil chemical status have occurred as a result of the wetting process. Take samples next to the wetted area.

Core for chemical analysis:

- use a drill rig with 37 or 50-mm diameter tube or a hand-held coring kit. Take three cores per site and bulk samples across layers;
- sample at depth intervals matched with the middle of soil horizons, or use a standard set of increments such as 0–15 centimetres, 15–30cm, 30–60cm, 60–90cm, 90–120cm, 120–150cm and 150–180cm. Use the same interval set for all measurements on a particular site including DUL, BD, CLL and chemistry; and
- dry samples for four to five days at 40°C and analyse for EC, chloride, cations, CEC, pH (H₂O and CaCl₂), B, Al, Mn, organic carbon and particle size.

Step 3: Wetting the profile for DUL determination

Purpose: wet the soil profile in preparation for measurement of DUL.

Establishing the site

- Assumining use of 4-metre-wide rolled plastic sheeting, dig a 10cm deep trench measuring approximately 3.8 x 4.2m (throw the soil to the outside). This results in a plot area of approximately 16m². If using a neutron moisture meter or other soil water monitoring device, locate the access tube centrally within the plot. Heap loose soil around the access tube to a radius of 15–20cm to ensure that rain falling on the plastic sheet will be diverted away from the tube (Photo 1).
- Use a 30m length of drip-tube (for example, DripEze™) capable of providing equal water delivery from all emitters along its length, even at low pressure. Plug one end of
the drip-tube, pin this end to the ground near the plot centre and then arrange the drip-tube in a coil across the plot area (Photo 1).

- Connect a water reservoir via tap and filter to the drip-tube, fill the reservoir and check operation of the dripper system.
- Cut a 4.4m length of 4m wide 100 micron black plastic sheeting and lay across the plot. Bury 10cm of each edge in the trench. If an access tube for monitoring is present, cut a small cross, force the tube through the cut plastic and seal it with duct tape (Photo 2).
- Where grazing is likely, or feral animals such as pigs are a problem, erect a fence around the plot.
- Start irrigation of the site, regulating flow rate to ensure that surface ponding does not occur outside the plot area.
- Control weeds in the 2m buffer area around the plot during irrigation and drainage.
- When it is estimated (or determined through monitoring) that the wetting front has reached full crop-rooting depth, turn off the water and leave the plot to drain.

Note: Care should be taken, particularly in sandy-textured soils, to ensure that the concentric rings of dripper line are laid sufficiently close to each other to ensure consistent wetting across the whole area. Where lines are too widely spaced it is possible to have ‘cones’ of wetting surrounded by areas of dry. On heavy clays it is suggested that lines be laid approximately 30cm apart, and on lighter textured soils 15-20cm apart, although this should be confirmed for individual soils.

How much water should be applied?
Rate of application and the required amount of water to reach DUL will depend on the texture of the soil and estimated depth of rooting.

Heavy textured soils (for example, black and grey vertosols) hold large quantities of water and wet and drain very slowly, so a ‘softly softly’ approach to wetting is recommended. Applying about 200 litres of water a week is a good rule of thumb. This can be increased if no surface ponding of water around the characterisation site is observed. Because of the high clay content (and consequently the small pore space) these soils drain very slowly. Expect that it may take three to six months for wetting to a potential rooting depth of 1.8m and one to two months for effective drainage to cease. Because of the slow wetting it is recommended that monitoring be undertaken during this phase, that is, occasional coring or use of a neutron moisture meter or other such device (see below).

On lighter textured soils, time to wet will vary from one day for deep sands to several weeks for medium-textured soils such as the loams and clay loams. Higher rates of water application are possible on these soils with rates of several hundred litres per day reported. Application rate should be reduced if surface ponding of water is observed on the soil surface outside of the characterisation area.

How long will it take for the soil to drain?
Time will vary with soil texture. Deep sands will drain in a couple of days, medium-textured soils in about two weeks and heavy clays over a number of months, although drainage rates in heavy clays are so low that, practically speaking, soils can be sampled after one or two months. Take care to control all weeds and crops within the surrounding buffer area during drainage (2m on all sides is recommended).
Monitoring the wetting process
Using an NMM or similar monitoring device: The most convenient way to gauge the progress of wetting is to use a monitoring device such as a neutron moisture meter (NMM). This requires the installation of an access tube in the centre of the characterisation site.

- Before installing an access tube, consider whether it will interfere with, be damaged by or cause damage during normal land management practices such as spraying or harvesting operations.
- Drill a vertical hole that closely fits the diameter of the access tube using either a hydraulic rig or hand equipment and insert the tube. For rigid soils, pour kaolinite clay slurry into the hole and insert the tube before the slurry has time to set. This ensures good hydraulic contact between tube and soil. A little slurry forced out of the hole indicates enough was used. The kaolinite should be mixed at a ratio of about 50:50 clay to water (by volume).
- Take moisture readings at regular intervals, recording and graphing the recharge.
- A standing platform (that straddles the plot) is recommended when undertaking readings. This allows the operator to access the tube without compacting the surrounding soil surface.

Figure 2 shows the wetting process, using raw data collected with a neutron moisture meter. Over time, as water is applied, the Count line will move to the right, representing profile recharge as irrigation water moves deeper into the profile. This line will eventually stabilise, indicating that saturation has been reached, then move back to DUL as drainage occurs. Note that the line is generally not linear, indicating differences in soil texture and bulk density through the profile and corresponding change in water holding capacity of the soil.

Coring: Where a neutron moisture meter or similar device is not available, the use of an auger or corer to check soil wetting prior to DUL sampling is a good practical option. Whilst gravimetric determination of soil water content is preferred, simply removing the core and ‘touching and feeling’ the soil to confirm moisture presence may suffice.

WHAT EQUIPMENT IS NEEDED TO SET UP A BD/DUL SITE?
Materials
- water reservoir (fire-fighting tank, 1000L skip, 200L drum etc);
- poly tap, piping, fittings and filter to join reservoir to irrigation drip-tube;
- drip-tube (embedded dripper type recommended), 13mm diameter and 30m in length, with a plug for one end;
- plastic sheet, black 100 micron, 4.4m length from a 4.0m-wide roll;
- rainwater or other good quality, low salinity water – about 1000 to 4000L depending on soil texture and starting soil moisture content; and
- if using a NMM: an access tube, a rubber stopper, enough kaolinite/water to make around 10L of slurry and duct tape.

Tools
- hacksaw;
- knife;
- small half-round file;
- flat and Phillips screwdrivers;
- pliers;
- shovel;
- spanners or other tools required for irrigation system fittings;
- (if using NMM tubes) a drill rig or soil auger to make the hole and insert the tube; and
- large bucket and a mixing stick for the slurry.

Maintenance and monitoring of site
- mobile water tank;
- NMM or soil-coring equipment to monitor wetting; and
- datasheet to collect data for use in graphing the progress of soil wetting.

Figure 2 The wetting process, using raw data collected with a NMM.
Step 4: Sampling for DUL and BD

Purpose: to sample for soil moisture content at DUL and to determine the BD.

Note:
- a) this activity should not occur until drainage has ceased;
- b) samples for BD can be taken at any time (in rigid soils), but it makes practical sense to sample at DUL so that DUL and BD can be determined together.

Rigid soils

For these soils, where both DUL and BD are to be field measured it is suggested that a process be used that provides information on both parameters using the one sample. Samples are taken for BD at predetermined depths (the middle of each layer) from which gravimetric moisture at DUL is also determined. Samples may be collected using a hydraulic driving system, surface-based hand augering/coring or from the face of a pit.

The hand coring method shown in Figure 3 and Photos 3 to 13 enables intact samples (75mm diameter x 50mm height) to be taken to a depth of 180cm without the need for a pit. Where a pit is preferred, a similar sampling process and tools are used, with a backhoe replacing the hand auger to access soil at depth. Taking 3 replicates x 7 layers per site (to determine DUL and BD) generally takes about three hours using the auger method, but varies due to soil conditions. BD and DUL can also be done using hydraulically operated systems with large diameter tubes. BD should not be measured using tubes of less than 75mm diameter due to the potential to significantly alter BD through soil compression.

Leave the plastic plot cover in place during sampling to provide a cleaner working environment. Cut holes to access the soil, taking care to avoid cutting the irrigation system (Photos 3 and 4).

- The recommended sampling depth for DUL and BD is 1.5 to 1.8m unless plant rooting depth is restricted by physical or chemical constraints, such as rock or high salinity.
- Record data (Appendix 3, Datasheet 1 – rigid soils). Measure and record dimensions of the sampling ring. Sample volume is critical to BD estimation, so it is important to measure ring dimensions accurately (+/-1mm) and to process samples carefully.
- Sample at depth intervals that match soil horizons or, if

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**Figure 3** Schematic of Hand Coring Process

- **Hand Auger**: 20-25cm diameter head
- **Steel Datum Pins**: Located either side of auger hole
- **Sample Ring**: 50mm height, 75mm diameter
- **Sample Location**: Straddles the mid-point of each soil layer
- **Hammer**: Slides vertically on shaft to tap ring into soil

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Photo 3: Cut hole in plastic.

Photo 4: Locate steel datum pins either side of core site.
appropriate, a set of standard depth intervals such as: 0–15cm, 15–30cm, 30–60cm, 60–90cm, 90–120cm, 120–150cm and 150–180cm.

- If using the method described by the accompanying photos, work accurately from a surface datum (small bolts or steel rod tapped in flush to the soil surface, Figure 3, Photo 4) and avoid contamination of the sample with loose material from higher levels or from the soil surface.
- Take care when trimming the sample to ensure accurate levelling of soil. Smooth out small imperfections in the surfaces of the sample and if excess soil or small pebbles are removed in the levelling process, replace with a suitable quantity of similar soil or sand.

Shrink/swell soils

The method described above for rigid soils can also be used for shrink/swell soils (such as the vertosols common in northern Australia and parts of the south), but there is also an alternative.

For shrink/swell soils it is possible to measure gravimetric soil water at DUL (using a 37 or 50mm diameter coring tube) and calculate BD, a much easier process than having to sample for BD in the field.

Processing samples for DUL and BD

If weighing immediately in-field:
- place samples in wet-strength paper bags;
- record wet sample weight after taring the balance with one of the paper bags;
- dry the samples at 105°C until at constant weight (usually about 48 hours);
- tare the balance with the dried paper bag and weigh the samples; and
- record the dry soil weight on Datasheet 2 (Appendix 3).

If weighing on return to office:
- place samples in sealed plastic bags and keep cool until return to office;
- weigh samples after taring the balance for the plastic bag;
- put each sample into a labelled tray, ensuring that all of the soil is removed from the bag, and dry them at 105°C; and
- tare the balance with one of the trays and record the dry soil weight.
For rigid soils (and shrink/swell where BD field measured) calculate DUL and BD by:
- using Datasheet 1 (Appendix 3) determine gravimetric soil water per cent and BD for each layer;
- check whether data meets required criteria (SAT-DUL >/= 5%) and if not met recalculate using same datasheet;
- calculate volumetric soil water content at DUL; and
- graph the volumetric water percentage and bulk density for the profile.

For shrink/swell soils (where DUL measured in field and BD calculated) calculate DUL and BD by:
- using Datasheet 2 (Appendix 3) determine gravimetric soil water per cent for each sample;
- calculate BD using criteria (PO-SAT >/= 3%; SAT-DUL >/= 5%);
- calculate volumetric soil water content at DUL; and
- graph the volumetric water percentage and bulk density for the profile.

Note: Datasheets (Appendix 3) may be copied and used for the recording and calculation of DUL and BD. Copies of the datasheet are also available for download at www.apsim.info.
PART II
CHARACTERISATION FOR CROP LOWER LIMIT (CLL)

Step 5: Identify and establish sites for CLL measurement

Purpose: to identify and establish site for the measurement of CLL. To ensure sufficient initial water in the soil profile for the selected crop to grow to its potential and to extract all available water before it senesces or reaches maturity.

Note: For successful measurement of CLL it is important that moisture is present to the full depth of potential rooting prior to flowering of the crop. To ensure that this condition is met it may be necessary to apply water using a drip irrigation system early in crop growth. A suggested method is to measure DUL before the start of the winter season, over-sow the commercial crop and either use the DUL site for measurement of CLL, or place drippers (with no plastic cover) in an adjacent area of emerging crop and apply water for the first few weeks of crop growth to ensure recharge of the profile. Take care if using the old DUL site to avoid sampling for CLL in previously compacted or disturbed areas.

Plot characteristics:
- locate CLL plot close to DUL plot, but not so close that lateral seepage occurs between the two plots (if measuring DUL and CLL concurrently). Where the CLL is measured after the DUL, use either the same site (with the provisos mentioned in the note above), or one located nearby;
- somewhere that will not interfere with normal farm practice (spraying etc); and
- select crop(s) common to the soil type and region. It is common to sample CLL opportunistically, setting up a site in whatever crop the grower happens to sow after DUL has been measured. Where the opportunity arises it may be possible to set up adjacent sites in two adjoining paddocks and collect CLL on two different crops. Sometimes it may be possible to set up a site that measures CLL for a range of crops, for example at a field day site.

Determine whether irrigation is necessary (see the note above):
- If summer rains have been followed by good breaking rains there should be no need to irrigate. If not, and unless it is appropriate to use the DUL site, transfer the DUL plot irrigation system to the cropping plot(s) and apply water equivalent to that of good rains.

If irrigation is necessary:
- apply water such that soil moisture content is somewhere between CLL and DUL; and
- do so sparingly since excessive water may prevent the crop from reaching CLL later.

Step 6: Core for soil moisture at anthesis

Purpose: to assist with determination of crop rooting depth and water extraction at maturity.

Coring at anthesis provides information on interim soil water status with which the data collected at crop maturity can be compared. Differences in these measurements provide knowledge of rooting depth and extraction patterns within the profile. This minimises the possibility of data misinterpretation, particularly in relation to water extraction at depth. This is useful where seasons have been erratic and it is not known whether the profile has been fully wet to depth during the preceding fallow or summer period. Without this measurement it is possible, when sampling for CLL, to make the mistake that the dry soil at depth was a result of current crop extraction, whereas in fact it was due to extraction by a preceding crop.

Procedure
Core for soil moisture:
- using a hand corer, to minimise crop damage, take samples at the previously established sampling depths;
- bag the samples in either paper or plastic bags, depending on the sampling procedure; and
- avoid sampling within at least 75cm of previous coring holes or access tubes if sampling on the old DUL/BD site.

Process samples for gravimetric water:
- process as per Step 4;
- use Datasheet 3 (Appendix 3) to calculate gravimetric and volumetric soil water percentage; and
- graph the results.
Step 7: Erecting rain-exclusion tent at anthesis

Purpose: to exclude rain that might otherwise prevent the crop extracting enough water to reach CLL.

Erect a rain-exclusion tent over each crop being studied (Photos 14 to 16):
- leave ends open to ensure ventilation;
- use a roof pitch of at least 20 degrees to shed water efficiently;
- use long star-pickets driven deep into the soil to prevent roof collapse if the surface soil becomes saturated;
- the length of the cover (7m) allows the ends to be rolled and placed in trenches (Figure 4(a)) dug along the inside of each side of the tent. Backfill the trenches with the roof crest pipe hung a little low. This anchors the tent against strong winds with permanently dry soil and begins to tension the cover;
- finish tensioning the cover by pushing the roof crest pipe up against the plastic (now anchored by soil in the trenches) and tying it in place; and
- dig a trench inside the drip line across the ends of the tent to prevent tent run-off or overland flow from entering the tent (Figure 4(b)).

CONSTRUCTING A RAIN-EXCLUSION TENT

Materials:
- six long star-posts
- three 3m lengths of 1” (approx) steel round or box section tubing
- wire to connect frame components
- cover:
  - fabric – Solar Weave, Solar Shield or similar (or clear plastic)
  - dimensions – 3m wide x 7m long finished size
  - two sides have reinforced edge with six eyelets along each side, ends not hemmed
  - eyelet spacing from bottom left-hand corner 2350cm, 2450cm, 3450cm, 3550cm, 4550cm and 4650cm – other side to mirror
- duct tape to prevent plastic cover from chaffing on tubing

Tools:
- mallet or picket driver
- pick to dig anchor trench
- shovel to excavate and backfill anchor trench
- pliers
- measuring tape
- marker pen
- Stanley knife
Step 8: Core for CLL at crop maturity

Purpose: to measure the CLL of a particular crop on a particular soil type.

Remove the rainout shelter:
- this allows unrestricted access for coring and clears the paddock of tent components ready for harvesting.

Core for soil moisture:
- take three cores at the established sampling depths spaced along the centre line of the tent and at least 50cm from each end; and
- look for, and note the depth to which, crop roots are present in each core.

Process samples for gravimetric water:
- process as per Step 4 (p10); and
- calculate gravimetric water content using Datasheet 1 or 2 (Appendix 3) to record and calculate CLL.

Graph the results:
- graph the CLL data.

It is common for some air drying to have occurred in the top two layers of the profile. For this reason it is recommended that values for these layers be changed to equal the value measured in layer three, unless soil texture changes sharply down the profile (duplex soil), in which case it will be necessary to make some judgement of the values to use based on similar soils in the APSoil database.

PART III

CALCULATION OF PAWC

PAWC can be calculated and graphed using Datasheet 1 (Appendix 3) for rigid soils (and shrink/swell where BD was field measured) or Datasheet 2 for shrink/swell soils (where BD was calculated from gravimetric soil moisture). As previously noted, the water availability for a particular crop on a particular soil is calculated as the difference between DUL and CLL within the crop’s root zone. The depth of this zone is estimated using both the rooting depth observed during coring and the changes in soil water determined at anthesis and crop maturity.

Tips on interpretation of data
- The DUL/CLL lines represent the wet/dry extremes of available soil moisture respectively. The anthesis measurement, normally positioned between CLL and DUL, assists with the interpretation of soil water trends and rooting depth.
- Coring for CLL may extend below the depth of the crop’s actual root zone. This may lead to the over estimation of PAWC for the crop being studied, unless depth of root zone was observed and recorded, and water extraction at time of CLL sampling compared with that at anthesis (Step 6), to define the actual depth of the root zone. This should not be an issue if the profile was sufficiently wet prior to measurement of CLL (Step 5).

Undertaking this process over a number of cropping seasons, together with insight into the ability of different pastures and crops to extract soil water, helps build a good understanding of the seasonal wetting and drying cycles of the soil. Once the DUL and BD have been measured for a particular soil type, the measurements do not need to be repeated. However, as CLL varies between crop species grown on the same soil, it is recommended that a range of crops be measured as the opportunity arises.
APPENDIX 1: IRRIGATION REQUIREMENTS FOR WETTING DUL/BD SITE

The quantity of water required is that which will fully wet the soil to the full depth of crop rooting. It is very difficult to accurately estimate the amount for an uncharacterised soil, but the method below provides a starting point that should minimise the water requirement and the time required to irrigate and drain the DUL/BD characterisation plot.

Estimation of water required for a range of soil texture classes

The following rules of thumb are based on data from field characterisation of soils representing a range of texture classes, where the millimetres of available water per centimetre of soil depth have been calculated (assuming that rooting depth is 150cm). It is reasonable to assume that a soil within a texture class intermediate to those provided in Table 3 would also have an intermediate water requirement.

**Example 1**

Assuming that the soil is a heavy clay which holds 1.5mm/cm to 150cm:

- Soil water capacity factor (mm/cm) = 1.5
- Expected rooting depth (cm) = 150
- Estimated soil water (mm) = 1.5 x 150 = 225
- Estimated soil water (L/m²) = 225
- Estimated water for 16m² site (L) = 225 x 16 = 3600
- Assume 20% inefficiency in application = 3600 x 120% = 4320

**Example 2**

Assuming that the soil is a deep sand which holds 0.5mm/cm to 150cm:

- Soil water capacity factor (mm/cm) = 0.5
- Expected rooting depth (cm) = 150
- Estimated soil water (mm) = 0.5 x 150 = 75
- Estimated soil water (L/m²) = 75
- Estimated water for 16m² site (L) = 75 x 16 = 1200
- Assume 20% inefficiency in application = 1200 x 120% = 1440

Please remember:

- that the assumption inherent in these calculations is that the soil is at lower limit when the water is applied – if the soil already contains available water, then the amount required to reach DUL will be less;
- that these estimates are based on a judgement about the soil chosen to represent the soil type at the site, so discrepancy between this estimate and the actual water requirement may occur;
- depth of wetting should be confirmed and sufficient drainage time allowed before sampling for DUL; and
- wet the soil slowly over time – small quantities of water over a long period provide the best wetting, particularly on heavy clays or sodic soils where entry and movement of water will be slow.

**Table 1: Rule of Thumb Soil Water Capacity Estimates (mm Water/cm Soil) for Common Soil Texture Classes**

<table>
<thead>
<tr>
<th>Texture class</th>
<th>Estimated PWAC (mm water/cm soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.5</td>
</tr>
<tr>
<td>Sandy loam to clay loam</td>
<td>0.8 to 1.2</td>
</tr>
<tr>
<td>Heavy clay</td>
<td>1.5 to 2.0</td>
</tr>
</tbody>
</table>
APPENDIX 2:
DETERMINATION OF SOIL TEXTURE

This section describes a method for field texturing, a useful skill and a source of information for the soil characterisation database.

Procedure for describing soil texture
Repeat the following steps for each sampling layer of the soil:
1. Take enough soil to fit into the palm of your hand, removing large stones, twigs, etc.
2. Moisten the soil with water, a little at a time, and knead until the ball of soil just fails to stick to your fingers. Then add slightly more water to get it to the sticky point, which is the drained upper limit (DUL) of the soil.
3. Work the soil in this manner for one to two minutes, relating its behaviour to that described in the soil texture guide. Inspect the sample to see if sand is visible. If not visible, it may still be felt or heard as the sample is worked.
4. Squeeze and feed the ball out between thumb and forefinger to form a ribbon. Note the maximum length of self-supporting ribbon formed.
5. Use the following notes and the soil texture guide to classify the texture of the soil.

A soil with a high proportion of:
- sand – will feel gritty;
- silt – will feel silty; and
- clay – will feel sticky.

Soil texture can change down the soil profile and is described using the following terms:
- uniform – the texture is the same throughout the profile;
- duplex – the texture changes by more than 20 per cent within 5cm of depth, often at about 15cm (these are also called texture-contrast soils); and
- gradational – the texture changes gradually down the profile. Many soils vary from a loamy surface to a clay loam and then to clay.

<table>
<thead>
<tr>
<th>Ball ...</th>
<th>Ribbon (cm)</th>
<th>Feel</th>
<th>Texture</th>
<th>Acronym</th>
<th>Clay (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>... will not form</td>
<td>0.5</td>
<td>Single grains of sand stick to fingers</td>
<td>Sand</td>
<td>S</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>... just holds together</td>
<td>1.3–2.5</td>
<td>Feels very sandy; visible grains of sand</td>
<td>Loamy sand</td>
<td>LS</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>... holds together</td>
<td>2.5</td>
<td>Slightly spongy; fine sand can be felt</td>
<td>Loamy fine sand</td>
<td>LFS</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>... holds together</td>
<td>1.3–2.5</td>
<td>Fine sand can be felt</td>
<td>Fine sandy loam</td>
<td>FSL</td>
<td>15</td>
</tr>
<tr>
<td>... holds together</td>
<td>2.5</td>
<td>Spongy, smooth, not gritty or silky</td>
<td>Loam</td>
<td>L</td>
<td>15–20</td>
</tr>
<tr>
<td>... holds together</td>
<td>2.5</td>
<td>Very smooth to silky</td>
<td>Silt loam</td>
<td>SL</td>
<td>0–25</td>
</tr>
<tr>
<td>... holds together strongly</td>
<td>2.5–4.0</td>
<td>Sandy to touch, medium sand grains visible</td>
<td>Sandy clay loam</td>
<td>SCL</td>
<td>20–30</td>
</tr>
<tr>
<td>... holds together</td>
<td>4.0–5.0</td>
<td>Plastic, smooth to manipulate</td>
<td>Clay loam</td>
<td>CL</td>
<td>30–40</td>
</tr>
<tr>
<td>... holds together</td>
<td>5.0–7.5</td>
<td>Plastic, smooth; slight resistance to shearing between thumb and forefinger</td>
<td>Light clay</td>
<td>LC</td>
<td>35–45</td>
</tr>
<tr>
<td>... holds together strongly</td>
<td>&gt; 7.5</td>
<td>Plastic, smooth, handles like plasticine; can mould into rods without fracture; moderate shearing resistance</td>
<td>Medium clay</td>
<td>MC</td>
<td>45–55</td>
</tr>
<tr>
<td>... holds together strongly</td>
<td>&gt; 7.5</td>
<td>Plastic and smooth, handles like stiff plasticine; can mould into rods without fracture; very firm shearing resistance</td>
<td>Heavy clay</td>
<td>HC</td>
<td>&gt; 55</td>
</tr>
</tbody>
</table>
APPENDIX 3: DATASHEETS

Datasheet 1: Rigid soil—calculation of DUL, BD, CLL and PAWC

Note that it will be necessary to duplicate this sheet where more than one rep is being sampled.

**Example**

<table>
<thead>
<tr>
<th>Sample no</th>
<th>Depth range (cm)</th>
<th>Layer thickness (cm)</th>
<th>Sample height (cm)</th>
<th>Tube radius (cm)</th>
<th>Core vol (cc)</th>
<th>Sample wet wt (g)</th>
<th>Sample dry wt (g)</th>
<th>DUL gravimetric (g/g)</th>
<th>DUL gravimetric (%)</th>
<th>Bulk density (g/cc)</th>
<th>DUL volumetric (mm/mm)</th>
<th>DUL volumetric (%)</th>
<th>PO volumetric (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-15</td>
<td>15</td>
<td>5</td>
<td>3.75</td>
<td>221</td>
<td>450</td>
<td>365</td>
<td>0.233</td>
<td>23.3</td>
<td>1.65</td>
<td>0.385</td>
<td>38.50</td>
<td>0.38</td>
</tr>
<tr>
<td>2</td>
<td>15-30</td>
<td>15</td>
<td>5</td>
<td>3.75</td>
<td>221</td>
<td>440</td>
<td>400</td>
<td>0.100</td>
<td>10.0</td>
<td>1.81</td>
<td>0.181</td>
<td>18.12</td>
<td>0.32</td>
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<td>30-60</td>
<td>30</td>
<td>5</td>
<td>3.75</td>
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<td>395</td>
<td>370</td>
<td>0.068</td>
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<td>1.68</td>
<td>0.113</td>
<td>11.32</td>
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<td>4</td>
<td>60-90</td>
<td>30</td>
<td>5</td>
<td>3.75</td>
<td>221</td>
<td>387</td>
<td>360</td>
<td>0.075</td>
<td>7.5</td>
<td>1.63</td>
<td>0.122</td>
<td>12.23</td>
<td>0.38</td>
</tr>
</tbody>
</table>

**Calculation Sheet**
### BD AND DUL – RECALCULATED WHERE SAT - DUL < 5% (COL O)

<table>
<thead>
<tr>
<th>SAT volumetric (mm/mm)</th>
<th>SAT volumetric (%)</th>
<th>SAT-DUL (mm/mm)</th>
<th>new BD (g/cc)</th>
<th>new DUL volumetric (mm/mm)</th>
<th>new DUL volumetric (%)</th>
<th>new SAT volumetric (mm/mm)</th>
<th>new SAT volumetric (%)</th>
<th>Sample wet wt (g)</th>
<th>Sample dry weight (g)</th>
<th>CLL volumetric (%)</th>
<th>CLL gravimetric (%)</th>
<th>new DUl</th>
<th>PWAC per layer (mm)</th>
<th>PWAC profile (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>N</td>
<td>O</td>
<td>1</td>
<td>Q</td>
<td>R</td>
<td>S</td>
<td>T</td>
<td>U</td>
<td>V</td>
<td>W</td>
<td>X</td>
<td>Y</td>
<td>Z</td>
<td>19</td>
</tr>
<tr>
<td>0.346</td>
<td>34.61</td>
<td>0.351</td>
<td>35.11</td>
<td>0.401</td>
<td>40.11</td>
<td></td>
<td></td>
<td>190</td>
<td>180</td>
<td>6</td>
<td>8</td>
<td>40</td>
<td>99</td>
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</tr>
<tr>
<td>0.286</td>
<td>28.63</td>
<td>0.11</td>
<td>1.51</td>
<td>0.351</td>
<td>35.11</td>
<td></td>
<td></td>
<td>199</td>
<td>190</td>
<td>5</td>
<td>9</td>
<td>14</td>
<td></td>
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</tr>
<tr>
<td>0.338</td>
<td>33.76</td>
<td>0.22</td>
<td>0.351</td>
<td>0.401</td>
<td>40.11</td>
<td></td>
<td></td>
<td>362</td>
<td>355</td>
<td>2</td>
<td>3</td>
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<tr>
<td>0.355</td>
<td>35.47</td>
<td>0.23</td>
<td>0.351</td>
<td>0.401</td>
<td>40.11</td>
<td></td>
<td></td>
<td>369</td>
<td>357</td>
<td>3</td>
<td>5</td>
<td>20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* if Column 'O' < 0.05 = (R - X) x thick / 10

### CROP LOWER LIMIT

<table>
<thead>
<tr>
<th>Sample wet wt (g)</th>
<th>Sample dry weight (g)</th>
<th>CLL gravimetric (%)</th>
<th>CLL volumetric (%)</th>
<th>new DUl</th>
<th>PWAC per layer (mm)</th>
<th>PWAC profile (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

### ESTIMATING PLANT AVAILABLE WATER CAPACITY

- **BD and DUL – Recalculated Where SAT - DUL < 5% (COL O)**
- **Crop Lower Limit**
- **PAWC**
Datasheet 2: Shrink/swell soil-Calculation of DUL, BD (from measured gravimetric moisture at DUL), CLL and PAWC

### EXAMPLE

**BULK DENSITY (BD) AND DRAINED UPPER LIMIT (DUL)**

<table>
<thead>
<tr>
<th>Sample no</th>
<th>Depth range (cm)</th>
<th>Layer thickness (cm)</th>
<th>Sample height (cm)</th>
<th>Tube radius (cm)</th>
<th>Core vol (cc)</th>
<th>Sample wet wt (g)</th>
<th>Sample dry wt (g)</th>
<th>DUL gravimetric (g/g)</th>
<th>DUL gravimetric (%)</th>
<th>Bulk density (g/cc)</th>
<th>DUL volumetric (mm/mm)</th>
<th>DUL volumetric (%)</th>
<th>SAT volumetric (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-15</td>
<td>15</td>
<td>5</td>
<td>3.75</td>
<td>221</td>
<td>450</td>
<td>300</td>
<td>0.500</td>
<td>50.0</td>
<td>1.05</td>
<td>0.524</td>
<td>52.43</td>
<td>0.574</td>
</tr>
<tr>
<td>2</td>
<td>15-30</td>
<td>15</td>
<td>5</td>
<td>3.75</td>
<td>221</td>
<td>440</td>
<td>301</td>
<td>0.462</td>
<td>46.2</td>
<td>1.10</td>
<td>0.506</td>
<td>50.63</td>
<td>0.556</td>
</tr>
<tr>
<td>3</td>
<td>30-60</td>
<td>30</td>
<td>5</td>
<td>3.75</td>
<td>221</td>
<td>395</td>
<td>280</td>
<td>0.411</td>
<td>41.1</td>
<td>1.17</td>
<td>0.479</td>
<td>47.95</td>
<td>0.529</td>
</tr>
<tr>
<td>4</td>
<td>60-90</td>
<td>30</td>
<td>5</td>
<td>3.75</td>
<td>221</td>
<td>387</td>
<td>280</td>
<td>0.382</td>
<td>38.2</td>
<td>1.21</td>
<td>0.463</td>
<td>46.29</td>
<td>0.513</td>
</tr>
</tbody>
</table>

### CALCULATION SHEET

**BULK DENSITY (BD) AND DRAINED UPPER LIMIT (DUL)**

<table>
<thead>
<tr>
<th>Sample no</th>
<th>Depth range (cm)</th>
<th>Layer thickness (cm)</th>
<th>Sample height (cm)</th>
<th>Tube radius (cm)</th>
<th>Core vol (cc)</th>
<th>Sample wet wt (g)</th>
<th>Sample dry wt (g)</th>
<th>DUL gravimetric (g/g)</th>
<th>DUL gravimetric (%)</th>
<th>Bulk density (g/cc)</th>
<th>DUL volumetric (mm/mm)</th>
<th>DUL volumetric (%)</th>
<th>SAT volumetric (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
</tbody>
</table>
### Estimating Plant Available Water Capacity

**Example Bulk Density (BD) and Drained Upper Limit (DUL) Crop Lower Limit (CLL) PAWC**

<table>
<thead>
<tr>
<th>SAT Volumetric (%)</th>
<th>Sample Wet wt (g)</th>
<th>Sample Dry weight (g)</th>
<th>CLL Volumetric (%)</th>
<th>PAWC per Layer (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T ( \text{sat} ) ((\text{mm} / \text{mm}) \times 100 = S \times 100 )</td>
<td>U</td>
<td>V</td>
<td>W ((\text{wet} – \text{dry}) / \text{dry} \times 100 = (U – V) / V \times 100 )</td>
<td>X</td>
</tr>
<tr>
<td>57.43</td>
<td>190</td>
<td>160</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>55.63</td>
<td>199</td>
<td>170</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td>52.95</td>
<td>362</td>
<td>320</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>51.29</td>
<td>369</td>
<td>330</td>
<td>12</td>
<td>14</td>
</tr>
</tbody>
</table>

**PAWC Calculation Sheet**

\[ z = \sum \text{column Y} \]

\[ a = \text{R} \times \text{A} / 10 \]

\[ b = \text{R} \times \text{P} \]

\[ c = \text{w} \times \text{P} \]

\[ d = \text{R} \times \text{Q} \]

\[ e = \text{R} \times \text{R} \]

\[ f = \text{R} \times \text{S} \]

\[ g = \text{R} \times \text{T} \]

\[ h = \text{R} \times \text{U} \]

\[ i = \text{R} \times \text{V} \]

\[ j = \text{R} \times \text{W} \]

\[ k = \text{R} \times \text{X} \]

\[ l = \text{R} \times \text{Y} \]

\[ m = \text{R} \times \text{Z} \]

\[ n = \text{R} \times \text{A} \]

\[ o = \text{R} \times \text{B} \]

\[ p = \text{R} \times \text{C} \]

\[ q = \text{R} \times \text{D} \]

\[ r = \text{R} \times \text{E} \]

\[ s = \text{R} \times \text{F} \]

\[ t = \text{R} \times \text{G} \]

\[ u = \text{R} \times \text{H} \]

\[ v = \text{R} \times \text{I} \]

\[ w = \text{R} \times \text{J} \]

\[ x = \text{R} \times \text{K} \]

\[ y = \text{R} \times \text{L} \]

\[ z = \text{R} \times \text{M} \]
Datasheet 3: For the calculation of gravimetric and volumetric soil water

Note that it will be necessary to duplicate this sheet where more than one rep is being sampled.

**EXAMPLE**

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Depth range (cm)</th>
<th>Layer thickness (cm)</th>
<th>Bulk density (g / cc)</th>
<th>Sample wet weight (g)</th>
<th>Sample dry weight (g)</th>
<th>Gravimetric (%)</th>
<th>Volumetric (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>D</td>
<td>E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0-15</td>
<td>15</td>
<td>1.20</td>
<td>198</td>
<td>160</td>
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<td>1.22</td>
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<td>150</td>
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<td>4</td>
<td>60-90</td>
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<td>1.35</td>
<td>370</td>
<td>291</td>
<td>27</td>
<td>37</td>
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</table>

**CALCULATION SHEET**

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Depth range (cm)</th>
<th>Layer thickness (cm)</th>
<th>Bulk density (g / cc)</th>
<th>Sample wet weight (g)</th>
<th>Sample dry weight (g)</th>
<th>Gravimetric (%)</th>
<th>Volumetric (%)</th>
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<tr>
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<td></td>
<td></td>
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<td>D</td>
<td>E</td>
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APPENDIX 4: TOOLS AND MATERIALS

Equipment Suppliers
This list is neither exhaustive nor intended to infer recommendation of particular suppliers.

- **Rain exclusion covers**
  Able to be fabricated by any canvas supplier. Covers have been obtained from NJ’s Canvas, Toowoomba (Ph 07 4630 1400) for about $140 each. While clear plastic may be used it is not advised due to the potential for the concentration of light and the development of hot spots within the crop canopy which may impact on crop growth.

- **Dripper systems**
  DripEze (DDN1320030; non-compensating, 2 L/hr drippers, dripper spacing: 0.3m) irrigation pipe or similar. Available from irrigation specialists.

- **Plastic sheeting for DUL plot**
  100 micron black builder’s plastic sheeting, 4m wide roll. Available at most hardware outlets.

- **Soil sampling equipment**
  Acre Industries manufacture general soil sampling equipment including hand coring kits and sampling tubes. Contact Cliff Edser, Mob: 0407 915 625.

- **Bulk density sampling kits**
  All-Turnit Engineering manufacture bulk density sampling kits as shown in this document. Contact Peter Ryan, Mob: 0412 746 061, Ph: 07 4633 0456.

- **Augering heads and handles**
  Dormer Engineering manufacture a range of augering systems suitable for soil sampling, Ph: 02 6672 1533.
CENTRAL WEST FARMING SYSTEMS

Presents

UNDERSTANDING PLANT GROWTH

Condobolin Agricultural Research and Advisory Station

23rd and 24th August 2011

Proudly Supported by:

The Low Rainfall Collaboration Project

Grains Research & Development Corporation
ACKNOWLEDGEMENTS

The support of the following people and organisations in contributing to these workshops and related material is gratefully appreciated

- Nigel Wilhelm (SARDI)
- Linden Masters (Farming Systems Specialist, EP Farming Systems)
- Ken Webber (NuFarm)
- Hugh Wallwork (SARDI)

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- AUSWEST
- Canola Breeders
- CBH Grain
- Seednet
Abbreviations
FI = floral initiation
DR = double ridge
TS = terminal spikelet initiation
HD = heading
At = anthesis
BGF = begin grain fill
PM = physiological maturity
Hv = harvest ripe

Development in wheat

Water stress and yield

![Diagram showing the relationship between water stress and grain yield. The x-axis represents growth stages (Germination, Emergence, Tillering, Flower initiation, Spike formation, Heading, Grain fill) at the time of stress, while the y-axis represents relative grain yield. The diagram indicates that maximum yield occurs when stress is applied before anthesis.]
Ear development in wheat

See also: Wheat: the Big Picture
HGCA (UK)
(link via MyUni)
KEY POINTS

Section 1  Emergence, tillering and ear initiation up to GS30

EMERGENCE AND EARLY LEAF AND TILLER DEVELOPMENT

Sowing depth is the key management practice in ensuring uniform, rapid and even emergence and seeding establishment. Seedlings have the capacity to emerge from as deeply as 15cm but field trials show that sowing below 6 cm generally reduces grain yield. The maximum depth of seedling is determined by the coleoptile length of the variety and is influenced by soil type. Varieties with short coleoptiles are more sensitive to deep sowing than those with long coleoptiles. The rate of germination and emergence is driven largely by soil temperature. The rate of emergence is quicker in warmer soils.

Depth of sowing is important because

- deep seed placement delays emergence, which is equivalent to sowing later, and
- seedlings emerging from greater depth are weaker and tiller poorly

Leaf and tillers appear in a regular sequence which is influenced mainly by temperature. The first tiller in wheat appears after leaf 3 has emerged and subsequent tiller appearance is synchronised to leaf appearance.

ROOTS

In cereals there are two root systems. The seminal roots develop from the embryo of the seed and are the first roots to appear after germination. In wheat 5 seminal roots can develop: a central root and two pairs of roots. In poorly developed seeds one or both of the second pair of seminal roots may be absent. The adventitious roots develop later and develop from the lower parts of the stems. The adventitious roots are also called crown or nodal roots. Rate of root elongation depends on temperature, the amount of available moisture and the resistance posed by the soil. Root growth in the subsoils can also be affected by the chemical properties of the soil – the pH, the concentration of boron and salt.

TILLERING

Production and growth of tillers is very sensitive to environmental and nutritional stress. Tiller buds are present at the base of the leaves and so there is a close connection between the number of leaves and the number of tillers produced. Whether they elongate and the degree to which they grow depends on growing conditions. Stress delays tiller appearance and slows the growth of tillers. The maximum number of tillers a variety produces is related to maturity: very early flowering varieties will produce fewer tillers than late flowering varieties.

The growth of the main stem and early-formed tillers can also suppress the development of tiller buds. Given the right growing conditions, these buds can develop if the more mature stems die or their growth rate is reduced. This is observed, for examples when crops are grazed or cut for hay which can lead to a proliferation of new tillers.

In the early stages of tiller production the growth depends on the allocation of food and water from the main plant. It is not until the tiller has established its own root system that it can become more or less independent of the mother plant. Some earlier studies have suggested that once a tiller has produced 3 leaves and has developed adventitious roots it can survive to produce an ear.
Most wheat crops produce non productive tillers which do not form an ear. These are the later formed tillers and they are generally much smaller than the main stem. Under times of stress the plant will reallocate its resources to sustain the growth of the main stem and the first one or two tillers. There is a net movement of sugars, N and some minerals from the smallest tillers to the larger, more competitive tillers. Because of this the non-productive tillers may act as reserves for nutrients and carbohydrates and they are sacrificed to help maintain the overall growth of the plant. They may also enable recovery if the productive tillers are damage or destroyed during crop growth.

The amount of competition for water, nutrients and light that the crop is under will determine the loss of tillers. While the small, late formed tillers can help buffer the plant against environmental stresses, their early growth relies on the diversion for sugars and N from the main stems and older tillers. Restricting the growth of these small tillers can enhance the productivity of the larger stems.

**DOUBLE RIDGE STAGE AND EAR INITIATION**

The double ridge stage marks the beginning of the ear initiation and marks the transition in the plant from the vegetative stage to the reproductive stage. It is at this stage that the ear of the mature wheat plant starts to develop and the time of ear initiation determines the time of flowering. The timing of ear initiation is affected by the maturity of the plant: early flowering varieties will initiate their ears quickly, while late flowering varieties will initiate their ears late. A variety’s sensitivity to daylength and low temperature are the main environmental factors determining the time of ear initiation.

**NOTES**
**EARLY GROWTH AND TILLERING**

The first three leaves have emerged, the fourth is tucked inside the third. The first primary tiller is just showing in the axil of leaf 1.

---

**EAR INITIATION**

The change from the vegetative to the floral state. The apical dome initiates primordia at a faster rate than they can turn into leaf primordial with the result that un-differentiated primordial stack up on the elongated apex. The development of the lower 'leaf' ridges, which are poorly defined at the top of the apex, will be arrested. The tissue between these ridges now grows and will become the 'spikelet' ridge. This stage is know as double ridge and is the key to the timing of some husbandry events, such as fertilizer application.

*Photos: ‘WHEAT: THE BIG PICTURE’*
Section 2 Jointing to ear emergence

Early ear development occurs between ear initiation and GS30. At this stage new tillers are still appearing and the number of tillers in the crop is increasing. From GS31 onwards the young ear becomes more developed. The spikelets and flowers within the spikelets develop. As development proceeds, the young ear is increasing in size and the plant is diverting more of its sugars and N to the developing ear. The greater the supply of these resources the bigger the ear can grow. This is especially important as the plant approaches booting as it is at this time that the ear is growing most rapidly and it has its greatest need to sugar and N. During this stage that the flower structures within the ear are developing and growth at this stage affects the potential number of grains that can be set.

Maximum tiller numbers occur in the early stages of stem elongation and they then start to decline as the weaker, later formed tillers die off. The amount of tiller loss depends on the level the maximum number produced and the level of competition for resources.

ROOT DEVELOPMENT

Seminal roots are the roots that develop first and they can grow deep into the soil. The nodal roots develop as the plant tillers and arise from the bottom of the main stem and tillers. They grow less deeply in the soil.

LEAF AREA DEVELOPMENT

The leaf area increases as the number of leaves on the stems increase and more tillers develop. Maximum leaf area is reached sometime before anthesis. The leaf area of the crop is a balance between the production and retention of leaves at the top of the canopy and the death of leaves at the base of the canopy. The bottom leaves tend to die first and the extent that this occurs is affected by the amount of light reaching the base of the canopy, the availability of N and P, and the amount of available water. Leaf death can be exacerbated by root disease and nematodes that restrict the ability of the plant to take up water and nutrients.

NOTES

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STAGES OF STEM ELONGATION

The stages of stem extension. Once the last spikelet, the terminal spikelet, has been produced the plant stem raises the immature ear up through the unfolding leaves of the upper stem. Seven remaining unfolded leaves have been stripped away from these stems to show the immature ear and the extending internodes. The bottom nodes of the shoot will not extend but the upper ones will.

Stem at 1cm (as shown on the left) is a key development stage for the timing of agricultural husbandry events. This is a time of intense competition for nutrients and reserves. The secondary and the weak primary tillers of the plant will abort as the mainstem and the strong primary tillers grow away. The later formed florets, at the tip of each spikelet, will abort before the ear emerges from the flag leaf sheath.

Photo: ‘WHEAT: THE BIG PICTURE’
Section 3 Flowering and grain filling

This is the final stage of reproductive development during which time the florets mature, the pollen develops and is released. It is period of growth that is very sensitive to environmental stress such as drought and heat.

FLORET FORMATION

Florets are the individual flowers in the head of wheat. Within a spikelet up to 9 or 10 florets can develop by most do not produce grain. In a typical wheat crop, only 30-40% of florets set grains. Floret survival is important because floret number determines grain number which is closely related to grain yield.

FLORET DEVELOPMENT, MEIOSIS AND ANTHESIS

The final stages of floret develop occur during booting-ear emergence. During this period the anthers develop and meiosis occurs which help determine the number of grains set within the ear. Meiosis is a key stage of development as it produces the male and female sex cells and affects how many of the florets are able to set grain. Crop fertility and yield is sensitive to stress at this stage. Meiosis occurs during the green anther stage when the anthers are still tightly enclosed within the flowers. The ear may be emerging at this stage. As the flowers reach full maturity and the pollen ripens, the colour of the anthers change and the yellow pollen stage is reached. Soon after, the pollen is shed.

GRAIN FILLING

Grain development goes through two major stages. In the initial 10-14 days after flowering the size of the grain does not change greatly, but there is rapid cell division within the young grain. After this phase, cell division stops and the cells grow rapidly as sugar transported to the grain is used to form starch. The moisture content is initially high but the grain becomes dehydrated as it approaches maturity. Physiological maturity occurs when the grain is fully developed and is capable of germination and this then progresses to the harvest ripe stage when the seed loses moisture.

There are a number of factors that determine grain size

Variety, location on plant, number of grains set, weather conditions during grain growth. Heat and water stress. (See notes on Grain Growth & development by Glenn McDonald).

Consider these key events:

Number of ears - first set by tiller number

Number of spikelets per ear - affected by genotype and environment

Number of grains per spikelet - potential grain numbers determined by number of fertile florets

Grain filling - determines final grain weight
### STAGES OF FLOWERING AND FERTILISATION

| ![Image](image1.jpg) | All the events around *anthesis* must be well co-ordinated for the successful release of *pollen* and fertilization of the *ovule*. The ear is quickly raised above the crop canopy by the growth of the last stem *internode* or *peduncle*. It remains protected inside the sheath of the *flag leaf* until the anthers are almost mature. |
| ![Image](image2.jpg) | Spikelets are arranged on alternate sides of the *rachis*. The collar is a rudimentary *spikelet* which only rarely sets grain. The last-formed, *terminal spikelet* is set at ninety degrees to the lateral spikelets, making the wheat ear a determinate structure. More spikelets are found on the mainstem than on the primary tillers. The final number is genetically limited. Cultural conditions will determine how many florets within each spikelet remain viable at *anthesis*. |
| ![Image](image3.jpg) | Each *spikelet* initiates between eight and twelve florets of which only four or five will be potentially fertile at flowering. The outer glumes are barren, their function is to protect. Similarly the *lemma* and *palea* of each *floret* protect the delicate structures inside. |

*Photos and diagrams: ‘WHEAT: THE BIG PICTURE’*
STAGES OF GRAIN FILLING

**Wetery ripe stage.** Pollination is completed and the start of grain growth. Rapid cell division is occurring and the grain is increasing in length.

**Early milk stage.** Grain has reached its full length and maximum cell numbers in the endosperm has been reached. The grain is green.

**Milk stage.** Grain is half grown and the embryo is visible. The grain has entered the main period of starch deposition. Grain is green.

**Soft dough.** Grain has reached its maximum fresh weight. The moisture content is high and the green colour of the grain begins to fade.

**Hard dough.** The grain has reached its maximum dry weight and the moisture content of the grain is declining. The grain has lost most of its green colour. The grain has reached physiological maturity.

**Harvest ripe.** The grain has reached a moisture content of 10-12%.

Grain development in wheat
(adapted from Kirby and Appleyard (1981) Cereal Development Guide)
Grain growth and development in cereals

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The structure of the cereal seed
The seed of cereal crops contains three main parts, the embryo (or germ), the endosperm and the seed coat. The embryo contains the first two to three seedling leaves, surrounded by the coleoptile, and the first seedling roots. The endosperm is the main part of the seed and it largely consists of dead cells filled with starch which is embedded in protein. This is the food source for the germinating seed until the first seedling leaves start to photosynthesise. The outer part of the wheat endosperm consists is a row of living cells called the aleurone layer. This produces many of the enzymes that break down the starch and protein in the endosperm during germination as well as containing many of the mineral nutrients, such as phosphorus. The outer part of the seed consists of a number of layers of cells that are fused to form the seed coat.

Growth of the seed
The starchy endosperm comprises more than 80% of the final weight of the mature cereal seed and so the weight of individual grains and the grain protein concentration is determined largely by the deposition of starch during grainfilling. All the resources for the growth of the seed - the carbon (in the form of sugars), nitrogen (as amino acids) and minerals- are imported from the rest of the plant during the growth of the seed. As the leaves and the stems die, the complex molecules contained in them are broken down to sugars and amino acids. Much of this is transported to the seed where they are converted into starch and protein within the endosperm. Essentially the seed is preparing itself for survival until conditions for germination are favourable in the following growing season. The greater the reserves of starch, protein and minerals in the seed, the more vigorous the seedling will be.

There are two main phases of grain development: (i) grain enlargement, which involves a period of cell division followed by cell enlargement and (ii) grain filling when the cells formed during grain enlargement are filled with starch and protein (Fig 1). After grain filling has stopped the grain dehydrates until it reaches harvest ripeness. The length of the phases is sensitive to seasonal conditions. Stress will tend to reduce the length of each phase leading to smaller grains, although under mild stress the grain can compensate by growing at a faster growth rate.

1. The grain enlargement phase.
Very soon after pollination, the rudimentary structures of the seed are established. The developing seed enters a period of cell division during which time the number of cells in the endosperm increases rapidly and these cells increase in size as water moves into the developing grain. The number of cells that are formed sets the upper limit of grain size. Stress during the first 10-15 days of this stage that is severe enough to reduce cell division will limit the number of cells formed and can reduce final grain size. The grain at this stage is described as watery ripe because an almost-clear watery sap is apparent when the seed is squeezed. There is no starch in the grain at this stage and the growth of the grain is slow (Fig 1).
Figure 1. The development stages of a wheat grain in relation to the changes in gain weight. The actual timing of the developmental events and the length of the different growth stages will be influenced by weather conditions and by genotype.

Grain enlargement lasts for about 15-20 days and once it is completed, there is no further increase in cell numbers within the endosperm. Further growth of the grain depends on the deposition of starch and protein during grain filling.

2. Grain filling

This is the phase of development when the grain weight increases most rapidly because of the deposition of starch and protein from sugars and amino acids that are imported into the developing grain. The grain filling period starts 10-15 days after anthesis and continues until the grain reaches physiological maturity 20-30 days later.

The moisture content of the grain is high and as the amount of starch in the grain increases, the consistency and texture of the grain changes, giving rise to a number of distinctive stages of development, which are:

Milk stage. This is the early stage of grain filling. Starch deposition in the endosperm has just commenced and the endosperm, which is quite soft at this stage, appears as a milky fluid when the grain is squeezed between the fingers. The embryo is nearly fully formed and is clearly visible. The grain has reached its maximum length, but is still only a small fraction of its final weight. Nutrients from the leaves and stems are being remobilised to the grain in increasing amounts. The developing seed is still green at this stage.

Soft dough stage. The endosperm is becoming harder as the amount of starch in the grain increases and the moisture content of the grain starts to decline. The embryo is fully formed and the green colour of the seed starts to fade.

Hard dough stage. At this stage the grain has reached its maximum dry weight and the grain has reached physiological maturity (but not harvest ripeness). The moisture content of the grain is quite high (eg 30%) but falls rapidly to 10-12% at harvest ripeness. The grain
becomes increasingly difficult to squeeze between the fingers. The grain loses its green colour. This phase coincides with a decline in greenness from the ears and the death of the upper leaves.

3. Dehydration and maturity.
This is the ripening stage. After the grain is fully mature its dry weight does not change, but its moisture content falls. At the end of this phase the grain becomes hard and it is at harvest ripeness.

What determines final grain size?
There are a number of factors that determine grain size – the variety grown, the location of the grain on the plant, the number of grains set on the plant, weather conditions during grain growth. Some of these are described below.

Position
Where a grain is located will affect how it grows and its final grain weight.

- Grain formed on the main stem and first tiller will generally be larger than grain in the later-formed tillers.
- Grain located in the central spikelets of an ear will generally be larger than grain in spikelets at the top and the bottom of the ear.
- Grain in the bottom two florets of the spikelet will generally be larger than those in the third and fourth florets.

Grain number and grain weight
The number of grains produced by a plant is determined shortly after flowering and is the culmination of growth up to this point. This sets the potential yield of the plant. In general, crops that set a large number of grains (that is, have a high yield potential) will produce smaller average grain size. This is for two main reasons:

- The additional grains come from the later tillers and the positions in the spikelets that produce smaller grains
- There is greater competition among the developing grains for the C and N and minerals necessary for grain growth.

Conversely, if grain set is reduced at flowering for some reason, but the conditions for grain filling are adequate, the average grain size can be high.

Heat stress
Grain filling and especially starch deposition is very sensitive to high temperatures. Grain size is greatest under mild grain filling temperatures (15-20°C) because the length of the grain filling period is extended. This favours starch deposition in the grain. Once average post-anthesis temperatures rise above 25-30°C, significant reductions in grain weight occur, even under well watered conditions, because the duration of grain filling is reduced and starch deposition is reduced. Under European conditions for example, 1000 grain weights of 40-45 g are common compared to 30-35 g, or lower, in South Australia. European crops also achieve this even after setting considerably more grains per plant. This difference largely reflects the lower temperatures and milder grain filling conditions in Europe. Temperatures >30°C can curtail starch synthesis in the developing grain, but have little effect on protein
deposition. Consequently, grain protein concentration (which is essentially the ratio of protein to starch) will increase and 1000 grain weight will be low.

*Water stress*

If water stress develops gradually, wheat plants have a great capacity to maintain grain growth in part by drawing on reserves of sugars from other parts of the plant, and particularly the stems. Also, the metabolic activates related to grain filling within the grain (as opposed to the effects on leaves) appear not to be greatly affected by drought stress as the water content of the grain is relatively insensitive to drought. In other words, although the rest of the plant may suffer from drought, the grain itself may not be severely stressed. Consequently, grain size may not be greatly reduced by reduced water availability after anthesis. The smaller grain size observed under very dry conditions may be the combined effects of high temperature (both from high air temperatures and an increase in ear temperatures from reduced evaporative cooling) and water stress, rather than drought stress alone. Severe drought stress will tend to reduce the length of the grain filling period and cause a reduction in grain weight. Water stress can increase the rate of loss of green leaf area. This may increase the supply of N (as amino acids) to the developing grain and increase grain protein deposition.
Critical growth stages for maintaining sound nutrition of crops

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General Principles

- Wheat requires fourteen essential elements to grow normally and complete its life cycle, which in the case of all annual crops is to produce viable grain.
- Wheat has evolved to be extremely efficient at accessing nutrients from its environment, and generally it is very successful. However, southern Australian soils are, in general, very infertile and so present a serious challenge to wheat’s ability to acquire nutrients.
- Soils provide the vast majority of nutrients to crops and it is only when the supply is below what is required for optimum performance that fertilisers are used to supplement the soil’s reserves.
- Wheat requires a supply of all the essential elements for almost the entire time the plant is growing. It is only during the very first and last stages of development, germination and from grain fill, respectively, that it can perform well on the nutrient reserves within itself.
- While a supply of all nutrients nearly all of the time is necessary for the optimum performance of wheat, there are critical times for supply of some elements to ensure healthy growth and grain production.
- For commercial crops, the economically optimum rate to supplement supply of a nutrient is to just below adequacy. However, it is rarely possible to achieve that level of precision in reality.
- There are four ways that the supply of a nutrient to a wheat crop can be supplemented by a fertiliser in a broad-acre, rainfed situation; boosting nutrient levels in the seed, adding nutrients around the seed as a dressing, adding the nutrient to the soil for the crop to find or spraying the nutrient directly onto the shoots of the crop.
- Wheat can only extract nutrients from damp soil.

NOTE: This paper focuses on critical stages for particular nutrients during the life cycle of a wheat plant and will not deal with most of the issues around rates and dates of using fertilisers in commercial situations. It is constructed in such a way that each nutrient, which may require supplementation via fertilisers in the Upper North, is discussed separately in terms of critical stages of demand and when intervention can be most effective. Nutrients which are supplied in adequate to abundant amounts in Upper North soils for wheat will not be covered.

The primary purpose of this paper is to highlight particular stages in a wheat’s life cycle when nutrient supply is most critical or when supplementing the nutrient is most effective (or not). For details sufficient to manage the nutrition of individual wheat crops, follow ups with your normal advisory sources will be necessary.
Nitrogen

- Nitrogen is the nutrient required in the largest amounts by wheat. It performs many functions within the plant but is best known for its effect on tillering. Without adequate N, wheat will not tiller well, or will even abort existing tillers. Adequate N supply is also essential for satisfactory protein levels in grain.

- N can be quite toxic to germinating seeds, although the rates of N normally used at seeding in the Upper North rarely cause such problems in wheat; the Wandearah area is an exception to this generalisation. They can be using N rates at seeding which are a risk to germination of crops, so some capacity for banding would be an advantage in this district. Remember that canola is especially sensitive to fertiliser toxicity and I would suggest that you try to avoid applying any fertiliser in the seed row of canola.

- If the supply of N from the soil drops below adequate levels, wheat can make use of supplementary N right up to, and including, early grain fill. Thus, the effectiveness of supplementary N is dictated more by environmental conditions (ie suitable conditions for applications) than the physiology of the crop, particularly in low rainfall environments.

- In crops yielding above 2 t/ha, maintaining good N supply from late tillering to head emergence is important to preserve the extra tillers required to reach such yield targets. Since this period generally coincides with increased release of N from soil organic matter in spring; N fertilisers are only required if this increased supply is still inadequate.

- Wheat can take up N directly through its shoots, but in most circumstances, most of the N applied as a foliar application still enters via the soil and the root system.

- As N is applied later in crop development, more and more of the extra N that gets into the plant is used to produce extra protein, rather than extra grain yield.

Phosphorus

- Phosphorus is required in large amounts by wheat and since nearly all southern Australian soils are too low in P reserves for acceptable wheat performance, it is a very important nutrient in the economics of wheat production. P is a central component in the energy capturing molecules of plant cells and also assists in many defence pathways of wheat. A supply of P is required by wheat throughout nearly all of its life cycle but it is particularly damaging to the plant if its supply is poor early in the season (up to and about stem elongation).

- Using seed high in P is a good way to ensure sound germination, rapid emergence and vigorous establishment.

- The most efficient way to supplement wheat with extra P (after boosting the seed content) is to apply P fertiliser in or near the seed row of the crop.

- When applying P fertiliser to wheat at seeding, the first 5-10 kg P/ha should be applied with the seed. If any more is to be applied, just under the seed row is the preferred position for maximum benefit.

- P can be applied to the shoots of wheat but this technique is proving too unreliable so far to be recommended.
**Sulphur**

- Sulphur is required in moderate amounts by wheat but few southern Australian soils are deficient in S for wheat. S is important in protein metabolism and also assists in many defence pathways of wheat. A supply of S is required by wheat throughout nearly all of its life cycle but wheat is very adept at moving S around within the plant so supplies later in the season are not so critical. Canola is very susceptible to S deficiency because a lot of S is required to make oil.
- Like N, the effectiveness of supplementary S is dictated more by environmental conditions (ie suitable conditions for applications) than the physiology of the crop, particularly in low rainfall environments.
- Also like N, S in its available form to wheat (sulphate) is very leachable, so applications at seeding or soon after are vulnerable in this respect but tend to be the most effective applications.

**Zinc**

- Zinc is the most common and widespread of trace element deficiency in southern Australia and has been seen in the Upper North. Its most obvious role in the plant is to help maintain the integrity of cell membranes. When it is in deficient supply, many capabilities of the plant start unravelling (eg disease resistance, water use efficiency, rapid grain fill and haying off).
- Seed rich in zinc can really boost early growth in deficient soils.
- Foliar sprays on wheat are effective but best benefits are realised at the 2 leaf stage. The impact of a foliar spray gradually declines at later growth stages.
- To boost the content of seed, a foliar spray can be applied during grain set and early fill.
- Zinc moves very slowly in the soil so applications at seeding time are best in or very near to the seed row. Fluid applications near the seed row give the plant a solid band of Zn to intercept more easily.

**Copper**

- Copper deficiency has been recorded in the Upper North but is not a widespread problem. Historically, it was overcome with applications of bluestone super mixes during the 1950s and 1960s. However, these historical applications are probably starting to wearing out now and the string of dry springs we have seen in recent years can make Cu deficiency worse.
- Copper is vital to the production of the building blocks for plants but it causes its most obvious problems at flowering. Copper is essential for the production of fertile pollen so if it is in deficient supply at flowering, flowers will not set, heads will not form normally and grain production can be severely reduced.
- A foliar application within 4 weeks of flowering will protect flowering and seed set.
- While soil reserves of copper can be boosted with applications into the soil at seeding, if springs are dry, Cu deficiency can still occur during flowering.
- With the proviso that they cannot guarantee protection during flowering, soil applications are the most cost effective strategy because they can last for decades.
- Stock grazing on feed low in copper can run into their own problems with Cu deficiency.
Manganese

- Manganese is a trace element whose availability in soil drops rapidly with increasing pH. In the upper North, it is not common but can occur on the very calcareous soils and limestone ridges. Mn is vital to maintaining disease resistance pathways in plants and for the production of the mortar which holds plants upright.

- Seed rich in Mn can really boost early growth in deficient soils.

- Foliar sprays on wheat are effective but providing that seed with reasonable Mn content is used, mid tillering timing is probably the most effective; sufficiently early to avoid major growth setbacks but late enough to prolong the benefits through to late in crop development. Unless you are very experienced at detecting the onset of Mn deficiency, plant tests are the most reliable early indicator of a deficiency for predicting the need for a foliar spray.

- To boost the content of seed, a foliar spray can be applied during grain set and early fill.

- Mn moves very slowly in the soil and is rapidly fixed in calcareous soils so applications at seeding time are best in or very near to the seed row. Fluid applications near the seed row give the plant a solid band of Mn to intercept more easily. Applying with an acidic fertiliser (eg MAP) can prolong availability.

As far as we can reliably ascertain, all the other 8 essential elements required for normal wheat growth are supplied by Upper North soils in adequate amounts under most circumstances. For nutrients such as boron and salt (sodium and chloride) these supplies can be so “generous” that toxicities can occur. Since these three nutrients are quite mobile in soils, over time they have been washed down through soil profiles and have tended to accumulate at the bottom of the long term wetting front of Upper North soils (20-80 cm). Where this has led to toxic amounts in these subsoils, B and salt toxicity can start occurring as lots of roots reach these deeper layers (often in spring as crops rely more and more on subsoils for a supply of water).

Potassium (K) deficiency is another topical issue in crop nutrition at the moment but it is most unlikely to occur on Upper North soils in the foreseeable future. Frequent hay production on deep sandy soils or on infertile quartz soils are the most likely situations where K deficiency may first occur.
Understanding how much soil moisture can be stored and becomes available to a crop.

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Notes adapted from a paper kindly provided by Dr Anthony Whitbread, formerly CSIRO Sustainable Ecosystems, Waite Institute, Adelaide and now, Crop Production Systems in the Tropics, Department for Crop Sciences, Georg-August-Universität, Göttingen, Germany

Knowing the size of your soils “bucket”, or the amount of plant available water a soil can store helps in determining how much water is available to crop roots at any given time throughout the season. Stored soil moisture at sowing can play an important role in reducing the risk of winter crop failure and soils with a large plant available water capacity or ‘bucket’ having the greatest potential for storing moisture.

Factors which affect the Plant Available Water Capacity (PAWC) include physical properties such as clay percentage, particle size, salinity and rooting depth. PAWC’s are established for specific soils by setting up “soil ponds” to wet the soil to maximum capacity to establish the “drained upper limit” (DUL) Crop rain-out shelters are used to establish the “crop lower limit” (CLL) – the point at which the plant can no longer extract moisture from the soil. Soil bulk density is also measured for each distinct layer in the soil horizon to establish the water holding capacity of specific soils. This establishes the “bucket”. The crop lower limit is the most important part of the soil water bucket, as this is the critical point at which the plant cannot extract any more water from the soil profile.

Different crops have different CLL’s. For instance wheat can extract more moisture from the soil than peas. This explains why wheat crops on pea stubbles will yield better than barley crops on wheat stubbles in some dry seasons. There is simply more moisture for the wheat crop to draw on to fill grain. Many of us have incorrectly assumed the higher yields of wheat to be only the effect of extra nitrogen or better root disease control on a crop after peas.

The Interaction between Soil and Water
Adapted from: From Soil, Water and Plant Characteristics Important to Irrigation
February 1996
http://www.ag.ndsu.edu/pubs/ageng/irrigate/eb66w.htm

Thomas F. Scherer, Extension Agricultural Engineer
Bruce Seelig, Extension Water Quality Specialist
David Franzen, Extension Soils Specialist

Soil is a medium that stores and moves water. If a typical spade full of a red brown earth were separated into its component parts, about 48% of the volume would be soil particles, organic
residue would occupy about 2% of the volume, and the rest would be pore space. The pore space is the voids between soil particles and is occupied by either air or water. The quantity and size of the pore spaces are determined by the soil's texture (see figure 1 for soil particle classifications), bulk density and structure.

Figure 1. Classification by size of the primary soil particles which define a textural group based on the U.S. Department of Agriculture soil classification system. Under SAND, V.F. refers to very fine and V.C. to very coarse.

Water is held in soil in two ways: as a thin coating on the outside of soil particles and in the pore spaces. Soil water in the pore spaces can be divided into two different forms: gravitational water and capillary water (Figure 2). Gravitational water generally moves quickly downward in the soil due to the force of gravity. Capillary water is the most important for crop production because it is held by soil particles against the force of gravity.

Figure 2. The two primary ways that water is held in the soil for plants to use is by capillary and gravitational forces.

As water infiltrates into a soil, the pore spaces fill with water. As the pores are filled, water moves through the soil by gravity and capillary forces. Water movement continues downward until a balance is reached between the capillary forces and the force of gravity. Water is pulled around soil particles and through small pore spaces in any direction by capillary forces. When capillary forces move water from a shallow water table upward, salts may precipitate and concentrate in the soil as water is removed by plants and evaporation.

Water Holding Capacity of Soils
There are two important levels of soil moisture content that reflect the availability of water in the soil. These levels are commonly referred to as: 1) field capacity and 2) wilting point. Field capacity is defined as the level of soil moisture left in the soil after drainage of the gravitational water. Water held between field capacity and the wilting point is available for plant use.

The wilting point is defined as the soil moisture content where most plants cannot exert enough force to remove water from small pores in the soil. Most crops will be permanently damaged if the soil moisture content is allowed to reach the wilting point. In many cases, yield reductions may occur long before this point is reached. Surface soils can dry below the wilting point due to evaporation from the surface under high temperature conditions (easily and frequently reached over late spring and summer).

When discussing the water holding capacity associated with a particular soil, the water available for plant use in the root zone is commonly given (Table 1).
Table 1. Available Soil Moisture Holding Capacity for Various Soil Textures.

<table>
<thead>
<tr>
<th>Soil Texture</th>
<th>Available soil moisture (mm/10cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>4 to 9</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>11 to 15</td>
</tr>
<tr>
<td>Loam</td>
<td>17 to 23</td>
</tr>
<tr>
<td>Clay Loam</td>
<td>14 to 21</td>
</tr>
<tr>
<td>Clay</td>
<td>13 to 18</td>
</tr>
</tbody>
</table>

Figure 3 shows the water holding characteristics of two typical soils in the Upper North. The PAWC of these two profiles are low by world standards and are partly the reason why crop production in these environments is so variable. These buckets have little capacity to buffer crops against adversely dry or warm conditions, especially in spring when crop demand for water is so high.

**Figure 3.** Soil water relationships for two typical soil profiles in the Upper North.

**Soil Moisture Tension**

The degree to which water clings to the soil is the most important soil water characteristic to a growing plant. This concept is often expressed as soil moisture tension. Soil moisture tension is negative pressure and commonly expressed in units of bars. During this discussion, when soil moisture tension becomes more negative it will be referred to as "increasing" in value. Thus, as soil moisture tension increases (the soil water pressure becomes more negative), the
amount of energy exerted by a plant to remove the water from the soil must also increase. One bar of soil moisture tension is nearly equivalent to -1 atmosphere of pressure.

A soil that is saturated has a soil moisture tension of about 0.001 bars, or less, which requires little energy for a plant to pull water away from the soil. At field capacity most soils have a soil moisture tension between 0.05 and 0.33 bars (5 to 33 KPa). Soils classified as sandy may have field capacity tensions around 0.10 bars, while clayey soil will have field capacity at a tension around 0.33 bars. At field capacity it is relatively easy for a plant to remove water from the soil.

The wilting point is reached when the maximum energy exerted by a plant is equal to the tension with which the soil holds the water. For most agronomic crops this is about 15 bars (1.5 MPa) of soil moisture tension. To put this in perspective, the wilting point of some desert plants has been measured between 50 and 60 bars of soil moisture tension.

The presence of high amounts of soluble salts in the soil reduces the amount of water available to plants. As salts increase in soil water, the energy expended by a plant to extract water must also increase, even though the soil moisture tension remains the same. In essence, salts decrease the total available water in the soil profile.

However, seeds can germinate at soil water contents which will not support later plant growth. Figure 4 shows that, while germination is slowed, crop seeds can still germinate at soil water contents near permanent wilting point for plant growth (-1.5 MPa). This is because seeds can take up moisture from water vapour in the soil and this may be the most important source of moisture for seeds in relatively dry soil. Soils will need to be wetter for the young seedling to grow and develop.

Figure 4. Number of days required for 80% seed germination of mustard, pea, barley and wheat placed in contact with soil (solid symbols), or separated from soil by a layer of fibreglass cloth (open symbols). Data for wheat are from Wuest et al. (1999); data for other species are previously unpublished. Wuest S. (2007). Seed Science Research. 17, 3–9

How Plants Get Water From Soil

Water is essential for plant growth. Without enough water, normal plant functions are disturbed, and the plant gradually wilts, stops growing, and dies. Plants are most susceptible to damage from water deficiency during the vegetative and reproductive stages of growth (see...
figure 5). Also, many plants are most sensitive to salinity during the germination and seedling growth stages.

![Figure 5](image)

**Figure 5.** The change in sensitivity to moisture stress of wheat from germination to maturity.

Most of the water that enters the plant roots does not stay in the plant. Less than 1% of the water withdrawn by the plant is actually used in photosynthesis (i.e. assimilated by the plant). The rest of the water moves to the leaf surfaces where it transpires (evaporates) to the atmosphere. The rate at which a plant takes up water is controlled by its physical characteristics, the atmosphere and soil environment.

As water moves from the soil, into the roots, through the stem, into the leaves and through the leaf stomata to the air, it moves from a low water tension to a high water tension. The water tension in the air is related to its relative humidity and is always greater than the water tension in the soil.

Plants can extract only the soil water that is in contact with their roots. For most agronomic crops, the root distribution in a deep uniform soil is concentrated near the soil surface (Figure 6). Over the course of a growing season, plants generally extract more water from the upper part of their root zone than from the lower part.
Figure 6. Over the course of a growing season, plants will extract about 40% of their water from the top quarter, 30% from the second quarter, 20% from the third quarter and 10% from the bottom quarter of the root zone.

Plants such as grasses, with a high root density per unit of soil volume, may be able to absorb all available soil water. Other plants, such as pulses, with a low root density, may not be able to obtain as much water from an equal volume of the same soil and hence are more vulnerable to drought.

**Crop Water Use**

Crop water use, also called evapotranspiration or ET, is an estimate of the amount of water transpired by the plants and the amount of evaporation from the soil surface around the plants. A plant's water use changes with a predictable pattern from germination to maturity. All agronomic crops have a similar water use pattern (Figure 7). However, crop water use can change from growing season to growing season due to changes in climatic variables (air temperature, amount of sunlight, humidity, wind) and soil differences between paddocks (root depth, soil water holding capacities, texture, structure, etc.).

Figure 7. Typical water use curve for most agronomic crops.

**APSIM**

The ability to reliably estimate the amount of available water in a soil profile (eg after a summer of intermittent but sometimes heavy rainfall events) and how a crop will perform on this combination of stored water and in-season rainfall will be a very powerful tool to support informed decision making.
APSIM (Agricultural Production Systems Simulator) is a farming systems model that simulates the effects of environmental variables and management decisions on crop yield, profits and ecological outcomes. APSIM simulates crop yield for different climate attributes, plant varieties, soil types and management decisions.

It has three modules:

- **Plant** – it handles a diverse range of crops, pastures and trees
- **Soil** – it handles soil processes including water balance, nitrogen and phosphorus transformations, soil pH and erosion
- **Management** – it handles the full range of management controls including sowing, fertilising, irrigation, tillage and rotations

The model operates by estimating the amount of water and nitrogen available to the crop each day and hence how much growth and development the crop can achieve under the prevailing weather conditions. To do this successfully, APSIM must “understand” soil water relations in the profile in which the simulated crop is expected to grow. This is why so much time and energy has been spent in recent years to develop soil water relationships for all the major soil types in the agricultural zones of Australia.

APSIM, with its commercial interface to the public of “Yield Prophet” is becoming increasingly adapted to southern Australian environments and work done recently in the Upper North have shown its merit at accurately estimating soil water conditions and subsequent wheat performance.
Critical growth stages for application of post emergent herbicide.

Notes supplied with kind permission of

Ken Webber,
Sales Manager – Eyre Peninsula, NuFarm.

Stage: Seedling Development.
Zadoks Code (Z) 12. This is the 2 leaf stage of the crop. It is generally the earliest recommended stage for application of Post-emergent herbicides. The crop has difficulty in breaking down herbicides applied earlier than this stage and takes a big check.

![Photo Z11.](image1.jpg)

Z13

Z14. This is the 4 leaf stage of the crop. Double Ridging occurs around this stage, although this does vary within the different varieties. Double Ridging is where the plant is changing from vegetative production to initiation of ear formation. This is a very sensitive stage with regards to phenoxy use and rates. Products such as Amine and Ester should not be used prior to or during this stage.

![Double Ridge stage](image2.jpg)

Double Ridge stage:

From Z12 through to Z17. Lower rates of herbicides are recommended depending on weed type. Generally at this stage weeds are smaller thus making the spray operation economical.
Stage: Early Tillering:
Z17, Z18. This is the 7/8 leaf stage of the crop. Tillering has started. The plant is a lot hardier. The weeds are generally bigger and tougher. Or there may be some late germinating weeds such as Saffron’s. Products such as Dicamba, Anime & Ester can be used.

At this stage the crop can handle higher rates. Economics very much depends on the herbicide used.

Stage: Mid Tillering:
Z24. Here the crop has a main shoot + 3 tillers. All the herbicides used from Z17 can still be used. But products with Dicamba should be stopped.

Stage: Tillering to Late Tillering:
Z25 – Z29. Here the crop has a main shoot + 4 or more tillers. Crop tolerance to most herbicides is very good. Robust rates can be used to control escapes, big weeds or later germinating weeds such as Skeleton Weed.
Stage: Stem Elongation:

Z30 – Z37. This is when the nodes/joints become visible. This is getting to the end of where herbicide should be applied. Salvage/desperation spraying is ok up to Z37. At this stage there should be 5-7 nodes or the Flag leaf just visible.

Photo. Z32.

The second node can be seen and the internode is bigger than 2cm. All subsequent nodes, Z33-Z39 are defined the same way.

Photos courtesy GRDC Cereal Growth Stages.
Fungicides and insecticides

Notes used with kind permission of
Dr Hugh Wallwork, Leader, Wheat and Barley Improvement, SARDI, Waite Institute.

Identifying the problem accurately is the key to the effective use of pesticides.
- Will the spray have a beneficial effect? When is the best time to apply it?
- A lot of pesticides are used unnecessarily

Fungicides
Fungal diseases are best controlled through protective sprays rather than suppressing existing infections. The key is to keep the level of inoculum low.
- Early sprays are likely to be more effective than late sprays.
- Be aware of the source of inoculum and conditions required for infection.
- If inoculum is likely to keep blowing in (rusts, net blotches) then an early spray is unlikely to be as effective as where the inoculum is entirely within a crop.
- A spray may not be needed if infection is unlikely to occur i.e. because it will not rain enough (septoria or scald), because humidity will be too low (yellow leaf spot), or because the temperature may not be favourable.
- Be aware of the variety’s resistance status and when adult plant resistance is likely to kick in.

Insecticides
- Crop monitoring is the key to good pest control. Monitor to estimate the pest density, and spray if the pest density exceeds the economic (or spray) threshold.
- Also monitor for beneficials in the crop, especially during spring when they are more abundant.
- Consider the use of selective insecticides, because minimizing the harm to beneficials will improve the overall pest suppression achieved.
- The use of seed dressings can delay the need for foliar applications and allow beneficial insects to build up in the crop.
- Also consider spot or border treatment where practical.
- Prophylactic (calendar) sprays are not recommended because they select for resistance, are harmful to beneficial insects and may lead to secondary pest flare-ups.
- Spray timing should aim to target the most susceptible life-stage of the target pest.
The most commonly used method of describing a particular growth stage of a crop is the Zadoks Decimal Code, which uses 10 distinct phases of cereal plant development. Each of these contains 10 individual growth stages.

<table>
<thead>
<tr>
<th>Development phase</th>
<th>Zadok Growth Stage Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>00 Germination</strong></td>
<td>GS00 dry seed</td>
</tr>
<tr>
<td></td>
<td>GS01 state of imbibition (water absorption)</td>
</tr>
<tr>
<td></td>
<td>GS03 imbibition complete</td>
</tr>
<tr>
<td></td>
<td>GS05 radicle (root) emerged from caryopsis (seed)</td>
</tr>
<tr>
<td></td>
<td>GS09 leaf just a coleoptile tip</td>
</tr>
<tr>
<td><strong>01 Seedling Growth</strong></td>
<td>GS 10 first leaf through coleoptile</td>
</tr>
<tr>
<td></td>
<td>GS 11 first leaf emerged</td>
</tr>
<tr>
<td></td>
<td>GS 12 two leaves emerged</td>
</tr>
<tr>
<td></td>
<td>GS 19 nine or more leaves emerged</td>
</tr>
<tr>
<td><strong>02 Tiller</strong></td>
<td>GS 20 main shoot only</td>
</tr>
<tr>
<td></td>
<td>GS 21 main shoot and one tiller</td>
</tr>
<tr>
<td></td>
<td>GS 22 main shoot and two tillers</td>
</tr>
<tr>
<td></td>
<td>GS 29 main shoot and nine or more tillers</td>
</tr>
<tr>
<td><strong>03 Stem Elongation</strong></td>
<td>GS 30 pseudo stem (leaf sheath) erection</td>
</tr>
<tr>
<td></td>
<td>GS 31 first node detectable</td>
</tr>
<tr>
<td></td>
<td>GS 32 second node detectable</td>
</tr>
<tr>
<td></td>
<td>GS 36 sixth node detectable</td>
</tr>
<tr>
<td></td>
<td>GS 37 flag leaf just visible</td>
</tr>
<tr>
<td></td>
<td>GS 39 flag leaf ligule just visible</td>
</tr>
<tr>
<td><strong>04 Booting</strong></td>
<td>GS 41 flag leaf sheath extending</td>
</tr>
<tr>
<td></td>
<td>GS 43 boots just visibly swollen</td>
</tr>
<tr>
<td></td>
<td>GS 45 boots swollen</td>
</tr>
<tr>
<td></td>
<td>GS 47 flag leaf sheath opening</td>
</tr>
<tr>
<td></td>
<td>GS 49 first awns visible</td>
</tr>
<tr>
<td><strong>05 Ear Emergence</strong></td>
<td>GS 51 first spikelet of inflorescence just visible</td>
</tr>
<tr>
<td></td>
<td>GS 53 inflorescence ¼ emerged</td>
</tr>
<tr>
<td></td>
<td>GS 55 inflorescence ½ emerged</td>
</tr>
<tr>
<td></td>
<td>GS 57 inflorescence ¾ emerged</td>
</tr>
<tr>
<td></td>
<td>GS 59 emergence of inflorescence complete</td>
</tr>
<tr>
<td><strong>06 Flowering (Anthesis)</strong></td>
<td>GS 61 beginning of anthesis</td>
</tr>
<tr>
<td></td>
<td>GS 65 anthesis ¼ way</td>
</tr>
<tr>
<td></td>
<td>GS 69 anthesis complete</td>
</tr>
<tr>
<td><strong>07 Milk Development</strong></td>
<td>GS 71 caryopsis (kernel) water ripe</td>
</tr>
<tr>
<td></td>
<td>GS 73 early milk</td>
</tr>
<tr>
<td></td>
<td>GS 75 medium milk</td>
</tr>
<tr>
<td></td>
<td>GS 77 late milk</td>
</tr>
<tr>
<td><strong>08 Dough Development</strong></td>
<td>GS 83 early dough</td>
</tr>
<tr>
<td></td>
<td>GS 85 soft dough</td>
</tr>
<tr>
<td></td>
<td>GS 87 hard dough</td>
</tr>
<tr>
<td><strong>09 Ripening</strong></td>
<td>GS 91 caryopsis hard (difficult to divide)</td>
</tr>
<tr>
<td></td>
<td>GS 92 caryopsis hard (not dented by thumbnail)</td>
</tr>
<tr>
<td></td>
<td>GS 93 caryopsis loosening in daytime</td>
</tr>
<tr>
<td></td>
<td>GS 94 over-ripe straw dead and collapsing</td>
</tr>
<tr>
<td></td>
<td>GS 95 seed dormant</td>
</tr>
<tr>
<td></td>
<td>GS 96 viable seed giving 50% germination</td>
</tr>
<tr>
<td></td>
<td>GS 97 seed not dormant</td>
</tr>
<tr>
<td></td>
<td>GS 98 secondary dormancy induced</td>
</tr>
<tr>
<td></td>
<td>GS 99 secondary dormancy lost</td>
</tr>
</tbody>
</table>
SEEDLING

WEEKS FROM SOWING – This figure will vary with climatic conditions and cereal varieties

<table>
<thead>
<tr>
<th>Weeks</th>
<th>One leaf</th>
<th>Two leaf</th>
<th>Three leaf</th>
<th>Four leaf</th>
<th>Five leaf</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 weeks</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>2 to 3 weeks</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>3 to 4 weeks</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>4 to 6 weeks</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>5 to 8 weeks</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>7 to 12 weeks</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

LEAF NUMBER main shoot only

Zadoks 11

ONE LEAF

When the first leaf is unfolded, the growing point from which the leaves, tillers, and ears are formed is below ground level. The first leaf has a blunt tip while all subsequent leaves have a pointed tip.

Zadoks (Z)

Zadoks decimal growth scale is based on ten cereal growth stages. These are: 0 germination; 1 seedling growth (leaves on main stem); 2 tillering; 3 stem elongation (nodes); 4 booting; 5 ear emergence; 6 flowering; 7 milk development; 8 dough development; 9 ripening. Each primary growth stage is then sub-divided into 10 secondary stages extending the scale from 00 to 99. So Z, 15, 22, 31 indicates a plant with 5 leaves on the main stem, two tillers and one node on the main stem.

Zadoks 12

TWO LEAF

The third leaf is present, but not fully expanded.

Zadoks 13, 20

THREE LEAF

The first tiller appears from between the leaf sheaf and the main shoot. This generally occurs between the three and four leaf stage.

Zadoks 13, 21

START OF TILLERING

Tillers are counted separately to the main shoot.

Zadoks 14, 22

EARLY TILLERING

When the main shoot has four to five leaves, two or more new tillers have formed.

Zadoks 15, 22

TILLERING

Tillers continue developing through this stage. All tillers have been initiated by the time the main shoot has five to seven leaves. Secondary roots develop during tillering.

Tissue testing / Sap Nitrate / NIR testing

Later Post Emergent herbicide application

Early Post Emergent herbicide application
### JOINTING

| 12 to 14 weeks | First node |

Zadoks 16, 21, 31

**START OF JOINTING**

Jointing commences when the first node can be found on the main stem.

**Jointing**

As jointing progresses more leaves are produced and the young head (yellow arrow) continues to move up through the shoot.

The last leaf to appear is the flag leaf.

The first node can be found by peeling back the leaves on the main stem to expose the node underneath. You will be able to feel the swelling with your fingers.

**NIR testing**

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### BOOT

| 13 to 16 weeks | Early boot |

Z 18, 22, 37

| 15 to 18 weeks | Full boot |

Z 19, 24, 38, 41

| 16 to 19 weeks | Milk/Dough → Maturity |

Z 19, 24, 49

| 18 to 21 weeks | Grain fill |

Z 19, 24, 59, 61

**WEEKS FROM SOWING** – This figure will vary with climatic conditions and cereal varieties

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### FLOWERING

| 25 to 28 weeks | Flowering (Anthesis) |

At flowering or anthesis, final grain number has been determined.

In barley, flowering occurs while the head is in the sheath.

Flowering is easily identified by the yellow anthers (red arrow) hanging freely from the ear.

Crop at most risk from frost

---

### MILK/DOUGH TO MATURITY

As the grains in the head develop, they go through the milk development ① then the dough stage ② before going through the ripening stage to reach maturity ③.

**Source:**

Rural Solutions, SA.

---

No more Capeweed or volunteer Legumes
A guide to consistent and meaningful benchmarking of yield and reporting of water-use efficiency

James Hunt & John Kirkegaard
This document provides guidance for groups within the GRDC National Water-use Efficiency (WUE) Initiative on how to estimate and present WUE results from their experiments and focus paddocks in a consistent and meaningful way. It can also be used by groups as a resource for growers to benchmark their yields and WUE. The WUE calculations in this document proceed in 4 steps depending on the data available and provides worked examples to assist.

The steps:

1. Estimating water-use
2. Calculating water-use efficiency
3. Benchmarking yield
4. Estimating transpiration and unproductive water-use
1   Estimating water-use

The first step toward benchmarking crop WUE is to estimate water-use. Water-use is defined as the total amount of water used to grow the crop during the season, and includes transpiration (water used by the plant to grow), evaporation (water lost from the soil surface), run-off and deep drainage.

Water-use = transpiration + evaporation + run-off + deep drainage

There are several ways of estimating water-use depending on the data available;

Method 1 – an OK method
Water-use (mm) = 0.25 × summer fallow rainfall + growing season rainfall

Data needed
• Monthly rainfall

This method assumes that 25% of rain falling during the summer fallow is stored for crop use. It also assumes that there is no water carrying over from the previous season, which is not the case after long fallows, pulse crops etc.

The months of the year that constitute the summer fallow and growing season periods will vary with location; e.g. in Tasmania the growing season might extend from March to January, whilst in northern WA May to September could be more appropriate. It is important that the months that are assumed to constitute the growing season are specified when reporting results.

Method 2 – a better method
Water-use (mm) = plant available water at start of growing season + rain from then until physiological maturity

Data needed
• Soil water sampled at or near sowing (analysis from soil core or in-situ probe)
• Estimate of your soil’s bulk density & crop lower limit
• Daily rainfall
• Dates of soil sampling and harvest

This method assumes the crop has used all available water at maturity – which is rarely true in wet springs or in high rainfall areas.

Method 3 – best method
Water-use (mm) = (soil water at sowing – soil water at maturity) + in-crop rain

Data needed
• Soil water sampled at (or near) sowing and maturity (from soil core or in-situ probe)
• Daily rainfall

This was the method employed by French & Schultz, who deliberately chose sites that were not prone to run-off, drainage or lateral water movement so:

Water-use = transpiration + evaporation

Be aware that for many crops there will have been run-off and drainage, but these will not be accounted for separately and are rarely measured. Evaporation, run-off and drainage can be thought of together as ‘unproductive water-use’;

Water-use = transpiration + unproductive water-use
A method for separating transpiration and unproductive water-use for further insight is described in Section 5.

2   Calculating water-use efficiency

Water-use efficiency (WUE) is simply grain yield (kg/ha) divided by water-use:

WUE (kg/ha.mm) = grain yield/water-use

A common error is to compare water-use efficiency to the French and Schultz (20 kg/ha.mm) or Sadras and Angus (22 kg/ha.mm) upper limits of transpiration efficiency— but this is incorrect! Remember these numbers are transpiration efficiencies and assume a given evaporation (110 or 60 mm); the calculation above includes evaporation which we know can vary with site, season and management. We are only interested in comparing the WUE of treatments with each other within a given season – and this is the basis on which GRDC are looking for a 10% increase when regionally scaled-up. It is not appropriate to compare WUE values between seasons.
3 Benchmarking yield using an upper-limit of water-use efficiency

French and Schultz (1984) proposed that the best possible wheat yield achievable for a given amount of water-use (potential yield) could be defined as;

\[
\text{Potential yield (kg/ha) = 20} \times (\text{water-use - 110})
\]

Sadras and Angus (2006) updated this benchmark to allow for the introduction of semi-dwarf wheats, increases in atmospheric carbon dioxide and crops grown on sandy soils where evaporation is very low. Their estimate of potential yield is;

\[
\text{Potential yield (kg/ha) = 22} \times (\text{water-use - 60})
\]

This provides a benchmark which can be used to assess paddock or experimental treatment performance. The best way to benchmark yield is to calculate what a crop yielded as a percentage of the benchmark.

\[
\% \text{ of potential yield achieved } = \frac{\text{actual crop yield}}{\text{potential yield}} \times 100
\]

For the sake of consistency within the GRDC WUE initiative, the Sadras and Angus benchmark should be used. Modern crops will often exceed the French & Schultz benchmark. When using Sadras and Angus, crops in some environments (particularly with heavy soils) will rarely come close to the benchmark (commercial crops yielding around 75% of Sadras & Angus will probably have achieved the most profitable yield at a reasonable level of input risk). The absolute WUE number is not as important as the relative differences between treatments or paddocks which can identify that something may be wrong with a particular paddock or its management.

It is worth noting that both French and Schultz and Sadras and Angus used dry grain yield to derive their relationships. When reporting results to industry it is more useful to report grain yield at deliverable moisture content (e.g. 12%), and it is recommended that this be done by groups within the WUE initiative. If comparing yield results at deliverable moisture content to a WUE benchmark, it is important to correct the benchmark value to the moisture content of the harvest yield.

\[
\text{Potential yield @ 12% moisture (kg/ha) = potential yield} \times 1.12
\]

Once estimated, the transpiration value can be subtracted from water-use to estimate unproductive water-use;

\[
\text{Unproductive water-use (mm) =} \quad \text{water-use (mm)} - \text{transpiration (mm)}
\]

This method cannot be used to compare experimental treatments which might have changed the transpiration efficiency (e.g. sowing time). However it can be used to compare treatments such as row spacing and plant density, or to partition the water-use in individual paddocks.

4 Estimating transpiration and un-productive water-use

If total dry matter at crop maturity is known, it is possible to separate and provide estimates of productive water-use (transpired by the plant) and unproductive water-use (lost to evaporation, drainage or run-off). This can be informative (see later Example C).

For wheat crops grown in southern environments we know that for each mm of water transpired by a crop, around 55 kg/ha of total dry matter is produced (this transpiration efficiency of 55 kg/ha.mm should be used for consistency within the GRDC initiative). Therefore;

\[
\text{Transpiration (mm) = total dry matter (kg/ha)/55}
\]

Once estimated, the transpiration value can be subtracted from water-use to estimate unproductive water-use;

\[
\text{Unproductive water-use (mm) =} \quad \text{water-use (mm)} - \text{transpiration (mm)}
\]

This method cannot be used to compare experimental treatments which might have changed the transpiration efficiency (e.g. sowing time). However it can be used to compare treatments such as row spacing and plant density, or to partition the water-use in individual paddocks.
5 Worked examples

Example A: Real paddock example using water-use method 2

This example from the Victorian Mallee in 2009 benchmarks two paddocks on a farm using yields, growing season rain and plant available water measured at the start of the growing season. Paddock 1 was sown early into pea stubble; Paddock 2 was sown later into wheat stubble.

<table>
<thead>
<tr>
<th></th>
<th>Paddock 1 (Wheat Sown 23 April 2009 into field-pea stubble)</th>
<th>Paddock 2 (Wheat Sown 12 May 2009 into wheat stubble)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A PAW start of April</td>
<td>22 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td>B Growing season rain (April-October)</td>
<td>192 mm</td>
<td>192 mm</td>
</tr>
<tr>
<td>C Water-use = A + B</td>
<td>214 mm</td>
<td>198 mm</td>
</tr>
<tr>
<td>D Grain yield (12% moisture)</td>
<td>2700 kg/ha</td>
<td>1090 kg/ha</td>
</tr>
<tr>
<td>E Potential yield = 22 × (C - 60)</td>
<td>3388 kg/ha</td>
<td>3036 kg/ha</td>
</tr>
<tr>
<td>F Potential yield @ 12% moisture (E × 1.12)</td>
<td>3795 kg/ha</td>
<td>3400 kg/ha</td>
</tr>
<tr>
<td>G % of potential yield @ 12% = 100 × (D/F)</td>
<td>71%</td>
<td>32%</td>
</tr>
<tr>
<td>H Water-use efficiency = D/C</td>
<td>12.6 kg/ha.mm</td>
<td>5.5 kg/ha.mm</td>
</tr>
</tbody>
</table>

Paddock 1 was able to achieve 71% of the benchmark (Sadras and Angus potential yield), which is excellent for a commercial crop. Paddock 2 was only able to achieve 32% of the benchmark. This clearly demonstrates the additive WUE benefits of break crops (peas) and early sowing.

Example B: A comparison of methods to demonstrate differences

This example from the CSIRO and FarmLink research site at Temora in 2011 compares current practice (the mid-season variety Gregory sown 9 May at 100 plants/m²) with novel management (the very slow variety Eaglehawk sown early on 15 April at 40 plants/m²).

<table>
<thead>
<tr>
<th></th>
<th>Current Practice - Gregory 9 May 100 Plants/m²</th>
<th>Novel Practice - Eaglehawk 15 April 40 Plants/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Summer fallow rain (November-March)</td>
<td>510 mm</td>
<td>510 mm</td>
</tr>
<tr>
<td>B Growing season rain (April-October)</td>
<td>207 mm</td>
<td>207 mm</td>
</tr>
<tr>
<td>C Water-use = 0.25 × A + B</td>
<td>335 mm</td>
<td>335 mm</td>
</tr>
<tr>
<td>D Grain yield (12% moisture)</td>
<td>5509 kg/ha</td>
<td>6809 kg/ha</td>
</tr>
<tr>
<td>E Potential yield = 22 × (C - 60)</td>
<td>6050 kg/ha</td>
<td>6050 kg/ha</td>
</tr>
<tr>
<td>F Potential yield @ 12% moisture (E × 1.12)</td>
<td>6776 kg/ha</td>
<td>6776 kg/ha</td>
</tr>
<tr>
<td>G % of potential yield @ 12% = 100 × (D/F)</td>
<td>81%</td>
<td>100%</td>
</tr>
<tr>
<td>H Water-use efficiency = D/C</td>
<td>16.4 kg/ha.mm</td>
<td>20.3 kg/ha.mm</td>
</tr>
</tbody>
</table>

In this example all methods gave a similar increase in WUE – around 4.0 kg/ha.mm or a 26% increase based on ‘best’ method, but % of potential yield differed substantially due to Method 1 & 2 underestimating water-use. However, the relative difference between treatments was the same in all methods.
### METHOD 2 - BETTER METHOD

<table>
<thead>
<tr>
<th>Method</th>
<th>Current Practice - Gregory 9 May 100 Plants/m²</th>
<th>Novel Practice - Eaglehawk 15 April 40 Plants/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Paw start of April</td>
<td>121 mm</td>
</tr>
<tr>
<td>B</td>
<td>Rain from sampling to harvest</td>
<td>207 mm</td>
</tr>
<tr>
<td>C</td>
<td>Water-use = A + B</td>
<td>328 mm</td>
</tr>
<tr>
<td>D</td>
<td>Grain yield (12% moisture)</td>
<td>5509 kg/ha</td>
</tr>
<tr>
<td>E</td>
<td>Potential yield = 22 × (C - 60)</td>
<td>5896 kg/ha</td>
</tr>
<tr>
<td>F</td>
<td>Potential yield @ 12% moisture (E × 1.12)</td>
<td>6603 kg/ha</td>
</tr>
<tr>
<td>G</td>
<td>% of potential yield @ 12% = 100 × (D/F)</td>
<td>83%</td>
</tr>
<tr>
<td>H</td>
<td>Water-use efficiency = D/C</td>
<td>16.8 kg/ha.mm</td>
</tr>
</tbody>
</table>

### METHOD 3 - BEST METHOD

<table>
<thead>
<tr>
<th>Method</th>
<th>Current Practice - Gregory 9 May 100 Plants/m²</th>
<th>Novel Practice - Eaglehawk 15 April 40 Plants/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Total soil water at sowing</td>
<td>468 mm</td>
</tr>
<tr>
<td>A2</td>
<td>Total soil water at maturity</td>
<td>340 mm</td>
</tr>
<tr>
<td>B</td>
<td>Sowing to maturity rain</td>
<td>237 mm</td>
</tr>
<tr>
<td>C</td>
<td>Water-use = A1 - A2 + B</td>
<td>365 mm</td>
</tr>
<tr>
<td>D</td>
<td>Grain yield (12% moisture)</td>
<td>5509 kg/ha</td>
</tr>
<tr>
<td>E</td>
<td>Potential yield = 22 × (C - 60)</td>
<td>6710 kg/ha</td>
</tr>
<tr>
<td>F</td>
<td>Potential yield @ 12% moisture (E × 1.12)</td>
<td>7515 kg/ha</td>
</tr>
<tr>
<td>G</td>
<td>% of potential yield @ 12% = 100 × (D/F)</td>
<td>73%</td>
</tr>
<tr>
<td>H</td>
<td>Water-use efficiency = D/C</td>
<td>15.1 kg/ha.mm</td>
</tr>
</tbody>
</table>

---

**Example C: Estimating transpiration (if total dry matter at maturity is known)**

A comparison of estimated transpiration based on total dry matter cannot be made in the two treatments used in Example B because they were sown at different times, which affects transpiration efficiency for dry matter. However, a comparison can be made between the same variety (Lincoln) sown on the same date (19 May) but at different plant densities (40 and 100 plants/m²). The 100 plants/m² treatment performs better relative to the benchmark, and by estimating transpiration and partitioning the water-use components we can see that this is due to more unproductive water-use (evaporation) in the 40 plants/m² treatment (170 mm vs 143 mm). Transpiration efficiencies for grain are very similar between treatments.

<table>
<thead>
<tr>
<th>Method</th>
<th>Lincoln 19 May 40 Plants/m²</th>
<th>Lincoln 19 May 100 Plants/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Water-use (method 3)</td>
<td>347 mm</td>
</tr>
<tr>
<td>B</td>
<td>Grain yield (12% moisture)</td>
<td>4974 kg/ha</td>
</tr>
<tr>
<td>C</td>
<td>Water-use efficiency = B/A</td>
<td>14.3 kg/ha.mm</td>
</tr>
<tr>
<td>D</td>
<td>Potential yield = 22 × (A - 60)</td>
<td>6314 kg/ha</td>
</tr>
<tr>
<td>E</td>
<td>Potential yield @ 12% moisture (D × 1.12)</td>
<td>7072 kg/ha</td>
</tr>
<tr>
<td>F</td>
<td>% of potential yield @ 12% = 100 × (B/E)</td>
<td>70%</td>
</tr>
<tr>
<td>G</td>
<td>Total dry-matter at maturity</td>
<td>9749 kg/ha</td>
</tr>
<tr>
<td>H</td>
<td>Estimated transpiration = G/S5</td>
<td>177 mm</td>
</tr>
<tr>
<td>I</td>
<td>Estimated unproductive water-use = A - H</td>
<td>170 mm</td>
</tr>
<tr>
<td>J</td>
<td>Transpiration efficiency for grain = B/H</td>
<td>28.1 kg/ha.mm</td>
</tr>
</tbody>
</table>
References


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MEASURING SOIL TEXTURE IN THE FIELD

Key points
- Soil texture is a measure of the relative proportion of the various soil particle size fractions in soil.
- Soil texture affects the physical and chemical properties of a soil.
- Field texturing is a quick method of determining soil texture, and enables an immediate interpretation of texture down the soil profile.

Background
Soil texture is an estimate of the relative amounts of sand, silt and clay particles in a soil. The physical and chemical behaviour of a soil is influenced strongly by soil texture (Bowman & Hutka, 2002), which will vary due to the differences in the type and mineral composition of the parent material, the soils position in the landscape, and the physical and chemical weathering processes involved in soil formation. Soil texture affects the movement and availability of air, nutrients and water in a soil (Hunt and Gilkes, 1992) and is often used to estimate other soil properties, particularly soil water properties, if no direct measurements are available (NLWRA, 2001). A simple measure of soil texture is the way a soil feels when manipulated by hand.

Measuring soil texture
Field or hand texturing is a measure of the behaviour of a small handful of soil when moistened and kneaded into a ball slightly larger than the size of a golf ball (NSW Agriculture, 1988) or bolus and pressed out to form a ribbon between the thumb and forefinger (figure 1). The behaviour of the soil during bolus formation, and the ribbon produced, characterises the field texture.

Field method
Take a sample of soil and remove the >2mm fraction (gravel—see below, roots, organic material) by sieving or by hand. The sample should be sufficient to fit comfortably into the palm of your hand. Moisten the soil with a little water and knead it into a bolus (figure 1). Continue to work the bolus, adding more soil and water if necessary, until the soil no longer sticks to your fingers and there is no apparent change in plasticity (usually 1–2 minutes). If the bolus is worked for a long time it may dry but it can be re-wet (the moisture of the sample will influence the length of the ribbon formed).

Using a clean, moistened hand, place the bolus between your thumb and forefinger and slide your thumb across the soil (shearing) to extrude a ribbon. Try to make a thin continuous ribbon about 2 mm thick and 1 cm wide. Measure and record the length of the ribbon produced using a rule. Soils with high clay content are further categorised by moulding the bolus into rods. If the rods fracture the soil is assigned a texture grade lighter than a medium clay. A breakdown of field texturing categories is given in table 1. This method has been adapted from McDonald et al. (1998).

Gravel (particles >2 mm) is removed from the soil prior to texturing because it does not contribute to chemical and some physical properties of soils.

Laboratory method
A laboratory determination of soil texture gives a more detailed and reliable measure of the relative amounts of sand, silt and clay particles in a soil. The common term for measuring soil texture in the laboratory is particle size analysis (PSA). Particle size analysis determines particle size distribution (PSD) of a soil and while field texture is closely related to the PSD (McKenzie et al., 2004), texture classes assigned from field texture and PSA are not always equivalent. For example, sodic soils have a heavier field texture than is suggested by the laboratory determined PSA. For a more detailed description of this method please refer to “Particle Size Analysis” fact sheet.

Figure 1: Manipulation of soil for field texturing. The properties of each soil when doing this determines texture.
This soilquality.org.au fact-sheet has been funded by the Healthy Soils for Sustainable Farms programme, an initiative of the Australian Government’s Natural Heritage Trust in partnership with the GRDC, and the WA NRM regions of Avon Catchment Council and South Coast NRM, through National Action Plan for Salinity and Water Quality and National Landcare Programme investments of the WA and Australian Governments.

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### Glossary terms

**Bolus:** the ball of soil formed by manipulating the soil by hand.

**Coherence:** the ball or bolus of soil holds together.

**Parent material:** weathered and unweathered rock or soil from which soil is formed.

**Plasticity:** the ball can be deformed and holds its new shape strongly; typical of clays.

**Shearing:** sliding the thumb across the soil to form a ribbon.

**Silkiness:** the smooth, soapy or slippery feel of silt.

**Sodic:** soils with a high level of exchangeable sodium (can lead to poor soil physical conditions).

### Further reading and references


### Table 1: Classification based on field texturing of soils. The combination of ‘Behaviour of Moist Bolus’ and ‘Ribbon Length’ gives an indication of Field Texture Grade. Adapted from McDonald et al. (1998).

<table>
<thead>
<tr>
<th>Field Texture Grade</th>
<th>Behaviour of Moist Bolus</th>
<th>Ribbon Length (shearing between thumb and forefinger)</th>
<th>Approximate Clay Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>Coherence nil to very slight, cannot be moulded; single sand grains adhere to fingers.</td>
<td>Nil</td>
<td>&lt;10% (often &lt;5%)</td>
</tr>
<tr>
<td>Loamy Sand</td>
<td>Slight coherence.</td>
<td>=5 mm</td>
<td>5–10%</td>
</tr>
<tr>
<td>Clayey Sand</td>
<td>Slight coherence, sticky when wet; many sand grains stick to fingers; clay stains the hands.</td>
<td>5–15 mm</td>
<td>5–10%</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>Bolus just coherent but very sandy to touch; dominant sand grains are of medium size and are easily visible.</td>
<td>15–25 mm</td>
<td>10–20%</td>
</tr>
<tr>
<td>Loam</td>
<td>Bolus coherent and rather spongy; smooth feel when manipulated, no obvious sandiness or ‘silkiness’; may be greasy to the touch if much organic matter is present.</td>
<td>=25 mm</td>
<td>=25%</td>
</tr>
<tr>
<td>Silty Loam</td>
<td>Coherent bolus; very smooth to silky when manipulated.</td>
<td>=25 mm</td>
<td>=25% (with silt)</td>
</tr>
<tr>
<td>Sand Clay Loam</td>
<td>Strongly coherent bolus, sandy to touch; medium size sand grains visible in finer matrix.</td>
<td>25–40 mm</td>
<td>≥25%</td>
</tr>
<tr>
<td>Clay Loam</td>
<td>Coherent plastic bolus, smooth to manipulate.</td>
<td>40–50 mm</td>
<td>20–30%</td>
</tr>
<tr>
<td>Clay Loam, Sandy</td>
<td>Coherent plastic bolus; medium size sand grains visible in finer matrix.</td>
<td>40–50 mm</td>
<td>30–35%</td>
</tr>
<tr>
<td>Silty Clay Loam</td>
<td>Coherent smooth bolus; plastic and often silky to the touch.</td>
<td>40–50 mm</td>
<td>30–35% (with silt)</td>
</tr>
<tr>
<td>Sandy Clay</td>
<td>Plastic bolus; fine to medium sand grains can be seen, felt or heard in clayey matrix.</td>
<td>50–75 mm</td>
<td>35–40%</td>
</tr>
<tr>
<td>Light Clay</td>
<td>Plastic bolus; smooth to touch.</td>
<td>50–75 mm (slight resistance to shear)</td>
<td>35–40%</td>
</tr>
<tr>
<td>Light Medium Clay</td>
<td>Plastic bolus; smooth to touch.</td>
<td>=75 mm (slight–mod. resistance to shear).</td>
<td>40–45%</td>
</tr>
<tr>
<td>Medium Clay</td>
<td>Smooth plastic bolus; handles like plasticine; can be moulded into rods without fracture.</td>
<td>≥75 mm (mod. resistance to ribbon shear)</td>
<td>45–55%</td>
</tr>
<tr>
<td>Heavy Clay</td>
<td>Smooth plastic bolus; handles like stiff plasticine; can be moulded into rods without fracture.</td>
<td>≥75 mm (firm resistance to ribbon shear)</td>
<td>≥50%</td>
</tr>
</tbody>
</table>
MEASURING SOIL TEXTURE IN THE LABORATORY

Key points

- Particle size analysis breaks a soil into texture classes—sand, silt or clay.
- Soil texture influences nutrient retention, water storage and drainage.
- Particles greater than 2 mm are removed before analysis.
- The soil textural triangle is used to determine soil type based on sand, silt and clay percentages.

Background

Particle size analysis (PSA) determines the relative amounts of sand, silt and clay in a soil. These size fractions are the mineral component of a soil and together determine soil texture. PSA is a laboratory alternative to field texturing (see Measuring Soil Texture in the Field fact sheet) and offers a more reliable determination of particle size distribution. There is only an approximate correlation between hand texturing and PSA (McDonald et al., 1998), because hand texturing relies on qualitative interpretation of texture while PSA measures exact amounts of individual particle sizes.

Soil texture is an inherent soil quality property that has a major influence on several other properties that influence agricultural potential (White, 1997). In particular soil texture influences nutrient retention, water storage and drainage. Soils with a higher proportion of sand retain less nutrients and water compared to clay soils.

Mineral components of soil

Coarse fragments

Greater than 2 mm and include coarse quartz, rock fragments and cemented material. This is commonly called the “gravel fraction”.

Sand

Comprise quartz and resistant primary minerals such as mica. Sand particles are between 2 mm and 20 microns in size (Note: there are 1000 microns in 1 mm).

Silt

Silts are typically composed of quartz and small mineral particles such as feldspars and mica, and are between 2 and 20 microns in diameter.

Clay

Clays are made up of secondary clay minerals and oxides/oxyhydroxides of iron and aluminium, and are less than 2 microns in diameter.

South-western Australia

Soil data from a range of projects conducted across the state is constantly added to the soils database managed by the Department of Agriculture and Food, Western Australia. Figure 1, taken from McArthur (1991), shows the soil types characteristic of south-western Australia.

Figure 1: Characteristic soils of the agricultural region of south-western Australia. Image courtesy of Natural Resources Assessment Group, DAFWA.
Particle size analysis (PSA)

PSA is a reliable, reproducible technique that eliminates factors that may affect field texture such as organic matter content, clay mineralogy, cation composition and the presence of cementing agents (Bowman and Hutka, 2002). The method comprises two parts, dispersion of the soil and separation of the particles into size groups.

**Dispersion and pre-treatment**

Pre-treatment of the soil may be needed to remove organic matter and salts such as gypsum. Iron oxides, calcium carbonate and magnesium carbonate should also be removed as they are common cementing agents in Australian soils (Bowman and Hutka, 2002). Pre-treatment of the soil will allow it to disperse completely.

**Fractionation**

Fractionation involves removing each particle size group (sand, silt and clay) from a pretreated soil and water mixture settled in a cylinder (figure 2). This is achieved by allowing the soil particles of different size to settle out of solution at different times (small clay particles take the longest). The fractions are subsequently dried and weighed and the sand, silt and clay must add up to 100%. Some calculations are needed for this method including the use of a scaling factor for the pipette analysis and a calculation for the sieve analysis. For a complete method, refer to Bowman and Hutka (2002).

**Using the soil texture triangle**

The soil texture triangle (figure 3) is used to convert particle size distribution into a recognised texture class based on the relative amounts of sand, silt and clay as a percentage, for example:

A—Sand 50% Silt 30% Clay 20% = **Silty Loam**

The grid on the triangle allows you to move to the left or the right of your position running parallel with either side of the triangle. It is best to start at the base with the sand. Position your finger along the base line at the 50% mark. Move your finger up the line running parallel with the right side of the triangle. Simultaneously use another finger to trace a line from the 30% silt mark until the two meet. Your two fingers will always meet at clay for the remaining percentage, in this case 20%. This is always the case that the first two sizes chosen will lead you to the third.

B—Sand 80% Silt 5% Clay 15% = **Sandy Loam**

Trace your finger along the 80% sand line while simultaneously tracing another finger along the 5% silt line until the two meet. This should be where clay is 15%.

**Further reading and references**


**Author:** Georgina Holbeche (The University of Western Australia).
WATER AVAILABILITY

Key points
- Available water is the difference between field capacity which is the maximum amount of water the soil can hold and wilting point where the plant can no longer extract water from the soil.
- Water holding capacity is the total amount of water a soil can hold at field capacity.
- Sandy soils tend to have low water storage capacity.
- Sub-soil constraints (acidity, hardpans etc.) can prevent crops accessing water in the subsoil.
- Structure and depth of crop roots affects access to available water.

Background
Of the water entering a soil profile, some will be stored within the rooting zone for plant use, some will evaporate and some will drain away from the plant root zone. Plant available water is the difference between field capacity (the maximum amount of water the soil can hold) and the wilting point (where the plant can no longer extract water from the soil) measured over 100 cm or maximum rooting depth (Hunt and Gilkes, 1992). Beyond the wilting point there is still water in the soil profile, however it is contained in pores that are too small for plant roots to access. Soil texture, soil structure and plant rooting depth are the crucial factors in determining the amount of water available for plants to access.

Soil texture
Increasing clay content in the soil profile is associated with greater water holding capacity. However, this does not mean more water is available for plants to use, as the clay helps create a complex soil matrix of smaller pores which hold water at greater suction pressures (figure 1).

In a uniform, coarse-textured soil (e.g. deep sand, sandy earth) low amounts of clay or silt result in poor soil aggregation and a free draining profile. This results in low storage capacity for either water or nutrients in the root zone. These soil types can also be water repellent due to the build up of waxes on the surface of sand particles, restricting the rate of water infiltration into soil and resulting in greater surface water losses.

In soils where there is a sharp change in soil texture in the subsoil (e.g. sand over clay duplex soils) the amount of water available for plants, depends on the texture of the surface soil, depth to subsoil and the nature/texture of the subsoil and its interface with the surface soil (figure 2). In soils with dense clay subsoil, for example, perched water stored above this less penetrable layer can result in too much available water, i.e. waterlogging (see Waterlogging fact sheet).

Cracking clays store water very differently to the previously mentioned soil types. Typically these clays are characterised by a light clay texture throughout the soil profile, with coarser material on the surface. As the soil shrinks and swells, seasonal cracking occurs. Water infiltration is affected as water flows preferentially into the cracks, whilst areas between cracks remain dry due to the massive soil structure and rapid movement of water. Due to its clay content, this soil type can store a lot of water but the availability of this water will be determined by infiltration patterns and rooting depth.

Soil structure
Soil aggregates create pores which store water for plants to access. A poor or non-existent soil structure with high clay content will have a reduced volume of soil pores. The
pores that are present are smaller so water is held at higher suction pressures, making the plant exert more energy to extract the water, rather than using that energy for yield. Coarser textured soils will generally have larger pore sizes and little soil structure, resulting in rapid water drainage. A lack of soil structure can also mean poor infiltration and sometimes a compacted subsurface which can result in waterlogging in the root zone.

Increasing soil organic matter content helps create and stabilise soil structure. Organic matter is considered integral in the capacity of a soil to maximise water storage through its effect on creating and stabilising soil pores and its absorption capacity. Large volumes of crop residues on the soil surface can also aid water infiltration and reduce evaporation.

Rooting depth

The large variation in the maximum rooting depth of different crops and the tolerance of plant species to different soil conditions, in addition to depth of soil, determines the capacity of a plant to access available water on many soils (Van Gool et al., 2005).

In many agricultural soils there are subsoil barriers which prohibit plant roots from accessing available water:

- **Physical barrier**—subsurface compaction which may allow the movement of water and nutrients, but restrict root growth.
- **Chemical barrier**—subsoil acidity and salinity prevents the plant roots from accessing the whole soil profile.

Management options

Apart from claying sandy soils, there are few options to influence soil texture to improve water holding capacity. However, improving soil structure and removing barriers to plant growth can improve both the storage capacity of the soil itself and increase the area/depth of soil which plant roots may utilise for exploration.

Potential management options:

- Deep ripping compacted subsoils (see Subsurface Compaction fact sheet).
- Liming to ameliorate soil acidity (see Soil Acidity fact sheet).
- Increase organic matter to improve water infiltration.

Further reading and references

Hunt N and Gilkes B (1992) ‘Farm Monitoring Handbook’. The University of Western Australia, Crawley, Western Australia.


Authors: **Jessica Sheppard** (Avon Catchment Council), **Fran Hoyle** (Department of Agriculture and Food, Western Australia)
Improved method of making soil monoliths using an acrylic bonding agent and proline auger

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ARTICLE INFO

Article history:
Received 2 February 2009
Received in revised form 18 May 2009
Accepted 18 May 2009
Available online 9 June 2009

Keywords:
Soil profile
Soil monolith
Display
Education
Soil morphology
Pedology
Acrylic bonding

ABSTRACT

This soil monolith production method, initially developed in the late 1990s, has now been successfully applied to over 100 soil profiles, dealing with the majority of Australian soils ranging from clays to sands, from uniform to texture contrast profiles, and from alkaline soils to even acid sulphate soils. The method outlined utilises intact soil profiles (150 mm diameter undisturbed soil cores collected with a Proline hollow flight auger). This technique is rapid and minimises site disturbance. A modern acrylic bonding compound (Bondcryl 737®) was selected as the bonding agent because it is strong, durable, UV resistant, and non-toxic. The bonding agent is applied to the soil profile as a series of fine misty sprays using a hand pump action spray bottle. After several applications the solution permeates through the outer 5 mm or more of the soil, bonding the whole profile together. The finished soil monolith has a moist soil colour, but with a natural non-glossy appearance. A decade has now passed since the first monoliths were made using this method, and those monoliths are still being transported and displayed regularly. They remain in good condition, giving us some confidence in the reliability of this method.

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1. Introduction

‘Soil monolith’ is the name given to a collected sample of a soil profile which has been preserved in its natural undisturbed condition. The main advantages of soil monoliths are that they are portable and allow a number of soils to be compared, examined and discussed at the one site, without having to inspect widely separated sites. Each soil monolith also tells a story through its physical and biological features, and many of the physical limitations to land use are often apparent.

Methods of making soil monoliths have been continually improving since the earliest records of soil monolith production (Vanderford, 1897) which involved merely exposing a soil bank and fitting a wooden box over the prepared core and breaking the soil off to fill the box. These finished monoliths were heavy and deteriorated rapidly when moved about (Brown, 1963). The lacquer cement method, developed in the 1930s by a number of workers in different countries (Voight, 1936; Gracanin & Janekovic, 1940; Storie, 1941) secured the monoliths to a board but did not bind the soil together very well (Brown, 1963).

Shortly after this era, a number of bonding agents were put forward to help improve the bonding or cohesion in the soil monoliths. These included such products as a vinylite (vinyl acetate vinyl chloride copolymer) solution (Berger and Muckenhirn, 1945; Wells, 1953) and cellulose acetate (Rosewell, 1969) which were effective in bonding the soil together, but tended to produce an unnatural glossy appearance. A diakon acrylic compound dissolved in 1,2-dichloroethane, recommended by Wright (1971) produced superior results, but was later found to be carcinogenic. In more recent times, Ursu (1982) found a soluble glue to be effective in binding the soil monolith together. Improvements have also occurred in methodology for collecting very large soil profiles (Ottersberg and Byron, 1987) and also rocky soils (Barahona and Iriarte, 1999), but an efficient and rapid method of collecting the standard 1 m deep soil profile for most soil monolith displays is the hollow flight auger technique recommended by Wright (1971). This technique uses a Proline power sampler to collect the cores with minimal disturbance to the site.

The method outlined in this paper utilises the advantages of the Proline hollow flight auger technique for collecting 150 mm diameter undisturbed soil cores (Wright, 1971) and combines this with a modern acrylic bonding compound which is strong, durable, UV resistant, and non-toxic. The method recommended for applying the bonding agent is as a series of fine misty sprays using a hand pump action spray bottle as recommended by Ursu (1982) and also Wright (1971) for loose calcareous loams. The bonding agent (Sealwall Bondcryl 737) recommended in our method functions both as a glue for bonding the soil to a backing board as well as a bonding agent for binding the soil itself together. In earlier methods up to three separate compounds are used to prepare monoliths (e.g. ISM, 1972).

The objective of this paper is to propose an improved method for preparing soil monoliths. The method outlined in this paper was initially developed in the late 1990s to make a set of soil monoliths representing the main soil types of the Eastern Australian coastal
zone. The method has now been successfully applied to over 100 soil profiles, representing the majority of Australian soil types ranging from well structured clays to structureless sands, from uniform profiles to duplex or texture contrast profiles, and from alkaline soils to even acid sulphate soils. A decade has now passed since the first monoliths were made using this method, and the monoliths are still in good condition after being transported and displayed to farmers, school groups, agricultural advisers, and soil scientists. This has given us some confidence that soil monoliths made with this method can indeed stand the test of time.

2. Materials and methods

2.1. Equipment and materials

All of the necessary equipment for making soil monoliths are listed for each stage of production in Table 1. The following outlined method covers all stages of monolith production from soil core collection in the field to final presentation.

2.1.1. Soil core collection

Preliminary site inspections are useful to ensure that the soil profile will have all of the desired features. When attempting to collect cores for soil monoliths, the weather and soil moisture condition are important factors to consider, as they affect the ease with which the intact core can be collected. A soil moisture content slightly drier than field capacity is ideal.

Table 1
The equipment and materials required to make soil monoliths using this method.

<table>
<thead>
<tr>
<th>Equipment required for monolith production</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Soil core collection (Figs. 1 and 2)</td>
</tr>
<tr>
<td>Proline auger (150 mm diameter) mounted on a truck, clear plastic sheet to wrap soil core, 1 m length of PVC pipe (150 mm) cut into 2 halves length wise to protect core during transport, webbing belts or tape to strap the split pipes together around the soil core, GPS and maps, permanent marking pens.</td>
</tr>
<tr>
<td>(b) Cutting the soil core in half (lengthwise) (Fig. 3)</td>
</tr>
<tr>
<td>Commercial diamond saw with a 450 mm water-lubricated blade (most stone masons have these), sheet plastic, strong soil sample bags, packing tape, masking tape, permanent marking pens.</td>
</tr>
<tr>
<td>(c) Bonding soil core to board (Figs. 4–6)</td>
</tr>
<tr>
<td>Well ventilated room or shed with electricity and water supply and fluorescent lighting, large work table, marine ply board cut to size (i.e. backing board), set square, tape measure, pencil, eraser, ruler, a drawing frame with inside dimensions to match core (i.e. 90 cm × 15 cm), paint brush, acrylic bonding and sealing agent (e.g. Sealwall Bondcryl 737), 250 ml wash bottle, graduated 1 L beaker, stirring rod, 2 L glass storage jar, paper towelling, rubber gloves, large sharp edged putty knife and spatulas, masking tape, permanent marker pen, wire brush.</td>
</tr>
<tr>
<td>(d) Picking back the mounted soil profile (Figs. 7 and 8)</td>
</tr>
<tr>
<td>Wooden guide frame (dimensions of 94 cm × 18 cm × 4 cm), putty knife, large spatula, small screw drivers, small tweezers, scissors, vacuum cleaner with a narrow nozzle attachment, angle grinder, hacksaw, paint brush.</td>
</tr>
<tr>
<td>(e) Impregnating the soil core with the acrylic bonding agent (Fig. 9)</td>
</tr>
<tr>
<td>Acrylic bonding and sealing compound (e.g. Sealwall “Bondcryl 737”), hand trigger action pump spray bottles (adjustable nozzle), a 250 ml wash bottle, a 1 L graduated plastic beaker, 3 × 2 L glass storage jars, disposable syringes (10 ml and 20 ml), absorbent paper towelling, clear plastic sheeting, masking tape, permanent marker pens, protective filter mask (cloth fibre).</td>
</tr>
<tr>
<td>(f) Final display presentation and storage (Figs. 10 and 11)</td>
</tr>
<tr>
<td>Semi-gloss paint (dull light neutral colour), paint brush, U-section black plastic frame, fabricated clear Perspex display case, display easel stand made from hardwood, plywood boxes for transit, graduated rule measure down the profile, site photo and text on soil type and features (brief with minimum use of jargon), Velcro to allow text to be modified to suit audience or issue.</td>
</tr>
</tbody>
</table>

Undisturbed soil cores (up to 95 cm long) can be quickly collected using a 150 mm diameter hollow flight proline auger mounted on a truck (Fig. 1). The auger turns around a split steel liner held together by a ring-shaped cutting shoe at the boring end, and another tight fitting ring at the top end. When the auger is full, the steel liner containing the core is placed horizontally on the ground. The cutting shoe and the holding ring are carefully removed and the upper half of the split liner is lifted exposing the soil (Fig. 2).

To minimise loss of soil moisture, the core has to be carefully wrapped in plastic sheeting and then encased in two halves of split PVC plastic storm pipe, held together by ducting tape to keep the core rigid during transport. A packaged soil core can be seen in Fig. 3.

If a Proline auger is not available, soil profiles can be collected from a soil pit using the traditional box collection method, and then prepared using the acrylic bonding agent method as outlined in the following sections of this paper.

2.1.2. Cutting the soil core in half (lengthwise)

The desired core moisture content for cutting is close to the plastic limit. To bring drier cores up to an appropriate soil moisture level, spray a light mist of water over the soil core or place a moist hessian bag over the core and leave for a few days. The most effective way to cut the soil cores in half lengthwise is with a stonemasons commercial diamond saw fitted with a 45 cm diameter, water-lubricated blade operated at 2000 rpm (Fig. 3). This procedure is essential when the

Fig. 1. Hollow flight (150 mm diameter) auger mounted on a truck for collecting soil cores for soil monolith displays.

Fig. 2. A soil core collected by the auger, ready to be wrapped and encased between PVC pipe halves for protection during the trip back from the field.
soil is gravelly or rests on hard weathered rock. The cutting operation is best left in the hands of a professional stonemason who is experienced in the operation of a diamond saw.

To prepare the wrapped soil cores for cutting, the strapping around the PVC half-pipes surrounding the cores needs to be undone and the half-pipes moved slightly apart to leave a 2 cm gap between them. The PVC pipe halves and the cores are then taped together with packing tape to leave this 2 cm gap. Leave the plastic wrapping around the soil cores within the half-pipes to help protect them from the water flow that keeps the saw blade cool, and help ensure the soil profile remains held together intact.

The soil core needs to be guided quickly through the saw in one pass, topsoil end first. After cutting the cores, place a plastic separating sheet on top of the cut surface of one of the soil core halves, bring the two soil core halves together and secure by strapping or taping the pipe halves together around it. A strong plastic bag taped around each end of the core will help to prevent the soil core from drying out.

A slightly different cutting procedure is needed for sandy soil cores and other soft soil cores with poor coherence and no gravel. Sandy profiles require special care, and can be cut in half by hand using either veterinary embryonic wire or a hacksaw. They need to have an adequate moisture content at the time of cutting, and are likely to disintegrate if allowed to dry out. Their moisture content can be maintained by applying several light misty sprays of water over the whole length of the core and leaching for a few days. Sandy soil cores are best processed to monoliths immediately after cutting, because of their lack of coherence when they dry out.

It is desirable to start processing the soil cores into monoliths within 2 weeks of collection. One great advantage of processing the soil monoliths quickly is that it allows any soil vegetation cover to be preserved in the monolith display, which adds to its credibility and is particularly impressive if the vegetation is deep-rooted. If the soil core remains wrapped up in plastic for more than a couple of weeks, the vegetation will rot away and be lost from the display.

2.1.3. Bonding the soil core to the display board

Unwrap the split core to expose both cut faces, leaving the rounded surface of the core inside the PVC half-pipe. Select the half core with the smoothest cut face. For a strong bond with the backing board try to achieve a flat surface by filling any hollows or low points in the cut face with a mixture of soil and 1:1 dilution of bonding agent.

To improve adhesion for dense clay soil materials, numerous shallow holes (1 cm deep) can be dug in the cut face using a narrow screwdriver or leatherwork implement, prior to adding the bonding agent.

The rectangular area where the monolith will be stuck has to be marked on the board. We typically use a 29.5 cm×119.5 cm board, with 15 cm×95 cm area marked on it 3 cm in from the left and from the bottom, leaving 21.5 cm at the top and 11.5 cm on the right hand side for labels, site photo and descriptive text. Monolith displays larger than this are difficult to transport safely by car.

To bond the half soil core to the backing board; apply a generous application (2 mm thick) of the 1:1 Bondcryl:water solution to the prepared flat soil core surface using a 250 ml wash bottle (Fig. 4). The penetration of the solution into the surface can be encouraged by rubbing it in by hand, wearing rubber gloves. This solution should be continually applied to the soil surface until it has been saturated to a depth of at least 3 mm.

Paint the area on the backing board intended for the soil monolith with a heavy 3 mm thick application of undiluted bonding compound and lower the backing board into position onto the soil core surface (Fig. 5). The board and soil core is then held into position by a person

Fig. 3. A soil core lined up ready to be cut in half by the diamond saw.

Fig. 4. Applying the 1:1 acrylic bonding agent (Bondcryl 737) solution to the prepared flat soil core surface.

Fig. 5. Bringing the backing board and the soil core half (still in protective PVC pipe half) together before the final turning over.
at either end of the core, each with one hand on top of the board and one hand under the PVC half-pipe containing the soil core. The core and board are then turned over together so the soil core ends up on top of the backing board with its cut face butted against the board.

The soil core is then moved carefully into position on the board, keeping the PVC ½ pipe over the core. The ½ PVC pipe is then taken off the core, and the plastic wrapping is left on. With both hands on the core, a firm pressure is applied in a controlled manner, pushing the soil core face onto the board to encourage good contact between bonding surfaces (Fig. 6). All excess bonding agent around the soil core is then wiped up with absorbent paper towelling. The adhesion or bond between the soil core and the board is then left to dry for 24 h. After drying, the picking back process can begin.

2.1.4. Picking back the mounted soil profile

The aim of picking back the mounted half soil core is to expose the natural face of the soil profile by removing the smooth rounded outer layer of the soil core that is usually smeared during the coring process. The procedure is as follows; Place the wooden guide frame over the glued half core on the board before starting to pick the core back as this helps to ensure that all of the monoliths end up with a standard maximum thickness (4 cm), and helps with the later fitting of the perspex display cover (Fig. 7). This thickness guideline can be varied if the profile has an interesting feature (e.g. an ant gallery).

Begin picking back by inserting the tip of the putty knife 1–2 cm into the core and attempting to lever off small slabs of soil. The aim here is to minimise the shiny smeared areas of soil on the profile which are left where the point of the knife is inserted, and to maximise the area of the natural soil surface exposed. Take care not to dislodge large rocks that are likely to disturb the soil profile. These may be cut back with an angle grinder or hacksaw at a later stage if necessary. Continue picking or levering until the core has been picked down to close to the height of the guide frame. At this point it is important to pay attention to detail, removing any shiny pick marks that may be present with smaller screw drivers and tweezers.

When picking back the soil profile, it is important to take great care to preserve any roots that are present in the soil profile for the display. These roots can then be trimmed later with scissors, leaving around 1–2 cm of the finer roots protruding from the surface for the display. Any protruding woody tree roots can be cut back with a hacksaw if necessary.

The final and most important stage of the picking back process involves using a domestic vacuum cleaner with a narrow nozzle attachment to clean the picked back surface by holding the narrow nozzle just above it (Fig. 8). This usually results in the soil monolith surface ending up with a very natural looking finish with few pick marks (Rosewell, 1969).

Sometimes smooth picking marks cannot be avoided with some clay soils. To remove these marks, spray the area with water and then dry the area with a hair dryer before applying a small dab of epoxy adhesive to the pick mark area and sticking a piece of rag to the glued area and allowing to dry. When the glue is dry, the rag is pulled off taking with it a thin coating of soil from the pick mark, revealing the natural soil surface in most instances.

2.1.5. Impreganating the soil monolith with the acrylic bonding agent

2.1.5.1. Bonding compound. After evaluating a wide range of products, we selected a water based, 100% acrylic bonding and sealing compound (Sealwall BONDCRYL 737®) as the bonding agent for our soil monolith production method. This commercial product is recommended as a cement modifier and bonding compound by its Australian supplier (see Table 1). This compound dries clear and so will not affect the natural appearance of the monolith. It has a high bond strength and is durable, non-toxic, and it has a high UV resistance which helps it resist discolouration from exposure to sunlight. Because it is water based, it can easily be diluted to penetrate low porosity or fine textured soils. Being very satisfied with this product, we have tended to favour it for the production of our monoliths. However, other similar acrylic bonding products that are commonly used in cement rendering or similar work, may produce comparable results for soil monoliths.

2.1.5.2. Applying the bonding agent to the soil profile. Two solutions of bonding compound in water are needed; a 1:3 Bondcryl to water dilution to get better penetration or absorption of the compound into
the soil; and a 1:1 Bondcryl to water dilution for injection through a syringe into soil cracks. Both solutions are a milky white colour when first applied, but they become clear when dry. The soil monoliths are impregnated by applying a 1:3 solution to the surface as a prolonged sequence of light misty sprays using a trigger action pump spray bottle with the nozzle adjusted to the finest mist setting (Fig. 9). A suitable protective face mask is worn while spraying to prevent inhaling the fine spray droplets. This solution is sprayed onto the monolith until the profile surface can not absorb any more. At this stage, the applications are stopped for 15–30 min to allow the profile to absorb the solution. Then another spray of 1:3 solution is applied, repeating the process over a whole day. The aim is to permeate the entire monolith surface to a depth of several millimetres with the bonding solution, without allowing it to fully dry out, or the bonding compound may set and form only a very thin surface coating. The capacity of the monolith to absorb the solution gradually decreases with each application. The finishing point is when the monolith becomes very firm and strongly coherent. This is usually achieved with 5 to 10 light misty spray applications.

After the final application, the monolith is then allowed to air dry for 24 h. After this period of drying cracks will develop in some soil monoliths. This is unavoidable in clays, but it can be desirable as the cracks reflect the true nature of the soil material. Any loose aggregates around the cracks can be secured by injecting a 1:1 dilution of the bonding agent into any gaps underneath or at the side of the aggregate with a hypodermic syringe.

Some soil profiles may benefit from additional spray applications every couple of days over a fortnight period, which can give the bond extra strength. Only in sandy soils is penetration uniform in monoliths. The bonding agent actually works by penetrating into small cracks and pores, and permeating about 5 mm or more into the soil surface to form a strong network of bonds when dry, holding the soil profile together.

Another advantage of this bonding agent is that it does not seem to mobilise or dissolve organic coatings or horizons in the soil (e.g. Bh or spodic/podzol horizon) as can occur with some solvents, and as such, this method was found to work equally well on a podzol soil profile from Eastern Australia with a “coffee rock” or Bh horizon.

2.1.5.3. Applying the bonding agent to sandy soil profiles. Sandy soil horizons that occur on or near the soil surface of texture contrast profiles, usually don’t pose any difficulty as these layers are usually held together by roots and rest on a firm clay subsoil. Difficulties can arise with profiles containing thick layers of unconsolidated sand. It is necessary in this situation to make formwork or a mould (usually with wooden blocks wedging a plastic sheet against the soil along the side of the soil profile) to hold the loose material in place while it is being impregnated with the 1:1 solution of bonding agent. The mould around this layer can be removed after 24 h of air drying, but the layer can take a week to fully dry. Sometimes the 1:1 bonding solution can just simply be applied with a wash bottle to the side boundaries of the soil profile and then allowed to dry overnight to form a thick consolidated “skin” around the sandy profile. When this is achieved, the 1:1 solution of bonding agent can then be poured onto the sandy surface between the outer skin, consolidating all of the loose sandy soil layer within the pre-solidified side boundaries. This process can produce a true sandy fabric finish in the front face of the soil profile, as
the loose sand is held in place by the treated sides of the profile and cannot slump during application.

2.1.6. Describing the soil profiles

The remaining half of the soil core not used to produce the monolith is used for description and classification. Samples can also be taken from this half of the soil core for laboratory analysis.

2.1.7. The presentation of the soil monoliths

2.1.7.1. Background paint. After the bonding and preservation stage of the monolith production is complete, the front face of the backing board area around each of the monoliths is painted with a light neutral colour in matte or semi gloss finish which does not clash or compete with the natural colours of the soil. Usually the surface of the board is sanded with a power sander to create a smooth finish prior to painting.

Information accompanying the monolith can be varied to suit the intended audience if detachable panels are used. Fewer words and simpler messages work best for a general audience. Photographs of land use activities that occur on the collected soil, and that possibly even demonstrate how they affect soil properties can stimulate further interest when mounted on an accompanying display board (Fig. 11). Such additional information can help to explain the significance of the soil or particular features important for management.

Although clear perspex covers can help to protect the soil monoliths displayed in museums from prying hands (Fig. 10), they also take away some of the 3-D impact of the profile on the viewer. Provided they can be supervised, monoliths are usually displayed uncovered at workshops and field days to maximise the impact on viewers (see Fig. 11).

3. Summary

The method of soil monolith production presented here incorporates a rapid method of soil profile collection that minimises site disturbance and combines this with a rapid method of preserving the soil profile which is safe and non-toxic compared to previous methods. It incorporates the best of the improvements in monolith production methodology that have been documented over the past 70 years and builds on this with the use of a more modern acrylic bonding agent.

Acknowledgments

The chemists of Maxwell Chemicals are gratefully acknowledged for their help in providing information during the early development stages of this method. The help of Mr Lowan Turton, NSW DPI Menangle, who processed the photographic images used in this paper is also gratefully acknowledged.

References


Fig. 11. Soil monolith display of the New South Wales State Soil, a red chromosol (ASC). Leaving the perspex cover off the display results in the display having much more impact on its viewers.
WATER

Monitoring Tools
Other Monitoring Tools available:

Groundwater salinity
Nitrogen (N) monitoring
Phosphorus (P) loss
Groundcover
Soil fertility
Soil structure
Soil health
Soil acidity
Subsoil Tool
Livestock (Sheep) IPM
Sustainable livestock carrying capacity
Herbicide resistance
Remnant vegetation (Biodiversity)
Energy efficiency
WATER MONITORING TOOLS

These monitoring tools have been developed to help farmers and advisers assess whether paddocks/farms are minimising water losses and thus reduce the risk of salinity. Note that there will be cases in the high rainfall zone where minimal leakage is neither possible, nor desirable for water quality reasons. The monitoring tools can be used in a ‘stand-alone’ way, or can be used as part of justifying and improving on-farm environmental performance using an Environmental Management System (EMS). They are suitable for winter-dominant rainfall environments in southern Australia.

The water monitoring tools have been developed on the basis rainfall and crop/pasture rotations records are collected. Farmers need to choose the nearest soil type in paddocks from a list provided. No other data recording is required, unless farmers choose to sample for more detailed information on soil texture or water holding ability.

There are three water monitoring tools to help farmers assess whether their farm is as environmentally acceptable as it could be – you can use some or all, and the most crucial tools are presented first.

*Note that the terms leakage and perenniality are used regularly in this guide. Their definitions are below:*

**What is leakage?** Leakage is the water that is not used by the plant and/or stored in the soil. Leakage can occur either from below the root zone or as runoff to streams (either from the surface or shallow sub-surface soil.) Leakage from farming systems is often seen as a bad thing – especially when it carries salt or nutrients and results in poor water quality and/or salinity problems through rising water tables. If you are in a catchment which has developing salinity problems and/or known rising groundwater, you can assume that almost all leakage is bad for the environment. However, if you live in an environment where the rainfall is high (above 750 mm/year) and there is no known suspicion of developing salinity problems, then if the water leaking is clean, leakage is good for the environment. From a farm production point of view, minimising leakage is almost always a good thing – maximum use of rainfall is likely to result in better pasture, crop or animal production.

**What is perenniality?** Perenniability is used to describe how much impact a plant type is likely to have on drying out the soil, and hence its ability to reduce leakage. Although many plants (eg phalaris, lucerne, trees, native grasses) are perennials (that is, they can live for a number of years), we know that not all perennials have the same ability to use rainfall and dry out the soil. Hence, a deep rooted perennial such as a tree has a much higher ‘perenniality’ rating than phalaris because it can dry the soil out to greater depth. Summer active perennials will have a higher perenniality rating than summer dormant varieties. The more green leaf area that plants have over summer, the more water they use. Therefore summer active perennials use more water (hence a higher perenniality rating) than summer dormant varieties. Similarly, deep-rooted plants will have a higher perenniality rating than shallow rooted plants because they take up more water and hence grow more. We have used available data and local knowledge of scientists to come up with perenniality ratings. As more research is done on the impact of different species on water use, the perenniality ratings can be modified and new species added.
Introducing the water monitoring tools

Three water monitoring tools have been developed. They are presented in order of their importance to help understand and monitor the impact of farming systems on the environment:

A) PERENNIALITY OF THE FARM: Perennial plants use water throughout the year but especially over the summer period, resulting in drier soils at the autumn break (the time when most leakage occurs). By determining the perenniality of your farm you can work towards a goal of how much perenniality you think you need for maximum environmental benefit. If you are in a salinity prone area this goal should be to have as much perenniality as practically possible (eg. in high rainfall areas over 40%). If you are not in a salinity prone area then a target perenniality may be less crucial for environmental purposes – however to maximise the use of precious resources (rainfall converted to pasture or crop production), then aiming for as much perenniality as possible is still the best strategy.

B) FREQUENCY AND AMOUNT OF LEAKAGE BELOW THE ROOT ZONE: Agriculture has unbalanced the plant water-use patterns of catchments. This has increased the salinity problem. It is important to try and design farming systems that stop these large occasional leaks, except in areas where there is known to be minimal risk of salinity developing. This tool helps you assess the leakage on your farm, with a view to reducing it (for production and/or environmental purposes) or at least understanding how much water you do not use from the rain that falls.

C) WATER USE EFFICIENCY OF CROPS: Water use efficiency (WUE) is the amount of grain (or pasture/meat) produced per mm of effective growing season rainfall. High yielding crops/pastures use more water than low yielding crops/pastures. The more water used by the crop, the lower the risk of leakage from your farm. In addition the calculation of $/mm WUE allows you to assess how profitable a particular paddock was in terms of rainfall used. This figure, in combination with WUE, allows you to assess which paddocks were farmed both most profitably and in the most environmentally acceptable manner.
TOOL A) PERENNIALITY OF FARM

**Goal:** To have sufficient perenniality for benefits to both production and the environmental benefits.

Both this tool and the likelihood of leakage tool (Tool B) will give the best assessment of the risk of leakage and hence impact of your farming practices on salinity, water quality and making the best use of rainfall.

The perenniality tools are most suitable for dryland paddocks. The results for irrigated paddocks, even if they contain lucerne, are less clear because irrigation water is often applied well before the soil has a chance to dry out. Perenniality ratings for irrigated paddocks could be developed from soil water data collected by farmers but at present we do not have such. For the moment, let's assume that irrigated paddocks will result in at least as much leakage as under annual species.

**Why is perenniality important?**

Before European settlement, native perennials occurred over much of the Australian landscape and used almost all of the rainfall. This meant that there was little or no leakage below the root zone.

With European settlement, most of the perennial natives were removed by grazing or cultivation and annuals established. This has changed the water balance so that leakage losses below the root zone are commonly 10-100 times greater than under natural systems. This is the major cause of the increasing salinity. Trees, native shrubs and native grasses used water throughout the year, but especially over the summer period, so that soils were very dry when the autumn rains came.

Maximising perenniality is especially crucial in salinity prone areas. If you are not in a high salinity prone area, then reducing leakage through increased perenniality is still important to make the best use of rainfall. To reduce leakage the key is to have the soil as dry as possible by the end of autumn. The soil ‘bucket’, in which winter rainfall can be stored before it “overflows”, should be as large as possible, as leakage losses largely occur over winter and early spring in our winter dominant rainfall environment.

As soil drying really only occurs from mid-spring onwards over the summer and autumn, perennials must be used because annual plants do not use water over this period. Most pasture (both annuals and perennials) and crop species use similar amounts of water over the growing season, particularly from May-August for areas where rainfall is below 600 mm/year or until September or October where rainfall is higher and/or spring weather is cool. There are few options for increasing plant water use over the cooler winter-spring period. Maintaining sufficient green leaf from November through to March is the best way to increase plant water use, and to create the largest possible soil water storage ‘bucket’. A ‘perenniality factor’ table has been developed (page 4) based on the size of the soil water storage ‘bucket’ created under different management situations.

A target of having 40% of your farm area growing perennial plants (eg. trees, lucerne) at any one time is something to work towards until you can analyse your own soil and rainfall data to determine your own farm-specific target. It is also useful to understand where your farm is in relation to catchment priorities (eg. is it in a high priority salinity area, are there major water quality problems in terms of nitrogen or phosphorus runoff?) Under most situations a dual production and environmental ideal goal is to have no or minimal leakage. To do this, use the leakage-monitoring tool B below. Look at the wettest years and assess how much water storage capacity you would need for no leakage to occur in those years. However, where average annual rainfall exceeds 750 mm/year it will not be possible to have no leakage.
Calculating the perenniality of your farm

Calculate the total area of the farm including individual paddocks, fenced-off remnants or established treed areas and reserves, and any other areas. If it is difficult to estimate the area of trees, try estimating the total treed area on the farm from an aerial photograph. Despite this seemingly relatively simple task, it can take quite a bit of time! Remember to include non-farmed areas such as the land around sheds.

STEPS TO CALCULATE FARM PERENNIALITY

☑ **STEP 1. Define the plant type in each paddock.** Estimate the proportions (area) of the farm under each plant type listed in Table 1.

☑ **STEP 2. Add up the areas of each plant type**

(eg. a 1000 ha farm might have 700 ha sown to a continuing crop or annual pasture phase, 100 ha sown as the first crop following lucerne, 50 ha of phalaris pasture, 100 ha of lucerne and 50 ha of trees/remnant vegetation).

☑ **STEP 3. Determine the perenniality rating** of each plant type by referring to Table 1.

☑ **STEP 4. Calculate the perenniality of your farm** by calculating the perenniality of each area of the farm sown to the different plant types, summing them and expressing the total as a percentage of the total farm area. You can use the proforma over the page to assist you.

*eg. [700 x 0 + 100 x 0.7 + 50 x 0.5 + 100 x 0.9 + 50 x 1] = 235 ha, which gives a perenniality of 235/1000 x 100 = 23.5%.*

**Table 1: Plant types and perenniality ratings for calculation of % perenniality of the farm**

<table>
<thead>
<tr>
<th>Plant type</th>
<th>Perenniality rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average annual crops or pastures</td>
<td>0</td>
</tr>
<tr>
<td>Crops or annual pastures with very high levels of dry matter production</td>
<td>0.1</td>
</tr>
<tr>
<td>Trees (either planted or remnants)</td>
<td>1</td>
</tr>
<tr>
<td>Lucerne-based pasture (at least 5 plants/m² or 10% lucerne)</td>
<td>0.9</td>
</tr>
<tr>
<td>Perennial grass pasture, eg phalaris (at least 5 plants/m² or 10% perennial)^a</td>
<td>0.5</td>
</tr>
<tr>
<td>Native grass pasture^a</td>
<td>0.5</td>
</tr>
<tr>
<td>First crop following lucerne pasture</td>
<td>0.7</td>
</tr>
<tr>
<td>Second crop following lucerne pasture</td>
<td>0.5</td>
</tr>
<tr>
<td>Third crop following lucerne pasture</td>
<td>0.2</td>
</tr>
<tr>
<td>Fourth and subsequent crops following lucerne</td>
<td>0</td>
</tr>
<tr>
<td>Irrigated pastures</td>
<td>Assume 0</td>
</tr>
</tbody>
</table>

^ Note that not all perennial grasses are likely to have the same perenniality ratings – summer active grasses will have a higher rating than winter active ones. As more research information becomes available we should be able to modify the perenniality ratings for species like fescue, cocksfoot, wallaby grass, red grass etc.
**TOOL A: PRO-FORMA SHEET FOR CALCULATING THE PERENNIALITY OF YOUR FARM**

<table>
<thead>
<tr>
<th>Column A</th>
<th>Column B</th>
<th>Column C</th>
<th>Column D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hectares (from calculation of farm areas)</td>
<td>% area (Column A/total farm area) x 100</td>
<td>Perennial Rating (from Table 1)</td>
<td>% Perenniality (Column B x Column C)</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Canola</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barley</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Annual pasture</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other non-perennials</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Native perennial grass pasture</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Other perennial grass pasture</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lucerne</td>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remnants</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total area of the farm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TOOL B) FREQUENCY OF LEAKAGE**

The leakage tool is designed to give you an idea of whether/how much your farming systems leak - the figures are indicative only, as would be expected for no additional data collection apart from rainfall and plant type.

**Introduction to leakage**

Natural woodlands and grasslands that were cleared for cropping and annual pastures once had very little leakage of rainfall from below the root zone. Trees, native shrubs and grasses used water throughout the year but especially over summer. As a result, soils were very dry by the time of the autumn break. Agriculture has markedly changed the balance and water losses have now increased 10 to 100 times.

Leakage losses mostly occur over the wet winter period in southern Australia (commonly June-August for cropping areas, June-October for most high rainfall catchments or areas, which have cool spring conditions); however leakage does not occur in all years. It is the large but occasional losses (eg. 40 mm leakage may occur in a 450 mm rainfall environment only 5 times in 20 years) that are mainly responsible for the increasing salinity problem. Therefore it is important to try and design farming systems that limit these large occasional losses.

Deep-rooted perennial species (particularly lucerne and trees) have the most potential to control most losses of water to below the root zone. Both soil type and the plant type affect the likelihood of leakage loss. For example, sandy soils often have high infiltration rates as well as low soil water holding capacities and are at greater risk of leakage losses. Growing deep-rooted perennials on these soils is of highest priority.
Before you start, find out whether you are in a salinity prone region

Prior to assessing the frequency of leakage, you should find out whether you are in a salinity prone area. Start with either contacting your local Department agency (Victoria - Department of Primary Industries or Sustainability and Environment in Victoria; NSW - NSW Agriculture or Department of Infrastructure, Planning and Natural Resources) or local Catchment Management Authority. Most areas have prioritised salinity management zones. However if you are not in one of these designated areas it does not mean that a salinity threat does not exist. Until otherwise informed reliably, your starting point should be that future salinity might be a problem. In some catchments, the ‘high priority’ salinity management zones have been decided upon on the basis of where it is currently worst, rather than where it has the potential to cause most damage to assets in the future. Areas without a threat of salinity tend to be in above 800 mm/year rainfall areas, but this is not always the case.

<table>
<thead>
<tr>
<th>STEPS TO CALCULATE FREQUENCY OF LEAKAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Record paddock name on Tool B proforma (next page).</td>
</tr>
<tr>
<td>2 Define plant type in the paddock using the categories in Table 2 for dryland paddocks (choose either the North-East, North-Central or Glenelg Hopkins options).</td>
</tr>
<tr>
<td>3 Define dominant soil type in the paddock on which the plant is grown (use Table 2). Note that the combination of slope and soil type is crucial to determining how much water runs off and how much is leakage below the root zone. We will refine these tools to include slope considerations in the near future. This will allow you to partition water loss between runoff and water loss below the root zone.</td>
</tr>
<tr>
<td>4 Look up the estimated plant available water capacity of the soil for your plant/soil combination from Table 2 for dryland paddocks.</td>
</tr>
<tr>
<td>5 Calculate winter rainfall from records. Use May-August rainfall except in years where September and/or October rainfall exceeds 60mm; in this case use May-September or May-October rainfall.</td>
</tr>
<tr>
<td>6 Assume plant water use of any species (crop, pasture or lucerne) from May-August is 120 mm or if May-September rainfall has been used, assume plant water use to be 180 mm (240 mm if May-October rainfall has been used).</td>
</tr>
<tr>
<td>7 Calculate estimated leakage from the sum of May-August rainfall (or May-September or October where September or October rainfall exceeds 60 mm/month) minus plant water use minus soil water holding capacity. A positive value is the estimated mm of leakage; zero or negative values indicate no leakage is likely.</td>
</tr>
<tr>
<td>8 Repeat for other paddocks of interest on the farm. (It is highly unlikely that leakage ever occurs under trees or lucerne, so to test for likelihood of leakage in a particular year calculate it initially for annual crops or pastures).</td>
</tr>
<tr>
<td>9 Calculate the megalitres of water leaving the farm as leakage. (Lets say that 20 mm leakage occurred from a 100 ha paddock in a particular year. 1 mm leakage from a hectare of land = 10,000 litres or 0.01 megalitres. So 20 mm leakage from 100 ha of land on the farm is 0.01 x 20 x 100 = 20 megalitres water lost in that year.</td>
</tr>
<tr>
<td>10 Use long-term rainfall records to see how often leakage is likely to occur under annual species in particular paddocks. Check whether the winter rainfall value exceeds a ‘threshold’ for predicted leakage. The threshold value is the sum of plant water use plus soil water holding capacity for your particular soil and vegetation type. If the May-August (or May-September, May-October) rainfall exceeds this threshold value, then leakage is likely to occur.</td>
</tr>
<tr>
<td>11 Determine long-term leakage losses from your farm by recording for particular years the paddocks in which leakage occurred. This information will provide a useful basis on which to discuss relative losses of water (and thus salinity risk) in your area, and to compare irrigation and dryland water losses. In future, when there are discussions about the relative contributions of irrigation and dryland farming to salinity, these figures can be used to show the likely degree of leakiness of particular farming systems.</td>
</tr>
</tbody>
</table>
The maximum amount of ‘soil water storage’ occurs immediately prior to the autumn break when soils are at their driest. Note that it is the combination of plant type (the depths to which their roots are likely to dry soils to) and the soil type which determines the amount of water that the soil can store before drainage occurs.

Table 2: Estimated amount of water (mm) which the soil could store (called plant available water capacity) before leakage would occur (can choose Riverina, North east Victoria or South west Victoria options or just choose the best soil description for your area) for dryland paddocks.

<table>
<thead>
<tr>
<th>Plant type</th>
<th>Assumed Plant Available Water Capacity of the soil (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very High</td>
</tr>
<tr>
<td>Description</td>
<td>Deep well structured, heavy textured soils</td>
</tr>
<tr>
<td>Riverina NSW</td>
<td>Well structured heavy soils</td>
</tr>
<tr>
<td>North east Victoria</td>
<td>Most good river flats including silty soils</td>
</tr>
<tr>
<td>South west Victoria Glenelg Hopkins, Corangamite</td>
<td>Older basalt plains soils</td>
</tr>
<tr>
<td>Annual species&lt;sup&gt;c&lt;/sup&gt; (crop or pasture) following an annual</td>
<td>140</td>
</tr>
<tr>
<td>Lucerne</td>
<td>280</td>
</tr>
<tr>
<td>Remnant vegetation</td>
<td>350</td>
</tr>
<tr>
<td>Perennial grass</td>
<td>180</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; crop following lucerne</td>
<td>240</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; crop following lucerne</td>
<td>200</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; crop following lucerne</td>
<td>160</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt; and subsequent crops</td>
<td>140</td>
</tr>
</tbody>
</table>

<sup>a</sup> Major limitations could be strongly sodic soils, saline soils acidity to depth, major and waterlogging problems and poorly structured soils.

<sup>b</sup> The reason for lower water holding capacity of heavy floodplains than most river flats is that heavy clays can have less favourable environment for roots to live. Clay soils can also hold water very tightly compared with sandier soils.

<sup>c</sup> Rooting depths under annual species generally assumed to be about 1 m depth, unless other information is available. For example a good cropping soil at Burrumbuttock NSW had a measured Plant Available Water Content (PAWC) of 115 mm under triticale – due to this crop being able to extract water to 130 cm depth. Thus, there will be cases where the PAWC figures can be increased from those in the table. The table is a guide only where no better information exists.
TOOL B: PROFORMA FOR CALCULATING FREQUENCY OF LEAKAGE ON DRYLAND PADDOCKS

<table>
<thead>
<tr>
<th>Paddock Name</th>
<th>Plant type (Table 1)</th>
<th>Dominant soil type (Table 2)</th>
<th>Plant available water capacity (mm) (Table 2 according to paddock soil and plant type)</th>
<th>Year of interest</th>
<th>Calculate rainfall available for leakage (Step 7) (winter rainfall minus plant water use over winter)</th>
<th>Estimated leakage (mm) (Column E minus Column C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e.g. Hill</td>
<td>Crop</td>
<td>Red cropping</td>
<td>100</td>
<td>1995</td>
<td>e.g. 244-120 = 124</td>
<td>124 - 100 = 24</td>
</tr>
</tbody>
</table>

TOOL C) WATER USE EFFICIENCY OF CROPS

Water use efficiency (WUE) is the amount of grain or livestock production produced per mm of effective growing season rainfall. High yielding crops use more water than low yielding crops where dry matter production is correspondingly higher. In some cases, high yields can occur with relatively lower dry matter production (high harvest index); thus WUE is a not necessarily always a good indicator of the water-using ability of crops. The more water used by the crop, the lower the risk of leakage from your farm; WUE figures themselves are not a good indicator for amount of likely leakage which is why we think tools B and A are most important.

(Proforma sheets for this tool are following $WUE instructions).

Goal: To achieve at least 80% maximum water use efficiency for all crops grown on the farm, and preferably 100%.

Steps to calculate WUE of crops:

✔ **STEP 1. Calculate grain yields for each paddock** (t grain/ha)
  
  (as an example, let's assume 3.2 t/ha for wheat and 1.6 t/ha for canola).

✔ **STEP 2. Calculate growing season rainfall as the sum of April-October rainfall figures plus one third of January-March rainfall** (mm) to determine growing season rainfall. The 1/3 of January-March figure is used to account for extra soil moisture stored in the profile at sowing time.

Some farmers use the software program Pycal to estimate the amount of stored soil water, in which case the January-March figures for rainfall are not needed. For the example, let’s say 267 mm fell in April-October plus 76 mm in January-March. Therefore growing season rainfall is calculated as 267 + 25 mm = 292 mm.
☑️ **STEP 3. For each crop type, select the evaporation loss** from Table 3 (eg. 110 mm for both wheat and canola).

☑️ **STEP 4. Calculate water use efficiency (WUE)** [kg grain/ha/(mm growing season rainfall minus evaporation)] using Tool C proforma on page 11.

(In our example wheat WUE = 3,200/(292-110) = 17.6; canola WUE 1,600/(292-110) = 8.8)

☑️ **STEP 5. Calculate your WUE as a percentage of the potential WUE** (see Table 4) for each paddock by dividing your calculated WUE by the potential values listed in Table 4 and expressing them as a percentage (wheat 17.6/20 x 100 = 88% of potential WUE; canola 8.8/10 x 100 = 88%).

☑️ **STEP 6. Rate water use efficiency figures** as excellent (95% of potential or greater), good (80-95%), marginal (60-80%) or poor (<60%).

☑️ **STEP 7. Compare your maximum and minimum figures for % potential WUE both within and between crop types** and think about the reasons for the differences (eg. differences in weed burdens, soil fertility, diseases, sowing times, etc?) for future planning/action. If your figures are generally marginal to poor, discuss figures with others to see whether the poor figures are district wide (and therefore due to seasonal conditions, such as a particularly wet year). Alternatively your rating could be associated with some aspects of your farm management, which could be improved, and analysing the best and worst % potential WUE figures for your paddocks may help indicate how you could improve yields.

☑️ **STEP 8. Consider how you might improve poor % potential WUE values in particular paddocks** – seek advice if you wish to discuss this issue further.

---

**Table 3: Assumed evaporation during the growing season**

<table>
<thead>
<tr>
<th>Crop type</th>
<th>Evaporation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>110</td>
</tr>
<tr>
<td>Barley</td>
<td>90</td>
</tr>
<tr>
<td>Oats</td>
<td>90</td>
</tr>
<tr>
<td>Triticale</td>
<td>90</td>
</tr>
<tr>
<td>Canola</td>
<td>110</td>
</tr>
<tr>
<td>Grain legumes</td>
<td>130</td>
</tr>
</tbody>
</table>

**Table 4: Potential water use efficiency values for crop types**

<table>
<thead>
<tr>
<th>Crop type</th>
<th>Potential WUE (kg grain/mm/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>20</td>
</tr>
<tr>
<td>Barley</td>
<td>18</td>
</tr>
<tr>
<td>Oats</td>
<td>22</td>
</tr>
<tr>
<td>Triticale</td>
<td>18</td>
</tr>
<tr>
<td>Canola</td>
<td>10</td>
</tr>
<tr>
<td>Grain legumes</td>
<td>12</td>
</tr>
</tbody>
</table>

**Calculating $/mm WUE for crops**

Calculation of $/mm WUE allows you to assess how profitable a particular paddock was in terms of rainfall used. This figure, in combination with WUE, allows you to assess which paddocks were both more profitable and more environmentally acceptable.

**Goal:** To maximise $/mm WUE and understand differences between paddocks. Note, due to large annual variations in crop price, it is sensible only to make relative comparisons between paddocks for each season.
Steps to calculate $/ mm WUE for crops

☑ STEP 1. Calculate gross margin/ha. Gross margins are calculated by multiplying together the yield and gross price and subtracting the enterprise (or variable costs) costs. Variable costs do not include fixed costs of production.

(In this example we will use an average gross margin of $334/ha for wheat and $329/ha for canola).

☑ STEP 2. Calculate effective growing season rainfall as per steps 2 and 3 of the water use efficiency calculations, that is (April-October)+ 1/3 (Jan-March) – Evaporation (Table 3).

(For this example we will use an effective growing season rainfall figure of 232 mm).

☑ STEP 3. Divide gross margin per ha by growing season rainfall.

\[ \frac{334}{232} = \$1.44/mm \text{ for wheat and } \frac{329}{232} = \$1.42/mm \text{ for canola}. \]

☑ STEP 4. Compare $/mm WUE figures of various paddocks and analyse why some paddocks might have been both more profitable and used more water than others.

TOOL C: PROFORMA SHEET FOR CALCULATING WATER USE EFFICIENCY OF CROPS (WUE)

<table>
<thead>
<tr>
<th>Column A</th>
<th>Column B</th>
<th>Column C</th>
<th>Column D</th>
<th>Column E</th>
<th>Column F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paddock name</td>
<td>Crop type</td>
<td>Yield (t/ha) (from paddock records)</td>
<td>April-Oct Rain +1/3 Jan-March (mm) (from rainfall records)</td>
<td>Assumed Evaporat’n (mm) (Table 3)</td>
<td>Actual WUE (kg grain /mm/ha) [\text{Column A} \times 1000 / (\text{Column B} - \text{Column C})]</td>
</tr>
<tr>
<td>e.g. Hill</td>
<td>Wheat</td>
<td>3.2</td>
<td>292</td>
<td>110</td>
<td>3.2 x 1000/(292-110) = 17.6</td>
</tr>
</tbody>
</table>
**TOOL C: PROFORMA FOR CALCULATING $/mm WUE**

<table>
<thead>
<tr>
<th></th>
<th>Column A</th>
<th>Column B</th>
<th>Column C</th>
<th>Column D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Paddock name</strong></td>
<td>Gross margin/ha ($/ha)</td>
<td>April-Oct Rain +1/3 Jan-March (mm) (from rainfall records)</td>
<td>Assumed Evaporation (mm) (Table 3)</td>
<td><strong>$ WUE ($/mm/ha)</strong> [Column A / (Column B – Column C)]</td>
</tr>
<tr>
<td>e.g. Hill</td>
<td>203</td>
<td>292</td>
<td>110</td>
<td>203 / (232-110) = 1.66</td>
</tr>
</tbody>
</table>

**Comments**

**Note:**

**Breaches of the Water Act.**

Breaches of the Water Act may occur if appropriate approval has not been sought from the local Water Authority when soil sampling, installing piezometers or neutron probe access tubes. In general, if any soil sample, piezometer, soil moisture tube, is **greater than 3 metres deep**, or if it intercepts the groundwater, it may have to be registered with the relevant water authority. Individual water authorities could have different approaches to registration. Breaches of the Water Act are an offence that involves a financial penalty.

Registration requires a series of steps that generally involve:

- contacting the local water authority and applying for installation licence
- this licence will require maps of locations, depth, purpose and information regarding near by infrastructure. A dial before you dig, that locates underground infrastructure, power etc may also be required. If the person has never registered a bore, or a hole in the ground so to speak, then it is strongly advised they contact the water authority to determine the steps involved.
- the cost to register - roughly $400 for first hole and an additional $50 for second etc, but this may vary with the water authority.

The registration process exists for several reasons. For example:

- in an attempt to prevent pollution by aquifer leakage, this is why soil sampling is included in the registration process if groundwater is intercepted.
- to provide an identification number and location of groundwater bores, and generate funds to run the groundwater data bases.
- to ensure no illegal groundwater extraction.

The registration process also means that only a registered driller can install the holes or collect the soil samples. If you unsure of the groundwater depth in your region, then using a registered driller removes any risk.
There are generally no exceptions to the rule, however there are variations in how water authorities govern the Act, so contact with water authorities is essential. Also, as a low cost risk management strategy, it is recommended to contact the dial-before-you-dig hotline (phone 1100 or www.dialbeforeyoudig.com.au) and ascertain the location of any infrastructure (power, telecommunications, gas etc.).
Water use by crops and pastures in southern NSW

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Key points

• Agricultural production seeks both high total water use (TWU) and high water use efficiency (WUE).

• High total water use influences the environment through minimising deep drainage, and associated waterlogging and salinity.

• Potential or water limited yield of wheat is about 20 kg/ha/mm of seasonal water use, and for broad-leaf crops is about 15 kg/ha/mm of seasonal water use (after deducting 100 to 120 mm).

• The water limited yield of annual pasture dry matter production is about 30 kg/ha/mm (after deducting about 30 mm).

• Potentially, dryland lucerne can yield about 12 kg/ha of dry matter for each mm of annual rainfall.

• Poor WUE can indicate management problems or constraints imposed by soil, nutrition, pests or disease.

• Identifying and addressing these agronomic constraints is the path to improved WUE.

Total water use

Total water use (TWU) refers to the amount of water used by a crop or pasture. Major differences in water use are due to different rooting depths of plants. Lucerne draws water from further down the soil profile (as deep as 3–4 m) than wheat (about 1.2 m) or annual pastures based on subterranean clover (60–70 cm). Lucerne has a greater capacity to access and use water, and so minimise deep drainage. Deep drainage and its associated salinisation are minimised by high total water use by plants. A cereal crop can obtain water, additional to rainfall during the growing season, if moisture is conserved in a fallow prior to sowing the crop. Ability to store fallow moisture is dependent on management (e.g. for weed control, stubble cover) of the fallow, and the soil’s capacity to store water. However agricultural production is influenced by both the total water use and the efficiency of the plant in using water to produce grain or forage.

Water use efficiency in grain production of wheat

Water use efficiency (WUE) is a measure of the forage (biomass) or grain yield produced for each mm of water use.

Figure 1. Relationship between grain yield of wheat and water use showing upper limits of water use (blue line, slope of 20 kg/ha/mm after allowing for 110 mm of water); data of French and Shultz 1984a (blue points); and data from five monitored crops in the Murrumbidgee Catchment in 2005 (numbers).
millimetre of water used (i.e. transpired) by a pasture or crop.

Interest in Australia was spurred by the work of French and Schultz (1984a, 1984b; Figure 1) on water use efficiency for grain production by wheat. French and Schultz estimated growing season water use as equal to in-crop rainfall (sowing to harvest), plus any soil moisture at sowing, minus any unused water at harvest. This growing season water was used by crop transpiration or lost by evaporation from the soil surface. French and Schultz estimated that 110 mm of water ($W_{\text{threshold}}$; Figure 1) was lost by evaporation from the soil surface, and that grain yield was potentially 20 kg/ha/mm of water transpired (i.e. growing season water use – 110 mm of evaporation).

In their data for low rainfall sites and regions (Table 1) French and Schultz estimated a lower $W_{\text{threshold}}$ (70 mm). This was consistent with lower evaporative loss (due to less frequent rainfall events). However, other sources of water loss are in surface run-off from rainfall, and in deep drainage below the rooting depth of the crop and French and Schultz did not measure these losses. So at a site with high rainfall and a poor surface condition the estimated $W_{\text{threshold}}$ was higher (170 mm; Table 1). This was presumed to be due to unidentifed runoff and the $W_{\text{threshold}}$ of 170 mm included both evaporation from the soil and surface runoff. The threshold amount of water ($W_{\text{threshold}}$) then was water which was lost by evaporation from the soil surface (range about 70–130 mm), but may under some circumstances include run-off and deep drainage if these are not independently estimated (up to 170 mm). Later authors (Robinson and Freebairn undated) have preferred to think of $W_{\text{threshold}}$ as the minimum amount of water needed before the plant will produce grain. A $W_{\text{threshold}}$ of 110 mm is a widely used estimate when determining WUE for grain production from cereals.

Other values determined in southern NSW for wheat are given in Table 1. The $W_{\text{threshold}}$ values are in the same range as French and Schultz, but WUE appears a little lower at 15–16 kg grain/ha/mm (Cornish and Murray 1989; Steiner et al 1985). These were estimates of the average values expected from reasonable agronomy and production conditions.

In contrast French and Schultz described the water limited or potential maximum (upper boundary of WUE) for grain yield production.

Similarly, WUE and $W_{\text{threshold}}$ can be estimated for broad leaf crops (Table 2). Maximum WUE was 13–15 kg/ha/mm, after deduction 80–110 mm ($W_{\text{threshold}}$).

Determining WUE will highlight inefficient use in a paddock or region. Data from southern NSW in 2005 indicated reasonable WUE (Figure 1), except for Site 4, which was well below the water limited potential yield. WUE can be improved by identifying and correcting limitations to crop growth, such as nutrient deficiencies, diseases and weeds, soil constraints and poor agronomy such as variety choice and delayed sowing.

**Water use efficiency and dry matter production**

The concept of water use efficiency can be extended to vegetative production of crops and pastures. French and Schultz (1984a) indicated that wheat had a potential WUE for total dry matter production at harvest (stubble + grain yield), of up to 55 kg/ha/mm, after allowing for 110 mm of water losses ($W_{\text{threshold}}$; Table 3).

Similar estimates can be made for pasture production. In Western Australia annual pastures yielded 30 kg/ha/mm of dry matter after deducting 30 mm of water use ($W_{\text{threshold}}$; Bolger and Turner 1999; Figure 2). As this data was obtained with high input pastures, the relationship probably represents the water limited (potential) yield. The dry matter yields of low input pastures reported by Bolger and Turner (1999) were less than indicated by this relationship, and data from central NSW were below this relationship (Blumenthal and Ison 1993). Data from southern NSW was near potential yield in 2006, but below potential in 2005. Site 4 in 2005 was well below water limited potential yield.

Lucerne can produce throughout the year and its dry matter production over the year can be related to annual rainfall (Figure 3). Data from central western NSW showed that lucerne dry matter production

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**Table 1. Estimates of water use efficiency (WUE) and threshold water ($W_{\text{threshold}}$) for grain production of wheat in South Australia and for southern NSW.**

<table>
<thead>
<tr>
<th>Location (reference)</th>
<th>$W_{\text{threshold}}$ (mm)</th>
<th>WUE (kg/ha/mm)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Australia</td>
<td>110</td>
<td>20</td>
<td>Upper limit of data (all data)</td>
</tr>
<tr>
<td>(French and Schultz 1984a)</td>
<td>70</td>
<td>20</td>
<td>Upper limit of data (low rainfall sites)</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>20</td>
<td>Upper limit of data (high rainfall, poor soil surface conditions)</td>
</tr>
<tr>
<td>Wagga Wagga</td>
<td>70</td>
<td>15</td>
<td>Average of data, dryland crops</td>
</tr>
<tr>
<td>(Cornish and Murray 1989)</td>
<td>126</td>
<td>16</td>
<td>Average of data, irrigated crops</td>
</tr>
<tr>
<td>Griffith</td>
<td>126</td>
<td>16</td>
<td>Average of data, irrigated crops</td>
</tr>
<tr>
<td>(Steiner et al 1985)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
was related to rainfall and produced 6.7 kg/ha/mm of rainfall on average (Bowman et al 2004; Figure 3, broken line). An approximate water limited potential yield of about 12 kg/ha/mm was estimated from this data (Figure 3, solid line) with no $W_{\text{threshold}}$. Again data from southern NSW appears to confirm the potential yield estimate (Figure 3, numbers).

**Estimating crop water use efficiency on farm**

The water use efficiency concept is easiest to use in a Mediterranean climate. This is because the summers are dry, and April–October rainfall alone is a good estimate of water supply to crops (French and Schultz 1984b). Run-off and deep drainage are the unknowns, and may be unimportant in most seasons and in low rainfall regions. Crop water use is approximated by rainfall from shortly before sowing to harvest.

However in the equi-seasonal environment of southern NSW, where rainfall in summer is only slightly less than winter rainfall, a crop may be sown with substantial water from summer rain already stored in the soil profile, or the crop may mature with unused water still in the soil profile. Soil moisture can be measured at the start and end of the season, or the amount of water at these times can be estimated. Farmers need some simple rules of thumb to assist them in these estimations (Figure 4).

While no simple rules can fully account for soil moisture at sowing or at harvest some guidelines are available (Robertson and Kirkegaard 2005). Working with canola in southern NSW these authors used some experimental data and simulation modelling of rainfall at Narrandera from 1904–2003 to conclude the following:

- Soil moisture storage at sowing can be estimated by taking summer rainfall (post harvest to sowing), subtracting 80 mm, and then using 40% of the remainder. This estimate was determined over a range of fallow management, but weed control was consistently good.

**Table 2. Indicative water use efficiency (WUE) and threshold water use ($W_{\text{threshold}}$) of broad leaf crops for grain production.**

<table>
<thead>
<tr>
<th>Crop, location (reference)</th>
<th>$W_{\text{threshold}}$ (mm)</th>
<th>WUE (kg/ha/mm)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canola, southern NSW</td>
<td>120</td>
<td>15</td>
<td>Average of data in seasons of favourable rainfall distribution</td>
</tr>
<tr>
<td>(Robertson and Kirkegaard 2005)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>11</td>
<td>Average (all data)</td>
</tr>
<tr>
<td>Lupins, estimate</td>
<td>80</td>
<td>13</td>
<td>Approximate upper limit of data</td>
</tr>
<tr>
<td>(D Luckett pers. comm.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field pea</td>
<td>100</td>
<td>15</td>
<td>Approximate upper limit of data</td>
</tr>
<tr>
<td>(Siddique et al 2001)</td>
<td>100</td>
<td>10</td>
<td>Approximate average of data</td>
</tr>
<tr>
<td>Faba bean, WA estimates</td>
<td>110</td>
<td>15</td>
<td>Approximate upper limit of data</td>
</tr>
<tr>
<td>(Siddique et al 2001)</td>
<td>110</td>
<td>10</td>
<td>Approximate average of data</td>
</tr>
</tbody>
</table>

**Figure 2. Relationship between water use and end of season dry matter production for annual pastures in WA (blue points and line; Bolger and Turner 1999), with data from southern NSW in 2005 (orange numbers) and in 2006 (green numbers).**

**Figure 3. Relationship between annual rainfall and annual dry matter production for dryland lucerne pastures in central western NSW (blue points and lines; Bowman et al 2004). The broken line is the average data, and the solid line is the potential yield. Data from southern NSW in 2005 (orange numbers), and in 2006 (green numbers) is presented.**
Table 3. Water use threshold ($W_{\text{threshold}}$) and water use efficiency (WUE) for potential dry matter production in wheat in South Australia (from French and Schultz 1984a).

<table>
<thead>
<tr>
<th>Crop interval</th>
<th>Water use threshold ($W_{\text{threshold}}$; mm)</th>
<th>Water use efficiency (WUE; kg/ha/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sowing to end of tillering</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>Sowing to anthesis</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>Sowing to maturity</td>
<td>110</td>
<td>55</td>
</tr>
</tbody>
</table>

**Estimating WUE of a crop**

**Example of Site 3 in Figure 1**

Sowing in early May; anthesis in early October; maturing in early December. $W_{\text{threshold}} = 110$ mm

Rainfall

<table>
<thead>
<tr>
<th>Jan–Apr</th>
<th>May–Nov</th>
<th>Oct–Nov</th>
</tr>
</thead>
<tbody>
<tr>
<td>103 mm</td>
<td>457 mm</td>
<td>130 mm</td>
</tr>
</tbody>
</table>

A = stored water at sowing

$= (103 - 80) \times 0.40$

$= 9$ mm

B = in crop rainfall

$= 457$ mm

C = unused soil water at harvest

$= (130 - 50) \times 0.50$

$= 40$ mm

Crop water use = A + B – C

$= 9$ mm + $457$ mm – $40$ mm

$= 426$ mm

Grain yield = 5100 kg/ha

WUE of this crop = $5100 \div (426 - 110)$

$= 16$ kg/ha/mm

Water limited potential yield = $(426 - 110) \times 20$

$= 6320$ kg/ha

**Figure 4. An example of the calculation of WUE and water limited yield.**
In a similar manner, soil moisture remaining at harvest can be estimated from rainfall between anthesis and crop maturity (Oct–Nov or Dec), minus 50 mm, and the remainder halved. This estimate is very variable and was developed for canola, so care should be used.

Limitations of the water use efficiency concept

The French and Schultz approach takes no account of the timing of rainfall. This can result in apparently low water use efficiency when, for example, severe dry conditions late in the growing season result in poor grain fill in a season with otherwise reasonable rainfall. Unseasonal late frost can damage a crop at flowering resulting in low apparent water use efficiency. In both these situations the crop may yield to its potential under the prevailing conditions. The farmer has done all that is possible to achieve the water limited or potential yield, but the seasonal conditions (timing of rain, frost) have limited what can be achieved.

There are also regional differences. Crops use more water under dry conditions to get the same yield as under humid conditions. Therefore, crops grown in dry areas tend to have lower WUE than in humid areas. Also in the northern wheat areas of eastern Australia soil moisture at sowing accounts for a higher proportion of water used by wheat crops than in the south. This leads to more efficient WUE because stored soil moisture is used by the crop and evaporation of stored soil moisture is negligible. As a result of these limitations to the calculation, water use efficiency targets for water limited yield need careful use by growers.

Usefulness of water use efficiency

WUE is useful when comparing results from paddocks or whole farms within a season and region, but far less useful when comparing regions or seasons within a region. Poor WUE in a paddock, when other paddocks or growers in the same region and season have higher WUE, probably indicates the crop yield was below what was possible; that is yield was not water limited, and there was some important management or soil based constraint on yield. Identifying and addressing these agronomic constraints is the path to improved WUE (Figure 5).

Acknowledgements

This Primefact was produced from a project conducted by Damien Doyle and Craig Muir (Industry & Investment NSW) for the Murrumbidgee Catchment Management Authority. The project was funded through the Australian and NSW Government’s National Action Plan for Salinity and Water Quality.

References and further reading


Robinson B, Freebairn D (undated) *Water Use Efficiency of wheat: Principles, practices, and pitfalls*, (Dept of Natural Resources, APSRU, PO Box 318, Toowoomba 4350).


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ISSN 1832-6668

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Job number 9671 PUB09/113