WATER SMART FARMING MANUAL

GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION

NATIONAL

STRATEGIES FOR OPTIMISING WATER USE EFFICIENCY OF YOUR GRAIN GROWING SYSTEM

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COVER: Darrin Lee checking his remote moisture monitoring stations that are connected wirelessly on his Mingenew WA property.

PHOTO: Evan Collis

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Chapter 1: Introduction

This manual describes the latest research on maximising your rainfall and provides new strategies for increasing your yield, farm profit and resilience to changes in rainfall.

Growing conditions in Australian grain regions are diverse, with varying soils, climates, seasonal patterns and crops. The research and data presented in this manual are based on the most reliable and current information available in the northern, western and southern cropping regions. Although some emerging areas of research may be restricted to a specific type of grain (such as wheat), the findings exhibit potential for broader application and so have been incorporated into this manual.

Who is this manual for?

This manual is intended for the following audiences in rain-fed grain growing systems across Australia:

- growers and advisers;
- those wanting to maximise water use efficiency (WUE) to get more from their rainfall; and
- those interested in understanding plant-available water capacity (PAWC), crop water utilisation and how to manage the unpredictability of weather forecasts.

How do I use this manual?

This manual is designed so that it can be read in several ways:

- **Option 1:** Read through from start to finish for a comprehensive manual on understanding and optimising farm water.
- **Option 2:** Select a chapter that covers a topic of interest to you. Start at the Contents on page 3.
- **Option 3:** Assess your farm to address any gaps in your farm water management. Start at Best Practice Farm Assessment Guide on page 8.

Throughout the manual, and in a section at the back (Useful Resources), there are links to helpful resources (websites, research papers, fact sheets) if more detail is required for specific areas, and the end of the document includes a list of references for the research mentioned in the manual.

What topics are covered?

The chapters of this manual are structured around the following themes, with each chapter starting with a summary of the essential points.

Chapter 2: Understanding your soils

How does your soil influence water infiltration and storage?

Soil types vary at the farm scale and across Australia. Techniques to better assess and understand your soils provide valuable information for making farming decisions.

Chapter 3: Plant-available water capacity

How can you determine and use PAW and PAWC on your farm?

Knowledge of a soil's capacity to hold water and supply it to a crop can help in cropping decisions. Plant-available water (PAW) and plant-available water capacity (PAWC) can be estimated using on-farm measurements or by accessing publicly available data.

Chapter 4: How crops use water

How does water use by crops relate to your decisions on-farm?

The concepts of crop transpiration, vapour pressure deficit, water-limited yield potential and critical growth period can help you understand why different practices influence water use.

Chapter 5: Preparing for the growing season

What practices before the start of the growing season can improve WUE?

Long and short fallows, fallow weed control, crop residue management and cover crops can all have an influence on WUE.

Chapter 6: Optimising water use during the growing season

How does cultivar selection, sowing time and nutrition influence WUE?

Selecting the right variety for the conditions, aligning sowing time to optimal flowering window, using optimum nutrition strategies and narrow row spacings can all help to optimise WUE.

Chapter 7: Using technology to improve water efficiency

What technology is available to maximise your rainfall?

Soil moisture monitoring, tools to assess spatial variability, online tools and apps are available to help guide decisions on crop selection, variable-rate applications, fertiliser, hay cutting and marketing.

Chapter 8: Managing risk

How to make tough decisions using uncertain weather forecasts

Climate science and models can provide predictions both leading into and during the growing season. By combining the decision analysis technique with probabilistic modelling, you can make decisions using uncertain forecasts.

How is GRDC improving knowledge in this area?

The Grains Research and Development Corporation (GRDC) is actively supporting and investing in a wide range of research initiatives related to soil water and plant water use. Some of the key areas of research supported by GRDC include:

- developing and testing innovative WUE practices and technologies that can enhance the productivity and profitability of Australian grain farms, while reducing the environmental impact of agriculture;
- investigating the factors that influence soil water retention, movement and uptake by plants, and developing practical methods for measuring, predicting and managing PAWC in different soil types and climatic conditions;
- examining the impact of climate variability and change on rainfall patterns, soil moisture and crop performance, and identifying strategies that can help growers adapt to these challenges;
- supporting the development and implementation of advanced decision support tools and models that can help growers make more informed decisions about irrigation scheduling, crop selection and other management practices; and
- collaborating with national and international research partners to promote knowledge exchange, capacity building and innovation in soil and plant water management.

To stay informed about these initiatives, regularly check the GRDC website, as well as GroundCover™ (groundcover.grdc.com.au), daily grains industry online news and the GRDC Grains Research Updates (grdc.com.au/resources-and-publications/grdc-update-papers), where subject matter experts travel around the country to share the outcomes of recent research.

Best Practice Farm Assessment Guide

What gaps are there in my farm water management?

Review your farm water knowledge and management against our Best Practice Farm Assessment Guide to look for gaps in your system.

The guide consists of four broad topics, each with their own checklist, that you will move through in this order:

- know your environment;
- use soil water status in decisions;
- choose practices to increase available water; and
- choose practices to better use your available water.

Work through each of the checklists, ticking each item that you have completed/can confirm/understand. Where you cannot tick the checklist item, follow the associated link to the relevant section of the manual, where you will find the information to better understand that checklist item. The aim is to be able to tick all checklist items in each of the four topics.

Know your environment

☐ I have characterised my soils for physical characteristics, chemistry and landform through:

  ☐ on-site assessment. If not, **How do I assess my soils?**

  OR

  ☐ existing datasets. If not, **How can I use existing data to better understand my own soils?**

☐ I know my soil constraints. If not, **How do soil constraints affect my decisions?**

☐ I understand my PAWC through:

  ☐ measurement on-farm. If not, **How can I estimate my PAWC using measurements?**

  OR

  ☐ existing datasets. If not, **How do I find existing PAWC information to estimate my PAWC?**

☐ I have assessed my spatial variability through:

  ☐ electromagnetic imaging (EMI) mapping or normalised difference vegetation index (NDVI) imagery. If not, **EMI surveys: How can I understand variation across my property?**

  ☐ existing datasets. If not, **How can I use existing data to better understand my own soils?**

☐ I understand my rainfall seasonality. If not, **How do rainfall patterns affect how crops use water?**

☐ I use the latest Bureau of Meteorology (BoM) tools to predict rainfall. If not, **What new forecasting products are available to help me assess climate risk?**

Use soil water status in decisions

☐ I understand my PAW through:

  ☐ soil moisture measurement. If not, **What is the best way to measure soil moisture?**

  OR

  ☐ modelling. If not, **What are some other useful tools to assist with decision-making?**

☐ I use weather forecasts to weigh up risk versus benefit in cropping decisions. If not, **How do I weigh up my options for an uncertain problem using the decision analysis technique?**

Choose practices to increase available water

☐ I make use of fallows with weed control to preserve moisture. If not, **How does fallowing influence stored water?**

☐ I understand how stubble management and cover crops influence water storage in my region. If not, **How does stubble management influence water storage?**

☐ I understand how previous crops influence soil moisture. If not, **How does a previous crop affect stored soil moisture?**

Choose practices to better use your available water

☐ I understand how crops use water and what the water-limited yield potential of my crops are. If not, **What is water-limited potential yield?**

☐ I know my critical growth periods. If not, **What is the critical growth period for maximising yield?**

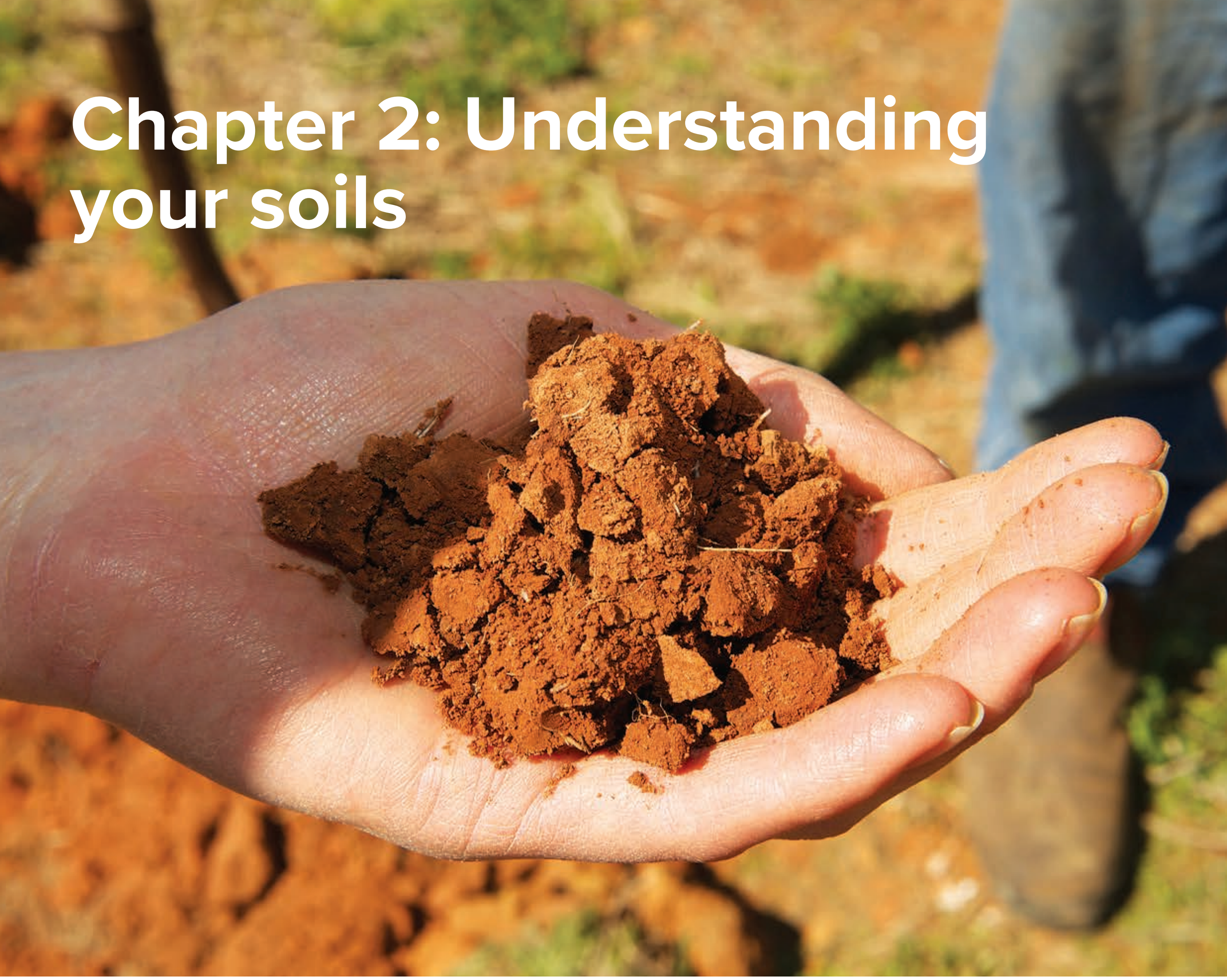
☐ I match my sowing time to my critical growth period using the latest information for my region. If not, **How do I select the best sowing time to maximise WUE?**

☐ I align nutrition to water conditions. If not, **Is it important to align nutrition to water conditions?**

☐ I use rainfall forecasts in nitrogen fertiliser decisions. If not, **How can I manage nitrogen fertiliser as a climate-risky decision?**

☐ I know the effect of different row spacings on my WUE. If not, **What is the best row spacing to optimise WUE?**

Chapter 2: Understanding your soils



How does your soil influence water infiltration and storage?

CHEAT SHEET

- Soil types are variable across Australia and within regions, and understanding your own soil – rather than only relying on district averages – will provide more valuable information for making farming decisions.
- Simple on-farm soil assessments can provide you with data on soil behaviour and can also help you make the most use of publicly available soil characterisations for PAWC.
- There are a wide range of resources to help you with soil sampling and characterising your soil.

Why is it important to understand my soil?

The soil type determines the water-holding capacity, the nutrient availability, the yield potential and the fertiliser requirement. The soil has other features that require different management strategies, such as amelioration due to soil constraints, which may change timing of sowing and ability to use in-season spray due to trafficability.

Soils vary across the landscape due to differences in factors such as parent material, climate, topography, biotic influences and time of formation.

Soil properties can vary at the farm scale in a subtle or dramatic fashion, so a general understanding of soils might be insufficient to understand your own soils. Regional-scale mapping cannot display this level of variability, so it is recommended that you use grower maps, geophysics tools (such as electromagnetic imagery, see Chapter 7) and traditional soil survey techniques.

Soil descriptors and classifications can also aid in assigning a simple and standardised name to the soil. You can then use those simple names when referencing your soil against publicly available soil information, giving you access to pre-existing research on soils like yours.

Different soil classification systems are used across Australia, with the most common being the Australian Soil Classification (Isbell & Terrain, 2021), which uses common soil type names such as vertosol and kandosol, followed by the more textural descriptions of the Greater Soils group classification (Schoknecht & Pathan, 2013; Department for Environment and Water, 2021; Stace et al., 1968).

Figure 2.1 shows examples of four different soil profiles, using classifications to describe the soil types and profile.

How do I assess my soils?

Physical characteristics (including soil texture, soil structure, chemistry and landform) are key components in understanding your soil.

The best strategy to characterise your soil is to either perform a simple soil profile examination or follow a more thorough sampling strategy.

For a simple soil profile examination, follow these steps.

1 Choose a landform or area that you want to better understand (see ‘Landforms’ on page 13 for more information on different landforms).

2 Dig a hole at least one metre deep. You can use a soil auger, soil core, backhoe trench, bank or roadside cutting.

3 As the soil profile is divided into layers (horizons) based on one or more of the key soil properties, you will need to keep the different layers separate. This is easiest with a hole or cutting, but with an auger you can also keep visually different layers separate.

4 Dig down to the expected rooting depth to access all layers that will influence your crop.

5 Collect samples representing each layer and assess each sample for physical properties, texture, structure and soil chemistry.

For a more thorough sampling strategy, the book *Soil Matters* (Dalgliesh & Foale, 2005) provides an in-depth guide to sampling and characterising soils. The book explains how to conduct a more thorough soil assessment, including factors such as how many samples are needed depending on paddock size and variability, and sampling patterns to ensure the sample is representative.

Physical characteristics of soil

The physical characteristics of soils include all the aspects that you can see and touch such as:

- texture;
- colour;
- layer depth;
- structure;
- porosity (the space between the particles); and
- stone or gravel content.

For farm water management, the most important physical characteristics of soil are soil texture and soil structure.

SOIL TEXTURE

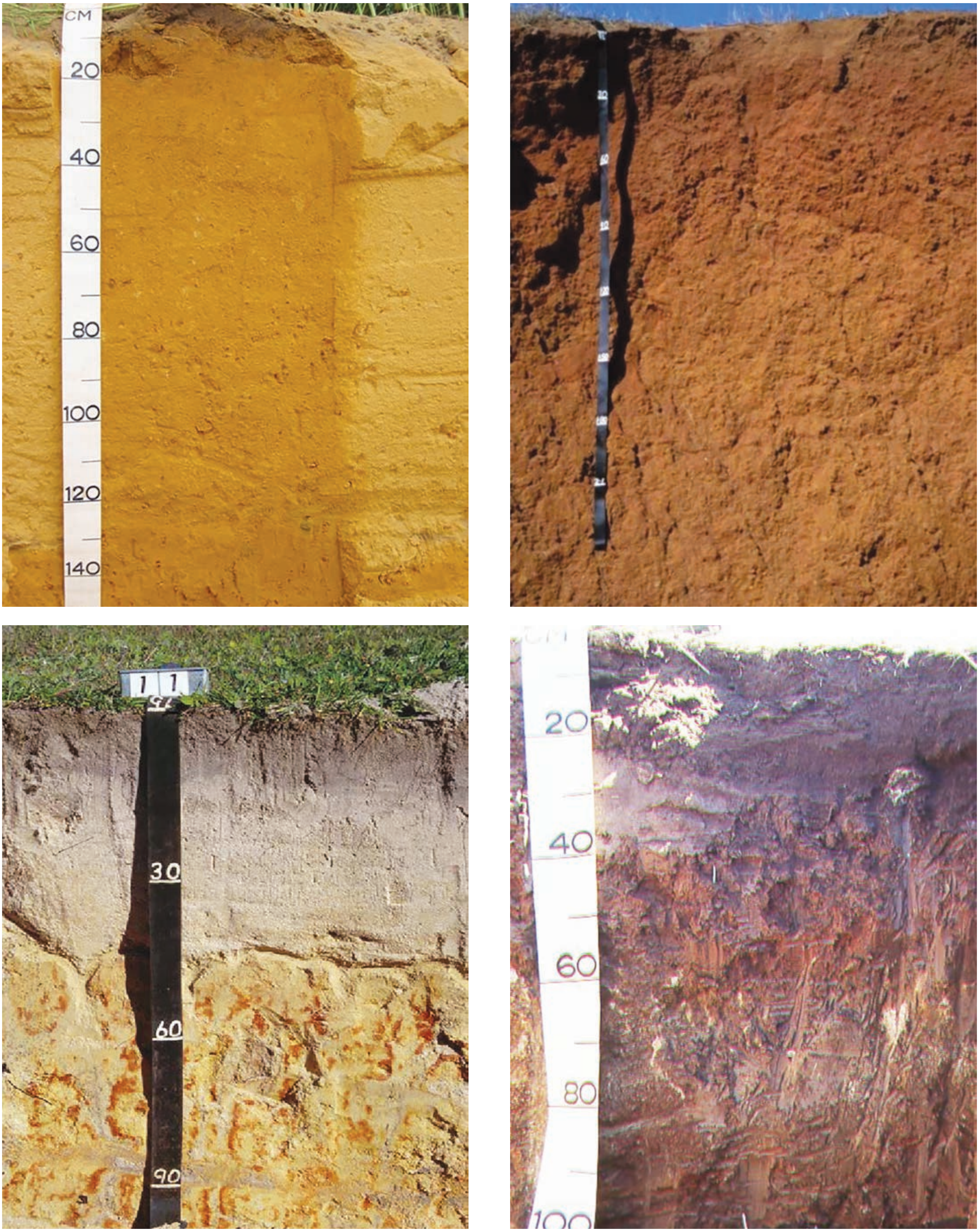
Soil texture refers to the percentage of sand, silt and clay particles that comprise the mineral fraction of the soil (Figure 2.1). Assessing the soil texture can assist with understanding soil properties such as PAWC and water infiltration rate (Table 2.1).

Table 2.1: The effect of soil texture on various soil properties.

	Texture grades				
Property	Sands	Sandy loams	Loams	Clay loams	Clays
Total available water	Very low to low	Low to medium	High to medium	Medium to high	Medium to low
Infiltration	Very fast	Fast to medium	Medium	Medium to slow	Slow
Nutrient supply capacity	Low	Low to medium	Medium	Medium to high	High
Leachability	High	High to moderate	Moderate	Moderate to low	Low
Tendency to hard setting on surface	Low	High to moderate	High to moderate	Medium	Medium to low
Susceptibility to compaction	Low	Moderate	Moderate to high	Low	High

Source: PIRSA (2014)

Figure 2.1: Examples of a range of soil types. Top left: gradational soil with sandy loam topsoil grading to sandy light clay subsoil. Top right: gradational soil with clayey sand topsoil grading to sandy clay loam subsoil. Bottom left: duplex soil, with a sandy A horizon over a clayey B horizon at 45cm. Bottom right: duplex soil with a loamy A horizon over a clayey B horizon at 35cm.



Source: Stuart-Street et al. (2020)

SOIL STRUCTURE

Soil structure refers to the way soil particles are arranged together and interconnected. Well-structured soils enable higher infiltration of rainfall, drainage and root growth. Poorly structured soils can be subject to waterlogging, erosion and compaction.

When classifying your soils, there are site-specific features that are useful to document such as whether the surface is hard setting, cracking or non-wetting, and crop features such as poor crop emergence and stubble amounts, which all influence erosion, water infiltration and crop emergence.

To test for a non-wetting soil surface, you can drip some water onto the soil. If it stays as a bead and does not infiltrate the soil, it may be non-wetting. Read more on non-wetting soils at soilquality.org.au/factsheets/water-repellency.

SOIL CHEMISTRY

Sending a soil sample to a laboratory can assist with classification and with soil management and amelioration options. Soil chemistry tests include pH, salinity, organic carbon, boron, aluminium, cation exchange capacity and carbonate (Fizz test), along with the current nutritional status and soil moisture content.

LANDFORMS

When describing soil, it is helpful to understand what type of landform the soil is from. This contributes to understanding how the soil was formed, how the soil can be used and what land management issues the soil and landscape might have for the landholder.

Some common landform elements include:

- crest;
- ridge;
- slope;
- midslope; and
- flat.

Landforms are important when drawing on existing mapping and APSoil information to estimate PAWC (see Chapter 3).

For more information about landform descriptions and definitions, see the *Australian Soil and Land Survey Field Handbook* (National Committee on Soil and Terrain, 2009).

How can I use existing data to better understand my own soils?

Once you have characterised your soils, there are several existing soil data resources you can use to learn more:

- Soil and Landscape Grid of Australia;
- Australian National Soil Information System;
- MySoil (Western Australia);
- eSPADE (NSW);
- SA-format soil and land attributes (SA);
- Common soil types (Queensland); and
- Land management manuals and mapping (Queensland).

The information from these databases can then be used to select a reference soil from APSoil, which will help you to understand your soil's PAWC and use soil information in farm production modelling.

IN A NUTSHELL

APSoil provides detailed soil and water capacity data on more than 1100 Australian soil samples (see Chapter 3). But to get useful results, you first need to understand your own soil. Both on-farm soil characterisation and the following databases are great tools to help select the best APSoil samples to use in your farm modelling and planning.

APSoil

APSoil is a database of soils across Australia that have been characterised for a range of soil properties including PAWC (see Chapter 3). Users can access the data via the APSoil application, SoilMapp or Google Earth.

Caution: it is important not to simply choose the sample closest to your property when using APSoil data. Soil types can change significantly within a short distance depending on topography, so you should first assess your soil types and choose the sample that best resembles your soils.

Best for: accessing existing data on PAWC to save you measuring it yourself, and for importing data when using APSIM or Yield Prophet®.

Link: apsim.info/apsim-model/apsoil/

National and regional databases

SOIL AND LANDSCAPE GRID OF AUSTRALIA (SLGA)

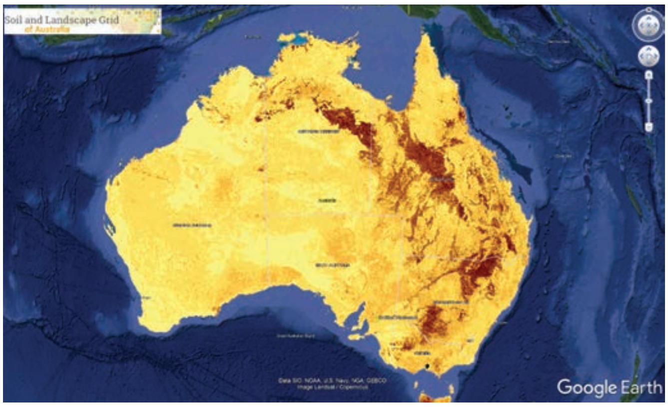
This database can be accessed in different ways, including via a web-based SLGA Viewer and via Google Earth. It provides maps with predictions for a range of soil characteristics, including organic carbon and clay and sand percentages.

Best for: a national grid with common terminology and a wide range of soil attributes, with easy navigation to your location using Google Earth or the web-based SLGA Viewer (Figure 2.2).

Links: esoil.io/TERNLandscapes/Public/Pages/SLGA/ViewData-KML.html

shiny.esoil.io/Apps/SLGAViewer/ (turn off the Soil Maps layer to navigate to a location of interest, then turn it back on)

Figure 2.2: The Soil and Landscape Grid of Australia showing the clay percentage at 0–5cm, accessed via Google Earth.



AUSTRALIAN NATIONAL SOIL INFORMATION SYSTEM

This database has all publicly available soil observation data, including data from the different state databases. It is under development and will be enhanced over time with more data and features.

Best for: a national database with a wide variety of soil observation data.

Link: https://portal.ansis.net/

MYSOIL (WESTERN AUSTRALIA)

Based on region and known characteristics, growers can identify their soil classification and learn more about their soils, including distinguishing features and common constraints.

Best for: Western Australian growers to use locally specific information and terminology to describe their soils, including a diagnostic tool based on location, surface texture and other soil features.

Link: https://www.agric.wa.gov.au/managing-soils/mysoil

ESPADE (NSW)

eSPADE is a Google Maps-based information system that allows free, easy access to a wealth of soil and land information from across NSW on desktop and mobile devices. The data accessible through eSPADE is sourced mainly from the NSW Soil and Land Information System. It includes soil survey maps and digital maps with modelled soil properties.

Best for: NSW growers to use locally specific information to identify their soils, including a range of characteristics.

Link: https://www.environment.nsw.gov.au/topics/land-and-soil/information/espade
https://www.environment.nsw.gov.au/eSpade2Webapp/

SA-FORMAT SOIL AND LAND ATTRIBUTES (SOUTH AUSTRALIA)

SA-format soil and land attribute datasets describe key characteristics relating to distinct elements in the landscape, also known as landscape components (for example, flats, rises, swales, sandhills). More than 40 attributes of importance for land use and natural resource management are ascribed to these landscape components.

Best for: South Australian growers to use locally specific information to identify their soils, including maps and fact sheets on a range of attributes.

Link: https://www.environment.sa.gov.au/topics/soil-and-land-management/soils-of-sa/describing-soil-land/sa-format

COMMON SOIL TYPES (QUEENSLAND)

A listing, map and description of common soil types across Queensland, based on the Australian Soil Classification system.

Best for: descriptions, with pictures, of common Queensland soils.

Link: https://www.qld.gov.au/environment/land/management/soil/soil-testing/types

LAND MANAGEMENT MANUALS AND MAPPING (QUEENSLAND)

Reports and maps summarising soils in different regions within Queensland, linking to the Queensland Globe mapping tool.

Best for: more in-depth information to analyse and assess Queensland soils.

Link: https://www.qld.gov.au/environment/land/management/soil/soil-data/reports

How do soil constraints affect my decisions?

Constraints, such as alkalinity, acidity, salinity or high concentrations of boron or aluminium that restrict the depth of roots, will limit the amount of water the roots can access from the soil, as shown in Figure 2.3.

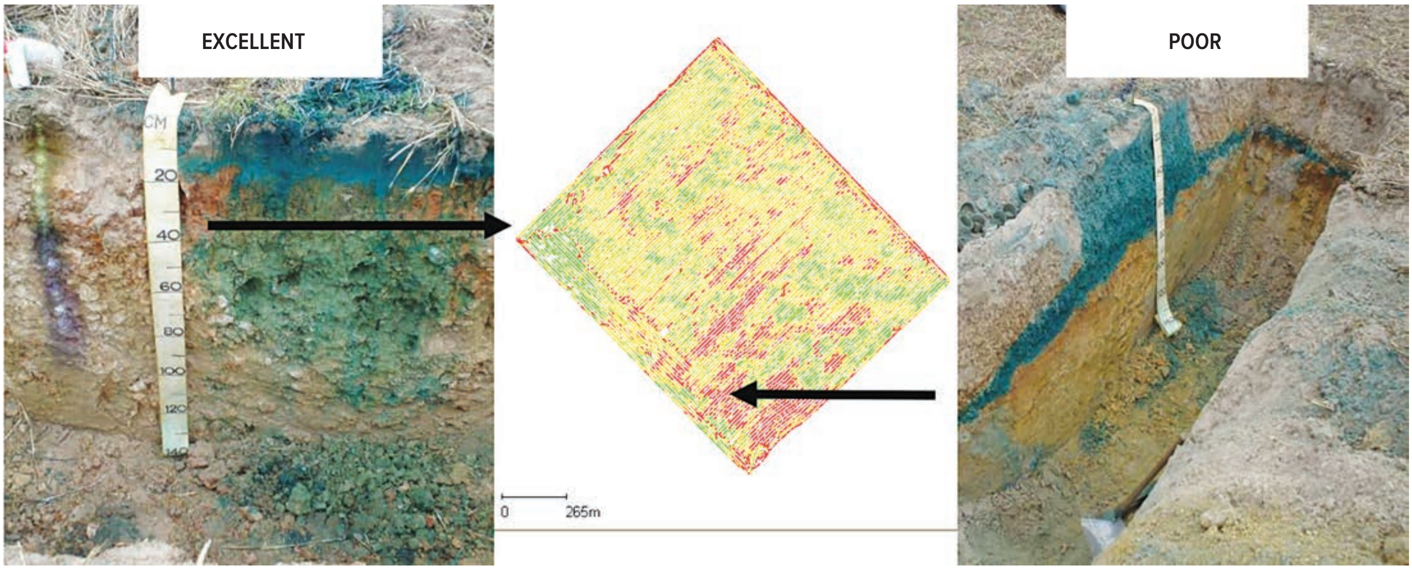
Methods to identify constraints:

- look at existing databases and maps to identify likely constraints based on location;
- soil testing at a range of depths;
- soil water probes can help estimate root growth restrictions by watching the changes in soil moisture at different depths (see Chapter 7);
- EMI mapping (see Chapter 7); and
- dig a soil pit to view the different soil layers and rooting depth.

Once a constraint is identified, an action plan can be developed based on the type of constraint. These include:

- mechanical methods such as liming with deep ripping, mouldboard plough or other deep incorporation methods;
- soil amelioration such as gypsum, liming or claying;
- nutrition strategies to match fertiliser supply and nutrient availability in the soil; and
- selection of crop varieties tolerant to that specific constraint.

Figure 2.3: Constraints reduce root depth, limiting the plant-available water capacity. In this image, dye has been added to demonstrate different rooting depth, which is correlated with yield mapping showing the soil that is constrained to 70cm root depth results in lower crop yields.



Root depth = 120cm
PAWC = 140mm

Root depth = 70cm
PAWC = 42mm

Source: David Hall, DAFWA

Chapter 3: Plant-available water capacity

How can you determine and use PAW and PAWC on your farm?

CHEAT SHEET

- You can use knowledge of a soil's capacity to hold water and supply it to a crop, combined with data on currently available soil water, to improve management decisions and yield estimates.
- The PAWC is the maximum amount of plant-available water that the soil can store.
- The PAWC is the amount of soil water held between the drained upper limit (DUL), above which water will drain away, and the crop lower limit (CLL), below which the roots of a crop can no longer extract the remaining soil water.
- PAW is the actual amount of soil water above the CLL at a particular time.
- You can choose to measure PAWC, or to estimate the PAWC using available soil databases and/or the APSoil database of PAWC characterisations based on similarity in soil characteristics.

What is plant-available water and why is it important?

Plant-available water is the amount of water that a soil can hold and release to a growing plant. It is a very useful concept that helps with making management decisions on-farm.

For example:

- A grower who understands how much water their different soils can store will better match their crop selection to soil type.
- When looking at soil moisture monitoring data, the grower who understands plant-available water will know how much of the soil water can be accessed by the crop, which will help them to estimate the crop's fertiliser needs (see Chapter 7).
- When looking at the seasonal forecast before seeding, a grower who knows how saturated their soil water profile is will have a better idea of what crop to select, when to sow, and/or how much fertiliser to apply (see Chapter 8).

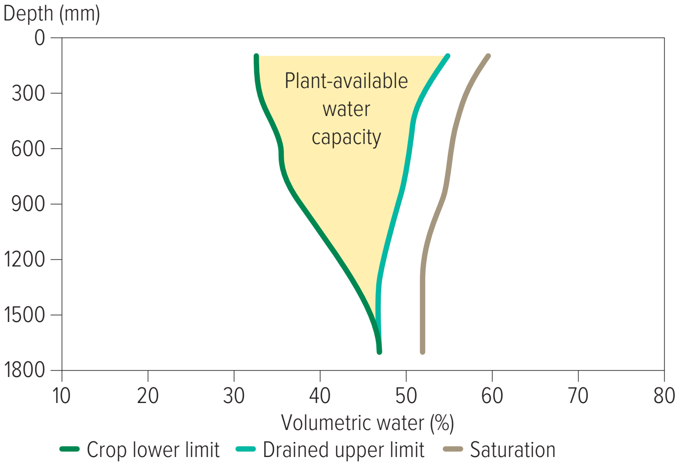
The two terms used in relation to plant-available water are plant-available water capacity (PAWC) and plant-available water (PAW); these two terms are similar but subtly different. PAWC depends on the soil type and the crop being grown on it, while PAW depends on these plus rainfall, run-off and evaporation. The differences are as follows:

- PAWC is the maximum amount of water a particular crop can extract from a particular soil.
- PAW is the current amount of water available to that crop.
- PAWC is sometimes referred to as the soil water 'bucket' – the amount of water a particular soil can hold against gravity – which is different from PAW, which describes the amount of water in the 'bucket' at a particular time.

The key elements of PAWC are the drained upper limit (DUL) and crop lower limit (CLL). The DUL is the maximum amount of water the soil can hold after drainage has ceased, while the CLL is the water remaining after a particular crop has extracted all that it can.

The PAWC is the difference between these two measures for the rooting depth of the crop, as shown in Figure 3.1.

Figure 3.1: Plant-available water capacity is the maximum amount of moisture a soil type can hold and deliver to a particular crop. The graph shows the difference between the crop lower limit and the drained upper limit at different depths. The sum of these differences is the PAWC.



Source: Neal Dalgliesh

What influences the size of the PAWC 'bucket'?

An important determinant of PAWC is the soil texture. The particle size distribution of sand, silt and clay determines how much water it can hold and how tightly it is held. Water is held on the surface of soil particles and as clay particles have a larger surface area than sand particles, a clay soil can hold more water than a sand soil (see Chapter 2).

The CLL may differ for different crops due to differences in root density, root depth, crop demand, duration of crop growth and sensitivity to subsoil constraints. The PAWC is generally higher for deeper rooting crops such as wheat, barley, cotton, sorghum and canola, and lower for crops such as peas and mungbeans. In addition, different tolerances for subsoil constraints (for example, salinity, sodicity, boron and aluminium) cause further variation between crops. Figure 3.2 demonstrates how the CLL creates a range of PAWC values for different crops.

How can I use PAWC and PAW information to make decisions?

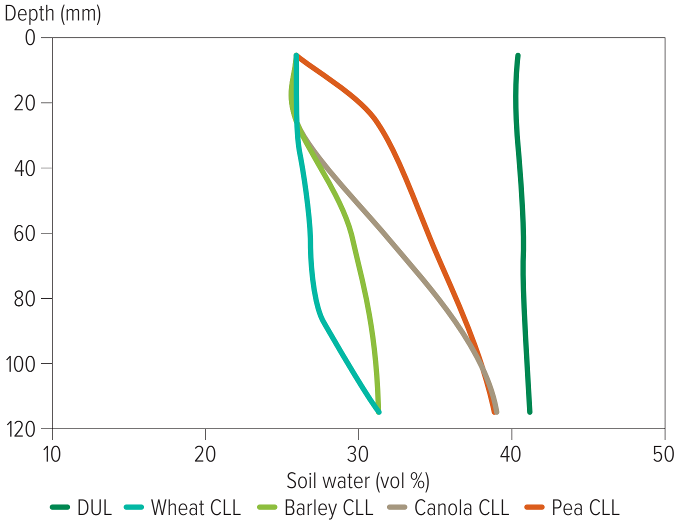
Knowing the capacity of the soil to store water is only half of the equation. Seasonal monitoring of PAW will provide you with information to make informed operating decisions on issues such as crop choice, variety selection and fertiliser timing and application rate.

Soil moisture monitoring can either be continuous or measured at key points during the season (see Chapter 7).

Examples where soil moisture and PAWC information can be used include:

- in pre-seeding crop selection decisions and seeding schedules;
- to better match the fertiliser rate and application timing with water resource availability; and
- in high-rainfall areas, where a comparison of water content and PAWC provides an indication of the potential for the soil 'bucket' to overflow, causing run-off or drainage.

Figure 3.2: CLL varies between different crops, as shown in this data developed by Birchip Cropping Group for CLL at 0–120cm for five different crops.



Source: Birchip Cropping Group

PAWC can be measured on-farm or can be estimated from existing data. On-farm measurement is somewhat labour-intensive but will provide significantly more accurate information. Existing PAWC data is publicly available but requires some careful analysis.

How can I estimate my PAWC using on-farm measurements?

The most common method of determining PAWC is to wet the profile to capacity to allow the measurement of soil water content at DUL, and to then exclude rain from an area of crop in the latter part of the growing season to allow the CLL to be measured. These limits define the PAWC.

A thorough step-by-step guide for this technique has been developed by GRDC and CSIRO (*Estimating Plant Available Water Capacity*), but the following is an overview of the procedure.

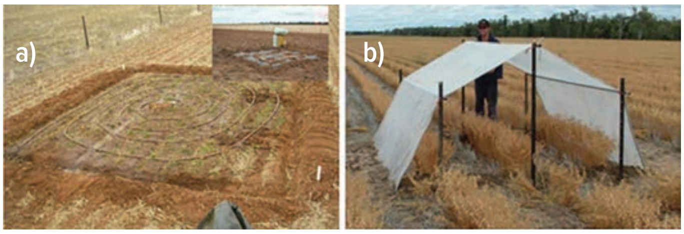
To determine the DUL:

1. Select a suitable site, considering soil variability, access to the site and importance of the soil type to your farm.
2. Set up an area of approximately 4m x 4m with drip tubing laid out in spiral (see Figure 3.3a).
3. Slowly wet-up the area.
4. Cover the site with plastic to prevent evaporation and allow the site to drain (see the step-by-step guide for indicative rates of wetting-up and drainage).
5. Sample the soil for moisture and bulk density.

To determine the CLL:

1. Select a site. A site close to a DUL measurement site is ideal, taking into consideration the crop type, since the CLL is only relevant for the same crop type.
2. Protect an area from anthesis/flowering with a rain-out shelter (Figure 3.3b) and leave in place until harvest.
3. Sample the soil for moisture and bulk density at harvest.

Figure 3.3: a) wetting-up for DUL determination; and b) a rain-out shelter used for CLL determination.



Source: Burk & Dalgliesh (2013)

Tips and common pitfalls when measuring PAWC

Although the measurement methods for DUL and CLL were developed to be straightforward and do not require any sophisticated equipment, it is important to watch for possible errors. The list below summarises some of the key pitfalls and common issues that CSIRO and its collaborators have come across in their experience of PAWC characterisations across Australia.

TIPS FOR MEASURING DUL

- Weeds need to be strictly controlled throughout the wetting-up process until sampling.
- In sandy-textured soils, the concentric rings of the dripper line must be laid sufficiently close to each other to ensure consistent wetting across the whole area.
- Allowing insufficient time for drainage may lead to overestimation of DUL, especially at depth. Heavier soils can take one to two months to drain.
- Insufficient water application or application at too high a rate leads to underestimation of DUL at depth. This is particularly an issue with heavy clay soils, dispersive sodic soils and strong duplex soils where water may move sideways. Both the GRDC *Estimating Plant Available Water Capacity* booklet and the *Soil Matters* book provide recommended rates and amounts for different soils.
- Bulk density sampling, which is often done in conjunction with DUL sampling, needs to be precise, as any error in bulk density values will be magnified during calculations. The procedure is described and illustrated in detail in the GRDC *Estimating Plant Available Water Capacity* booklet.
- Snakes like to hide under the plastic, so take care when wetting and sampling the plot.

TIPS FOR MEASURING CLL

- The CLL measured for one crop type may not apply to a different crop type. Crop rooting depth and crop duration are the main drivers behind differences in CLL.
- It is important to perform CLL measurement in paddocks with a well-established and healthy crop. The CLL method relies on crop roots fully exploring the soil, but if the crop had insufficient moisture to establish its root system prior to anthesis, the CLL may not reflect maximum soil water extraction.
- In wetter climates, rainfall in the weeks just prior to the erection of rain-out shelters at anthesis may refill the PAWC 'bucket'. If the PAWC is large, this may prevent the crop from using all soil water and result in an overestimate of CLL.
- If sampling is not deep enough to capture the full root zone, PAWC will be underestimated. This is likely if the CLL and DUL do not reach the same value at the bottom of the profile.
- Rain-out shelters have blown loose or away on occasions, so it is important to secure the sides firmly into the soil.
- For duplex soils on hill slopes greater than 3 to 5 per cent, or soils at the break of slope, subsurface lateral flow can cause soil wetting despite the presence of a well-constructed rain-out shelter. Keep an eye on late season rainfall and note any unusual wetness in samples collected.
- Sampling after harvest when the soils are dry and hard or have hard layers can be challenging. Digging a soil pit can be a better alternative than soil coring from the surface in these situations.

GENERAL TIPS FOR MEASURING PAWC

- Soil variability may mean there is more than one PAWC profile within the paddock. Variability in depth of layers, for example, texture contrast in duplex soils, can occur over small distances. This makes mixing replicates and selecting a representative soil difficult.
- High soil variability can cause the DUL and CLL measurements to effectively be from different soils (even though they are usually only 2 to 3m apart). It is essential to measure DUL and CLL on the same soil type. Yield or soil maps may assist in deciding where to sample.
- To allow interpretation and use of the data by others, PAWC characterisations should be accompanied by as much extra information as possible, including descriptions of the landscape position, surface condition (for example, cracking, waterlogging), colour, Australian soil classification and any local classification soil name.

How do I find existing PAWC information to estimate my PAWC?

More than 1100 Australian soils have been characterised for PAWC, and you can access this information through the APSoil application, Google Earth via the APSoil website, or the SoilMapp app.

Links and further information are available at the APSoil website (see Chapter 2).

The APSoil database can be used to estimate PAWC when it is not possible to determine PAWC in the paddock. However, the nearest APSoil PAWC characterisation may not be the most appropriate as its soil properties could be quite different. Soil properties can change significantly within a short distance depending on topography. It is therefore important to find an APSoil that has similar soil properties as those at the location of interest (see Chapter 2).

Within a specific region, the soil properties that affect PAWC are influenced most by landscape position and parent material (the source of sediments or type of rock in which the soils are formed). Soil surveys that produce maps of soil landscape units (SLUs) or land resource areas (LRAs) group parts of the landscape that have similarity in landscape position and parent material.

Vegetation has an influence too and can also often serve as an indicator of the underlying soil types.

The soil survey resources described in Chapter 2 can be used to evaluate whether an existing PAWC characterisation from APSoil or that from a neighbour or a local farming group is for a similar soil or soil landscape unit.

Various digital soil map resources in Chapter 2 can also help establish similarities in soil properties. The Soil and Landscape Grid of Australia resource provides a digital map with predictions of lower limit (LL) and DUL for different soil depths. The LL predictions are based on soil measurements in a laboratory and correspond roughly with the CLL, except at the bottom of the root zone where the crop's root length density may be insufficient to extract all available water or where subsoil constraints such as salinity may affect rooting and water extraction (Verburg et al., 2021). As such, LL does not distinguish between different crops. The comparison of DUL with LL is sometimes referred to as available water capacity (AWC) to acknowledge that plant effects are not considered.

It is important to note that these digital maps are predictions and that they, along with most of the available soil survey maps, were developed on national or regional scales. Therefore, they do not pick up on soil differences at the paddock scale, which may affect the accuracy of the soil property estimates when used at that scale, including estimates for LL and DUL.

It can be useful to consider the various resources, along with your own observations, as lines of evidence that together help build a more accurate picture. The following questions can help you notice the differences and similarities between the lines of evidence that might require an adjustment to the PAWC estimates.

- Do the predicted soil properties and texture match that of the site?
- Are the landscape features in the surrounding area reflected in the information?
- Do you have any subsoil constraints that may limit crop rooting depth or effectiveness?

A series of GRDC Update papers illustrated this approach for a few regions in NSW and Queensland using a five-step approach (Thomas et al., 2019; Cocks et al., 2020; Verburg et al., 2020). The exact order of the steps can vary slightly and is not critical. The steps also depend on the available information. The key is to check for consistency between the different information sources and your own local observations (see Chapter 2). If soil survey information is not available, the first step can be skipped, but it is useful to consider whether patterns within the local landscape are reflected in digital map predictions.

Five steps for accessing APSoil PAWC data

1. **Identify the soil landscape unit.** Consider the descriptions of the landscapes and categories in the soil survey maps to assess whether they match your site of interest. Draw on local landscape and soil observations to help with this assessment.
2. **Determine the soil type.** Consider the descriptions of soil types in the soil resources and compare with local soil observations.
3. **Assess soil properties.** Consider the soil properties affecting PAWC, especially texture or particle size analysis and subsoil constraints (salinity or shallow soil depth) in the descriptions of the identified soil type and as obtained from digital soil maps. Compare with local soil observations and look for consistency between the resources. Are observable patterns in the soil properties across the local landscape reflected in the information?
4. **Estimate PAWC.** Compare estimates of PAWC for the identified soil type in the soil survey resources, from digital map predictions of DUL and CLL, and/or from a matching APSoil characterisation based on informed choice of similar soil.
5. **Adjust PAWC.** Based on possible rooting depth and soil constraints in step 3, the PAWC estimates may need to be adjusted (for example, shallower rooting depth or stronger tapering of the CLL in response to subsoil salinity). It is also recommended to evaluate over time whether the estimated PAWC provides the right levels of yield estimates.

How do I use APSoil?

See also Chapter 2

In Google Earth, the APSoil characterisation sites are marked by a shovel symbol (Figure 3.4), with information about the PAWC profile appearing in a pop-up box if you click on the site. The pop-up box also provides links to download the data in APSoil database or spreadsheet format. In SoilMapp, the APSoil sites are represented by green dots (Figure 3.5). Tapping on the map results in a pop-up that allows one to discover nearby APSoil sites (tap green arrow) or other soil (survey) characterisations.

The discovery screen then shows the PAWC characterisation as well as any other soil physical or chemical analysis data and available descriptive information. Most of the PAWC data included in the APSoil database has been obtained through the five-step method previously outlined, although for some soils estimates have been used for DUL or CLL. Some generic, estimated profiles are also available. Although paddock-measured profiles are mostly georeferenced to the site of measurement, generic soils are identified with the nearest town.

How do I measure and use PAW?

The PAW is a variable that changes throughout the season and between different crops. Once the PAWC has been estimated or measured, combining this information with soil moisture data can determine the current PAW, typically expressed in millimetres (mm).

When the soil profile is at maximum capacity (at the DUL), the PAW is the same as PAWC. Conversely when the soil profile is empty (at the CLL), the PAW is zero. It is possible for the moisture in the surface soil to fall significantly below the CLL, which means the first rain will not all be available to the crop as some of it will fill the soil back up to the CLL. Generally, the amount of water involved is small so does not affect management decisions. However, in heavier vertosols, this may need to be considered.

For soil moisture levels between the CLL and the DUL, the PAW can be calculated by subtracting the CLL from the current soil moisture level. The most precise method for determining the current soil moisture, and therefore the PAW, is to use soil moisture probes (see Chapter 7).

As the CLL can differ depending on the crop, the PAW can vary between crops for the same soil moisture level, so it will need to be reassessed for each crop.

Frequently asked questions

Why do I need to measure my PAWC if I do not irrigate?

Knowing the PAWC allows realistic limits to be set for yield potential when used in conjunction with the seasonal monitoring of PAW. This allows growers to:

- better optimise the application of fertiliser, particularly when used in conjunction with models such as Yield Prophet®;
- adjust seeding plans, such as sowing time and crop selection; and
- decide whether to modify surface soil texture to improve the PAWC, such as through clay spreading on sandy rises.

How can PAW be zero when monitoring shows moisture?

At low moisture levels, although there is water in the soil, it can be unavailable to the crop as it is too tightly bound in the soil. This happens at moisture levels below the CLL, which depends on soil type and plant species. After a prolonged drought or at the end of a cropping season, it is common to record water content levels below CLL **in the surface soil** due to air-drying.

CASE STUDY: USE OF TECHNOLOGY IN MANAGING SOIL MOISTURE - PETER MCKENZIE, GUNNEDAH

Peter McKenzie is an experienced agricultural consultant based in Gunnedah, NSW, who works closely with growers to help them make informed decisions about their farming practices.

He emphasises that there is no one-size-fits-all answer for managing soil moisture in grain cropping, as there are so many factors that vary farm-to-farm.

“There’s different soil types; do they have a large PAWC to work with or is it pretty small?” he says.

“We need to consider the grower’s preferred crop rotations, their attitude towards risk, and the seasonal weather outlook, along with a range of other factors that vary between farms.”

To help his clients navigate these challenges, Peter uses a combination of hard tools such as soil moisture probes and computer models such as APSIM, as well as soft tools such as grower knowledge and experience.

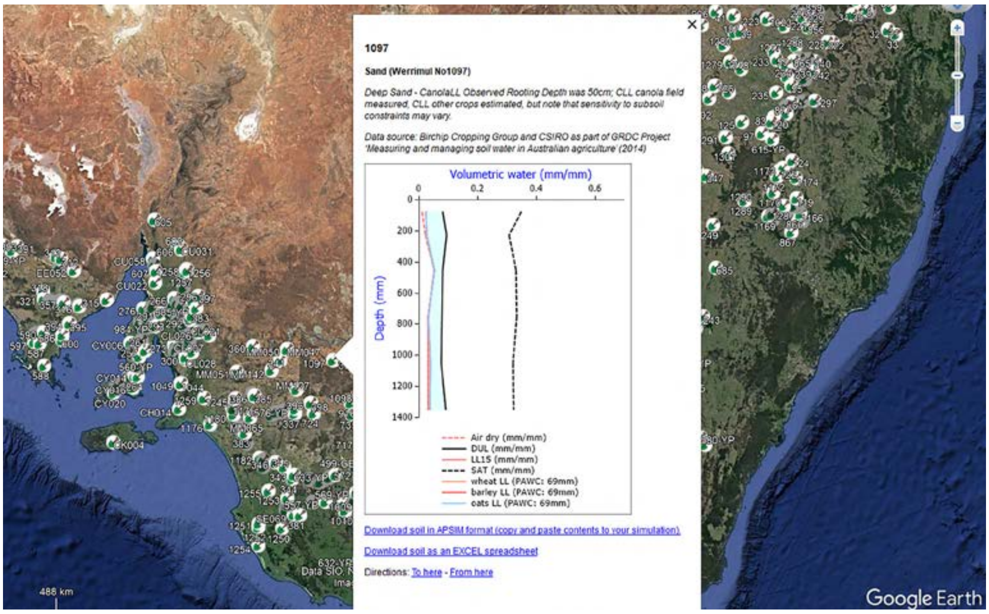
“It’s incredible what we can potentially achieve with technology – integrating SoilMapp data, EM and soil moisture probes with a knowledge of PAWC can provide so much valuable decision-making information.”

There are various decisions that Peter and his clients make based on their knowledge of a soil’s PAWC and PAW.

“There’s individual crop planning – we can look at a paddock, we know what moisture we’ve got, so what can we do with it?” he says.

“Then you’ve got rotation planning, and we can do APSIM modelling at different soil water levels to predict which rotations will give the highest gross margins. Then we can be prepared with flex points – decision points – where we choose which rotation we’ll go ahead with based on the moisture we have.”

Overall, understanding a soil’s PAWC is critical for effective decision-making in grain cropping. As Peter notes, “Plant-available water capacity is a fundamental property of the soil, and it’s essential for growers to know how much water their soil can hold and how much of that water is available to their crops.”



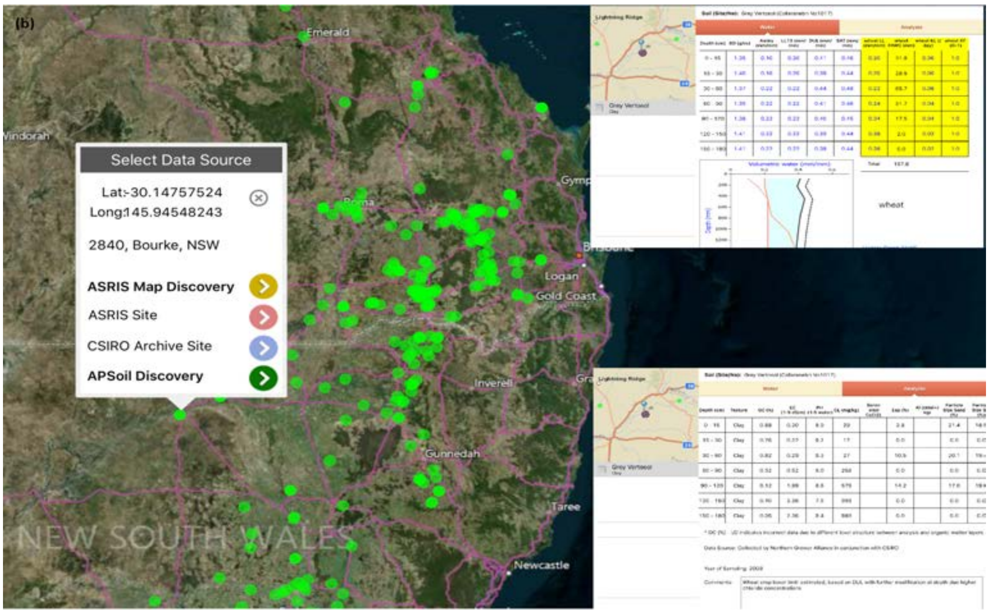
1097

Sand (Werrimul No1097)

Deep Sand - CanolaLL Observed Rooting Depth was 50cm; CLL canola field measured, CLL other crops estimated, but note that sensitivity to subsoil constraints may vary.

Data source: Birchip Cropping Group and CSIRO as part of GRDC Project 'Measuring and managing soil water in Australian agriculture' (2014)

Figure 3.4: Google Earth PAWC data from APSoil.



Select Data Source

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2840, Bourke, NSW

Figure 3.5: SoilMapp PAWC data.

Chapter 4: How crops use water

How does water use by crops relate to your decisions on-farm?

CHEAT SHEET

- There is an upper limit of yield for a given availability of water, known as the water-limited potential yield, which is driven by crop transpiration and soil evaporation. This limit varies across soil types, climates and crops.
- Analysing the difference between your actual yield and water-limited potential yield reveals yield gaps and can help to increase yield.
- There is a critical period during which water deficit strongly influences grain number and therefore yield. Aligning this growth period with periods of minimum water stress will increase the yield potential.

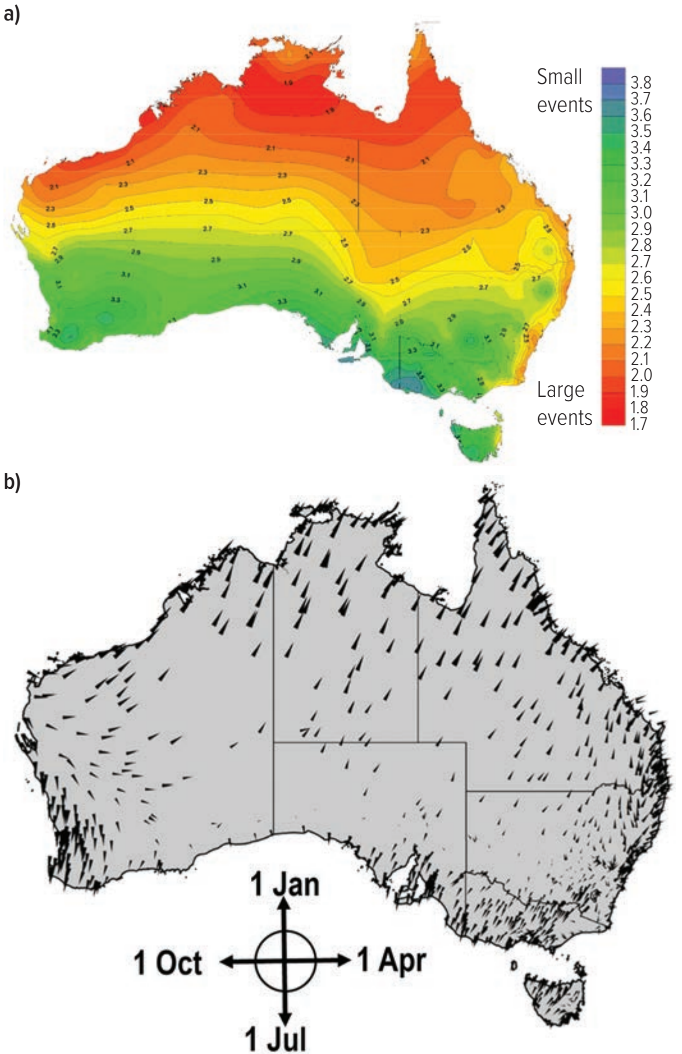
This chapter will explain how water is used by crops. This can help you understand which farming practices and decisions will maximise the available water.

The next two chapters, 'Chapter 5: Preparing for the growing season' and 'Chapter 6: Optimising water use during the growing season', will cover practical decisions you can make based on the principles covered in this chapter.

How do rainfall patterns affect crop water use?

Chapter 8 addresses rainfall from a climate risk perspective. This chapter focuses on three features of rainfall relevant to dryland agriculture: amount, seasonality and size of events. The amount of rainfall sets the boundary for major patterns of land use, with cropping feasible above a certain annual rainfall and rangelands feasible in the riskier, lower-rainfall environments.

Figure 4.1: Rainfall maps of Australia:
a) The size of rainfall events influences the fate of water, e.g. small events favour soil evaporation.
The map shows size-coefficients of rainfall for the winter semester in Australia; a high coefficient indicates dominance of small events.
b) The seasonality of rainfall shapes cropping options.
The length of arrows represents the intensity of seasonality, and their direction indicates the time of the year with the greatest rainfall concentration.



Source: Williamson (2007)

Rainfall seasonality (Figure 4.1b) drives three cropping environments in Australia; the summer-rainfall region of Queensland and northern NSW, the winter-rainfall regions of south-eastern and south-western Australia, and a transition zone between the northern and southern region in eastern Australia.

For the same amount of annual rainfall, the summer regime allows for a greater crop diversity and higher cropping intensity, whereas winter rainfall favours an autumn-sown spring cereal (for example, wheat or barley) system in rotation with pastures, pulses and, more recently, canola.

Seasonality has a major impact on the proportion of water available from pre-season and in-season rainfall, with implications for management and risk. In the winter-rainfall regions, wheat relies primarily on in-season rainfall, compared with a larger contribution of stored soil moisture in summer-rainfall regimes.

The frequency of large rainfall events increases from south to north (Figure 4.1b). For the same amount of rainfall, large events lead to deep drainage and run-off as sources of inefficiency, whereas small events lead to more soil evaporation.

What is vapour pressure and how does it relate to water use?

The transpiration process requires water moving from soil to the root of the plant, and from root to leaves. Once in the leaf cavities, just below the stomata, water changes from a liquid to a vapour and moves out through the stomata into the air surrounding the leaf.

The rate of water loss from leaves is proportional to the vapour pressure deficit (VPD) – the difference between the vapour pressure in the saturated leaf cavities and the less-than-saturated atmosphere (see Figure 4.2 and Glossary). The lower the VPD, the higher the rate of transpiration, and vice versa.

Vapour pressure deficit is the driving force of crop transpiration.

VPD has a large impact on water flow from the leaf to air but little impact on the flow of CO_2 from air to plant. An increase in VPD will increase the transpiration rate (and therefore water loss) but will not change the flow of CO_2 (and therefore biomass production), so the crop will produce more biomass per unit transpiration under low VPD conditions. This can be useful in understanding the effect of different practices on WUE. For example, an early sown crop

Figure 4.2: Vapour pressure as function of air temperature. The green point shows the actual vapour pressure at 20°C for a relative humidity of 50 per cent. The black point shows the actual vapour pressure at 30°C for a relative humidity of 50 per cent. The orange points indicate two humid conditions for an equal temperature. The vapour pressure deficit corresponds to the gap between actual and saturated values for a given temperature.

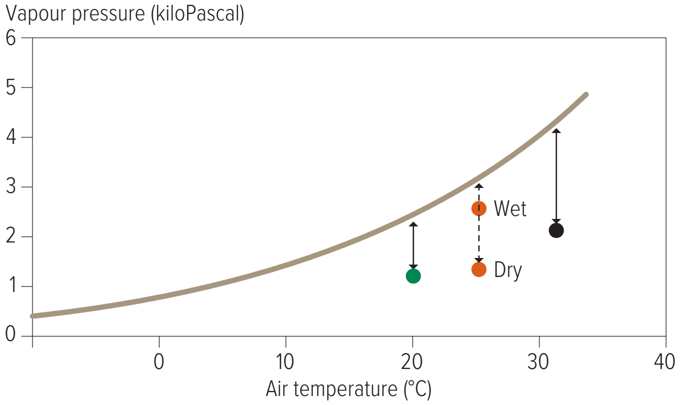
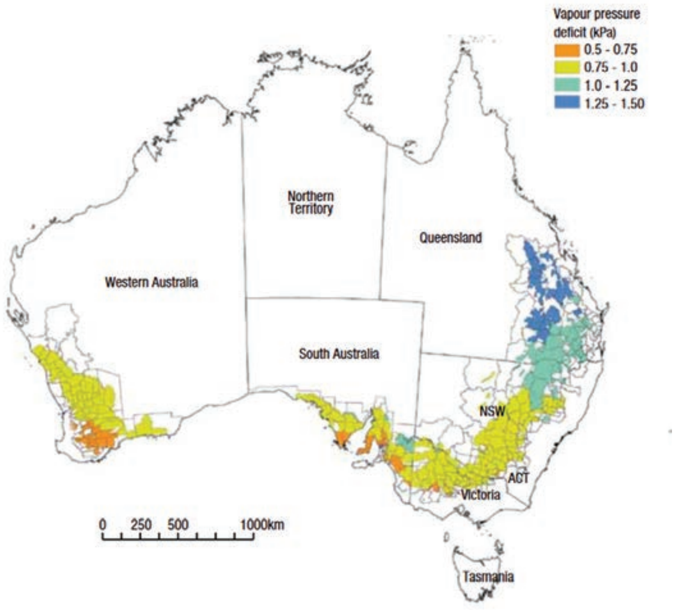
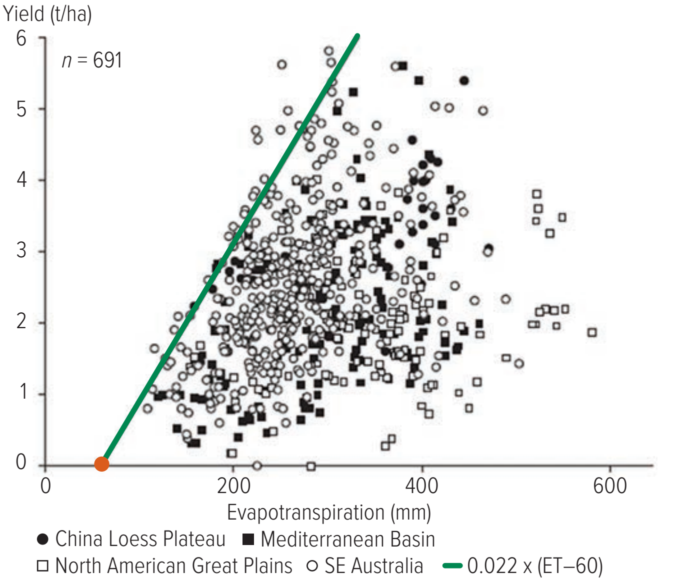


Figure 4.3: Vapour pressure deficit at flowering in wheat-producing areas of Australia.



Source: Doherty et al. (2010)

Figure 4.4: Relationship between yield and evapotranspiration for wheat crops in south-eastern Australia, Mediterranean basin, China Loess Plateau, and North American Great Plains. The boundary line has a slope of 22kg/ha/mm, and the x-intercept is 60mm. The orange dot indicates the x-intercept.



Source: Sadras & Angus (2006)

produces more biomass with the same amount of transpiration than late-sown crops (Sadras & McDonald, 2011).

Maximum crop yields and WUE will occur when flowering occurs in conditions with lower VPD to favour the biomass–transpiration relationship.

The VPD at the (typical) critical flowering window for wheat increases northwards and inland across Australia (Figure 4.3), meaning more soil water is required in northern and inland regions to obtain the same flowering performance.

What is water-limited potential yield?

Seasonal rainfall typically accounts for about one-third of the variation in yield of wheat in Australia, and research has demonstrated a boundary line representing the upper limit of wheat yield for a given evapotranspiration (Figure 4.4).

Two parameters define the boundary shown in Figure 4.4:

- the intercept marked in orange is commonly interpreted as seasonal soil evaporation; and
- the slope of the line represents the maximum yield for a certain crop transpiration.

As shown in Figure 4.5, soil evaporation and the slope of the boundary are not fixed, but vary with soil type, rainfall and agronomic management.

Management practices that increase the rate of canopy cover, such as high fertiliser rate, narrow rows, high sowing density and earlier sowing, would normally reduce soil evaporation, moving the line in Figure 4.5 to the left.

Within Australia, soil evaporation increases southwards for winter crops due to the greater proportion of in-season rainfall dominated by small rain events wetting the topsoil more often (Figure 4.6).

The slope of the line is steeper in southern Australia compared with the northern region due to the reduction in VPD.

The slope was initially defined at 20kg/ha/mm for south-eastern locations in the early 1970s but has increased to approximately 25kg/ha/mm with newer, higher-yielding varieties.

The maximum yield potential has increased by 25 per cent to 25kg/ha/mm in southern Australia since the 1970s.

How can ameliorating resource limitations improve yields?

Crop biomass production depends on the ability of the canopy to capture radiation and CO_2, and on the ability of the root system to capture nutrients and water. The rate of capture and efficiency in using resources to produce biomass is influenced by weather, soil, weeds, pathogens and pests. To illustrate capture and efficiency in the use of resources, consider the effect of soil compaction in a sandy Mallee soil as shown in Figure 4.7.

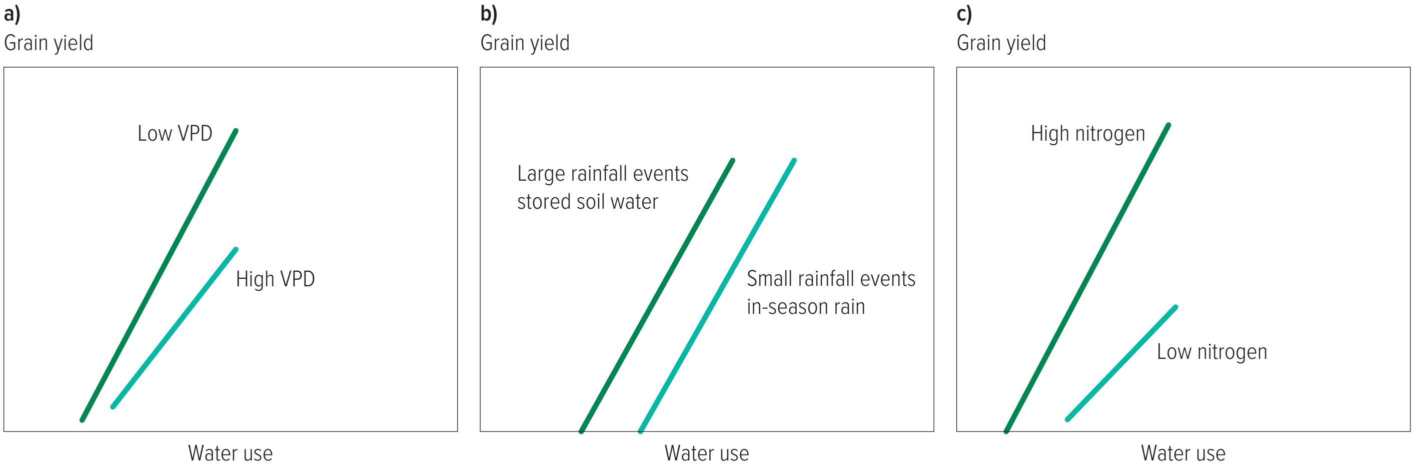
Therefore, in compacted soil, limited capture of all four resources – radiation, CO_2, nutrients and water – restricts root and crop growth. In a comparison of crops on compacted soil and soil where deep-ripping removed compaction shown in Figure 4.8, removal of soil stress improved root growth and canopy size with a twofold increase in capture of radiation from 18 to 40 per cent early in the season (Figure 4.8d). Control crops yielded between 1.2 and 2.9 tonnes per hectare and the yield improvement from ripping ranged from zero to 43 per cent depending on season and position in the landscape (Sadras et al., 2005).

Co-limitation of nutrients affects yield outcomes

Co-limitation, defined as the simultaneous limitation of yield by multiple resources, incorporates the ability of one resource to influence the availability of a second resource. For example, a crop with low nitrogen supply can respond to phosphorus that stimulates root growth and enhances capture of nitrogen, and vice versa.

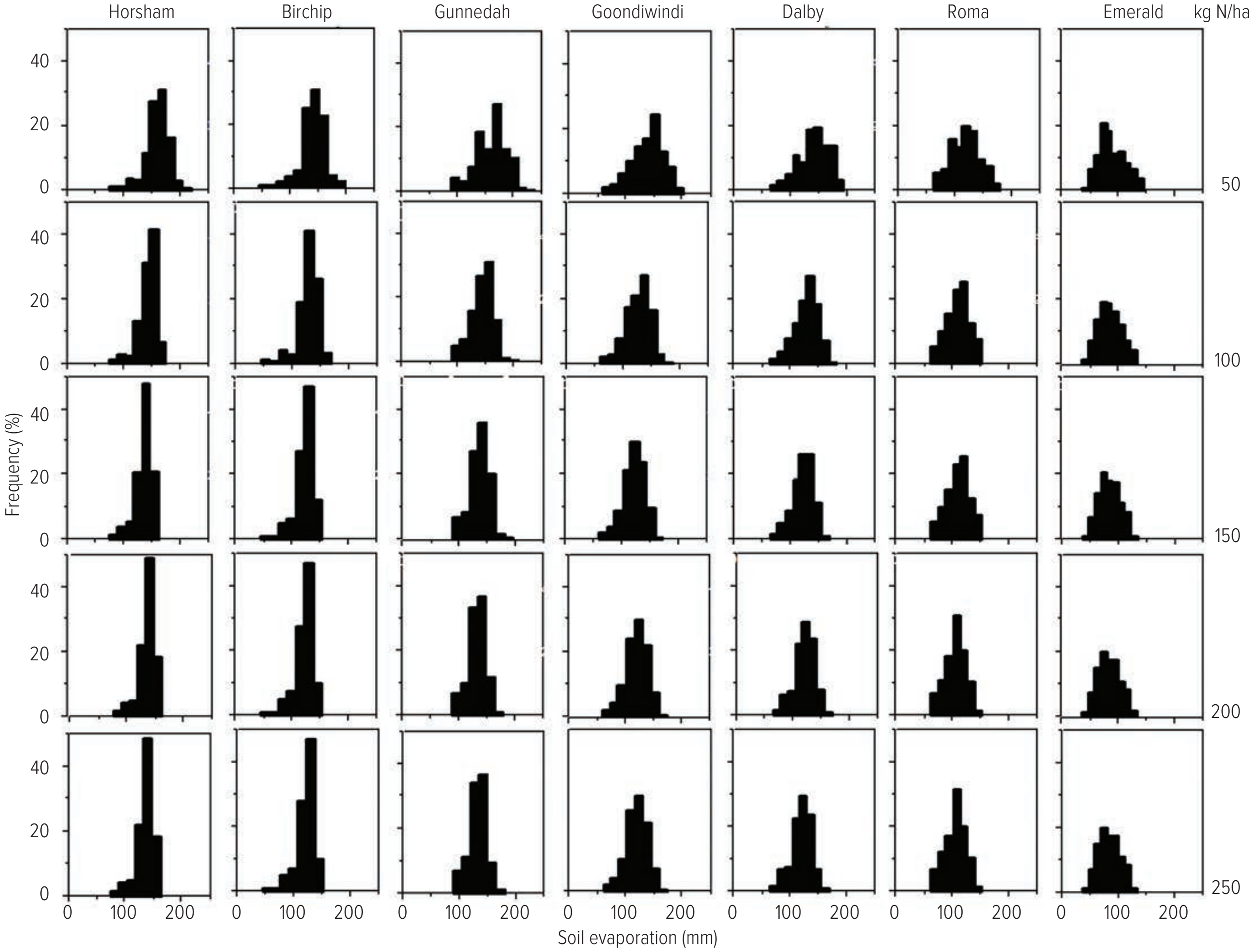
Cereals in Australia are usually co-limited by water and nitrogen; however, application of phosphorus, potassium and sulfur can

Figure 4.5: Influence of climate and nitrogen supply in the parameters of the French and Schultz benchmark. a) Reduction in slope with increasing vapour pressure deficit. Vapour pressure deficit is a measure of air dryness; it increases inland and northwards, and it also increases with late sowings. b) Increased soil evaporation with increasing frequency of small rainfall events and crop dependence on in-season rainfall as opposed to dominance of large rainfall events and crop reliance on stored soil water. c) Nitrogen deficiency reduces the slope and increases soil evaporation.



Source: adapted from Sadras & McDonald (2011)

Figure 4.6: Modelled soil evaporation in winter crops highlighting: the declining evaporation from south (Horsham) to north (Emerald), the declining evaporation with increasing nitrogen supply, and the season-to-season variation in evaporation captured in the distribution of frequencies.



Source: Sadras & Rodriguez (2010)

increase the efficiency of the use of nitrogen. Studies have found that simultaneous rather than sequential alleviation of stress is more likely to return higher yield (Sadras & Richards, 2014).

When it comes to water use, the importance of co-limitation is that growers must meet nutritional needs when attempting to maximise WUE.

What is the critical growth period for maximising yield?

Growers are generally aware that yield is most sensitive to stress at flowering, although experiments conducted to establish the most vulnerable stages show a longer period, from late stem elongation to approximately 10 days after flowering for wheat, barley and oats, with the most sensitive stage shortly before flowering (Figure 4.9).

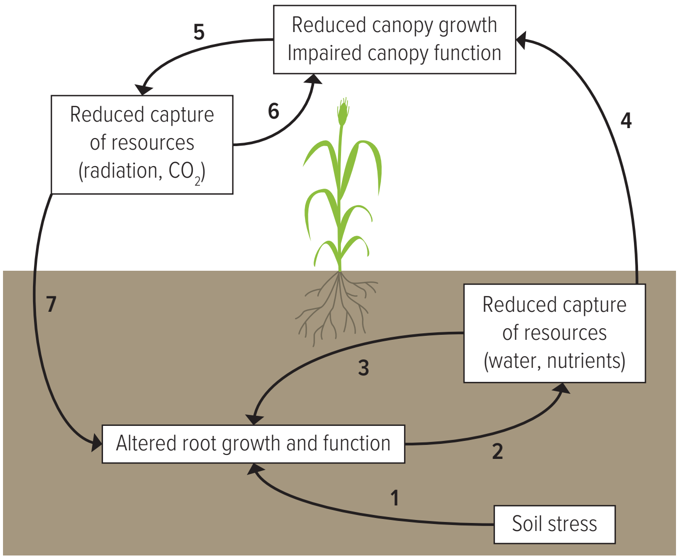
For field peas, chickpeas, lentils, lupins, faba beans and canola, the most vulnerable stage was found to be pod set, or about 200 degree-days after flowering (Figure 4.9).

Figure 4.10 presents patterns of water supply and plant demand that are most likely to be experienced in Australian grain growing regions based on statistical analysis, with patterns with low numbers representing seasons with more severe water stress.

For wheat and field peas, the more severe stress patterns (1 and 2) have water-stress onset before flowering, with water supply well below the demand during the critical period of grain set (Figure 4.9). For example, wheat (pattern 1) has water stress starting about 500 degree-days before flowering, stress intensifying gradually, with the supply of water at flowering at only 40 per cent of the demand. This is the most severe of the dominant water-stress patterns, and many locations feature this pattern in approximately one-third of seasons.

The less severe drought pattern 3 develops after flowering and affects both grain set and filling; however, these conditions lead to higher yield than patterns 1 and 2 (Sadras et al., 2012b), and therefore should be potentially considered less of a concern than seasons with earlier water stress.

Figure 4.7: Effect of soil compaction on crop capture of soil and above-ground resources highlighting reinforcing loops.

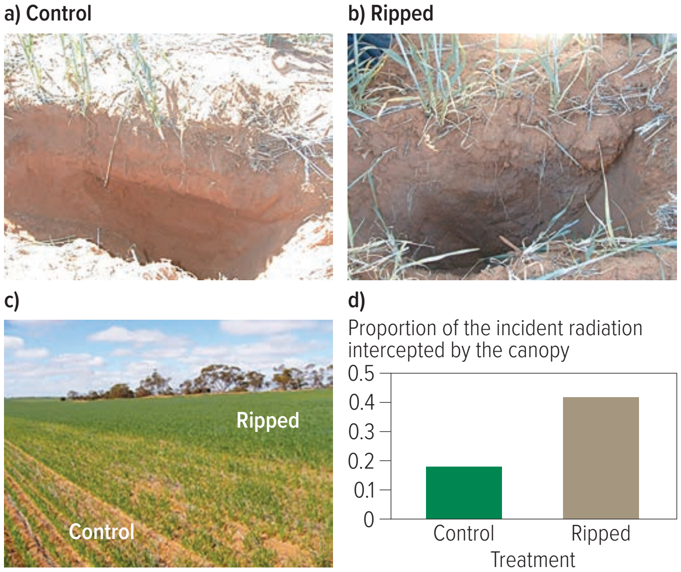


Source: Sadras et al. (2005)

In chickpeas, pre-flowering stress is not evident, and water stress of varying intensity develops close to or shortly after flowering. However, there is a resemblance as the most severe water-stress conditions occur earlier, rather than later.

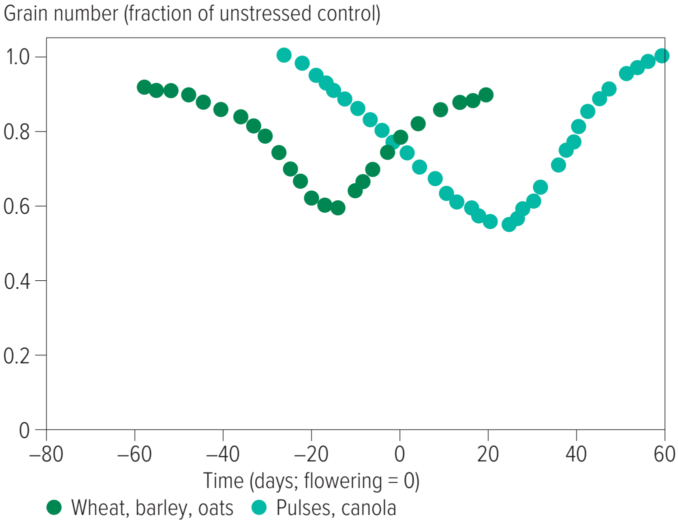
Therefore, aligning the critical development window (Figure 4.9) with likely periods of low water stress (Figure 4.10) will maximise yields. Modelling has identified combinations of sowing date and cultivar to manage the trade-offs between stresses across Australia for wheat, barley, canola and pulses, as explained in Chapter 6.

Figure 4.8: Comparison of wheat crops in compacted sandy Mallee soil and crops where compaction was alleviated with deep ripping. a) and b) highlights the compacted soil layer constraining root growth. c) Difference in canopy size. d) Difference in radiation interception early in the season. Deep ripping was achieved with a three-tyne ripper with tynes spaced at 0.45m and extending to a depth of 0.6m.



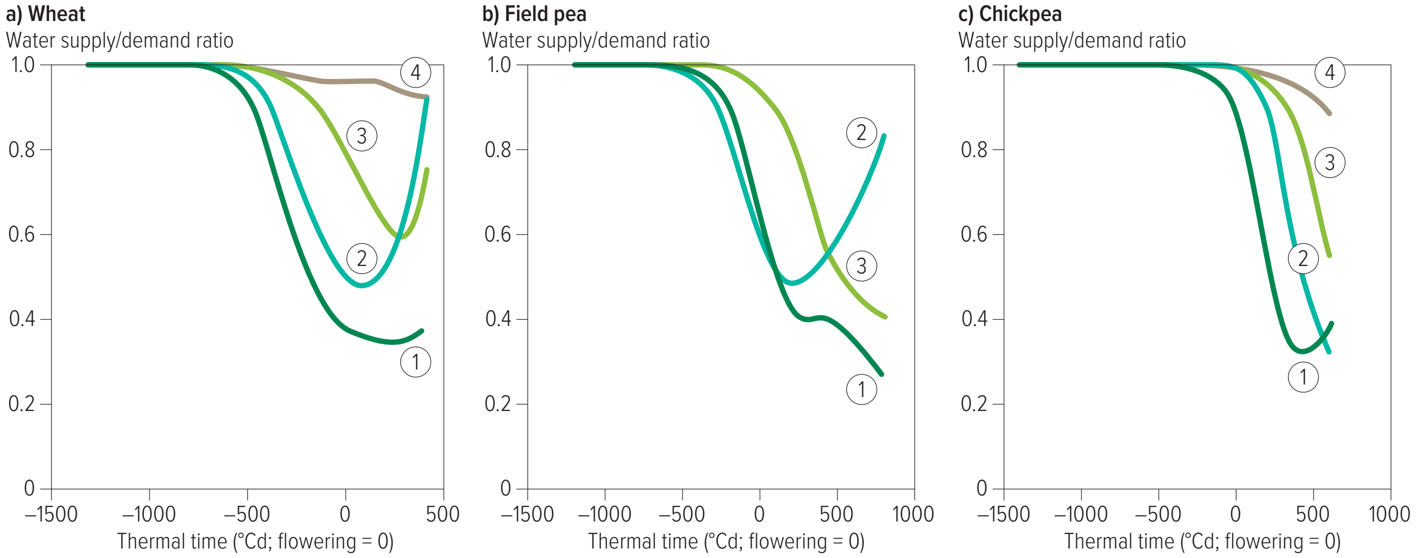
Source: Sadras et al. (2005)

Figure 4.9: The critical developmental window for the definition of grain number in cereals, pulses and canola.



Source: Critical period of wheat (Fischer, 1985); barley (Arisnabarreta & Miralles, 2008); oat (Mahadevan, et al., 2016); lupin and field pea (Sandaña & Calderini, 2012); chickpea (Lake & Sadras, 2014); canola (Kirkegaard, et al., 2018)

Figure 4.10: Patterns of water supply and demand in a) wheat, b) field pea and c) chickpea. Patterns of drought are numbered from 1 for more severe water deficit, to 3–4 for less severe or no water deficit.



Source: Drought patterns of a) wheat (Chenu et al., 2013); b) field pea (Sadras et al., 2012b), and c) chickpea (Lake et al., 2016)

Chapter 5: Preparing for the growing season

What practices before the start of the growing season can improve WUE?

CHEAT SHEET

- Management practices in the years leading up to the current growing season can have important influences on the current growing season.
- Both short and long fallows provide the opportunity to store water to be used by the crop.
- Effective fallow weed control is an important management tool to improve the benefits of out-of-season rainfall and preserve soil moisture.
- Crop residue management only tends to have a consistent influence on stored water in the northern region.
- Cover crops can be a good tool in northern and high-rainfall areas to convert excess fallow rainfall to biomass, without loss of PAW at sowing.
- Crop sequencing influences both residual soil moisture at harvest and fallow efficiency.

The pre-crop period is an important phase of the farming system that influences the yield of the current season's crops. How the paddock is managed in the year prior to the current crop will influence the amount of plant-available moisture, nitrogen, and weed and disease pressure.

Figure 5.1 lists the pre-crop management practices that influence yield and WUE, as developed for the GRDC Water Use Efficiency Initiative. The project was targeted at the southern region, but the same principles are relevant to the western and northern regions.

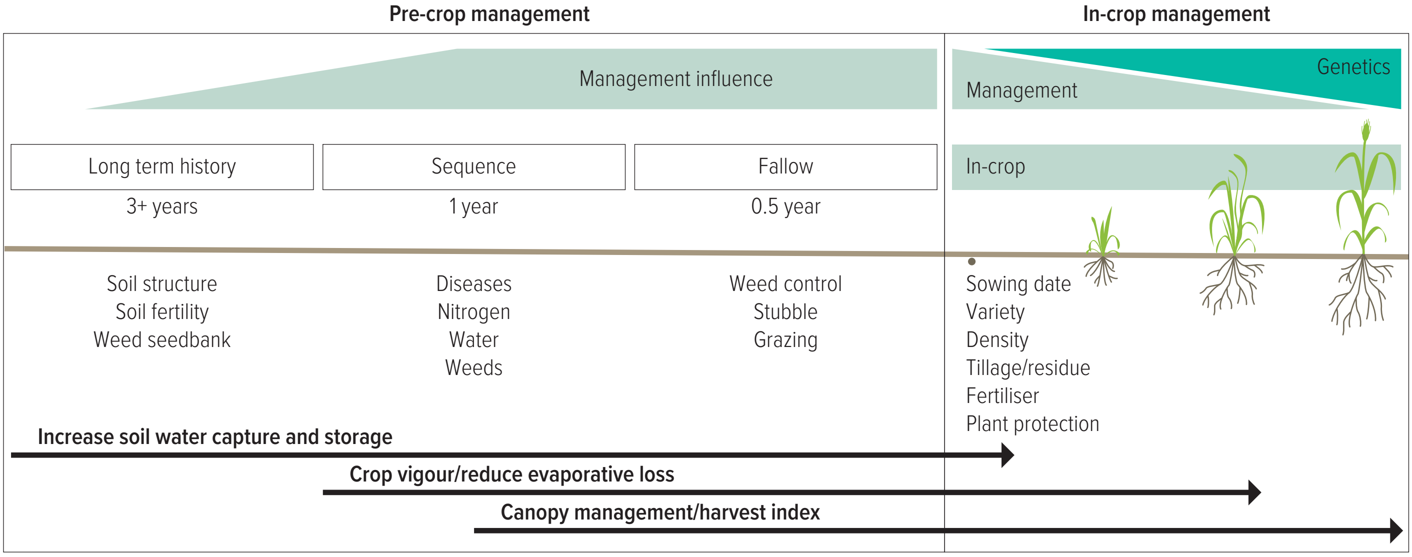
The WUE initiative found that significant improvements in WUE in the southern region can be attributed to certain pre-crop practices, with fallow weed control providing improvements in WUE of 38 to 140 per cent and break crops between 18 and 82 per cent (Kirkegaard et al., 2014a).

How does fallowing influence stored water?

Fallowing is a way to supplement in-season rainfall to improve the yield and reduce the seasonal variability in grain yield. The value of fallowing to winter crop production varies considerably across the country. Table 5.1 examines the importance of out-of-season rainfall across a wide range of locations. As you move from the northern region to the southern and western regions, the proportion of out-of-season rainfall declines and becomes more variable.

This shows that the benefit of summer fallows is lower and less predictable in the southern and western regions than it is in the northern region. Although the proportion of annual rainfall that

Figure 5.1: A diagram showing the different management options available to growers for improving crop water use efficiency and grain yield.



Source: Kirkegaard et al. (2014a)

Table 5.1: Rainfall distribution and variability for different locations in the northern, southern and western regions. The total April–October rainfall is used to represent the growing season rainfall for winter crops. Variability in growing season (April–October) and out-of-season (November–March) rainfall is given as the coefficient of variation for rainfall for the period 1960–2021.

Location	Annual rainfall (mm)	Percentage of annual rainfall received between April and October	Variability of rainfall (%)[A]	
			April–October	November–March
Emerald, Qld	586	34	61	34
Dalby, Qld	648	40	72	31
Moree, NSW	587	43	42	38
Dubbo, NSW	607	53	40	39
Wagga Wagga, NSW	553	61	35	46
Birchip, Vic	346	66	37	50
Horsham, Vic	415	70	30	45
Roseworthy, SA	421	74	24	39
Minnipa, SA	325	74	28	51
Merredin, WA	327	72	27	58
Wongan Hills, WA	358	78	26	54
Katanning, WA	461	78	21	56

[A] This figure is the coefficient of variation, which is the ratio of the standard deviation to the mean, expressed as a percentage. The higher the coefficient of variation, the more variable the data.

Source: Hunt & Kirkegaard (2011)

Table 5.2: Average yield increases (t/ha) and the coefficient of variation based on modelled effects of summer fallow rainfall.

State/region	Mean yield increase from summer fallow rainfall (t/ha)	Yield increase (%)	Variation^ of benefit (%)
Central and southern NSW	1.5	50	28
Victoria	1.1	36	21
SA	0.7	25	52
WA	0.4	18	85

^This figure is the coefficient of variation, which is the ratio of the standard deviation to the mean, expressed as a percentage. The higher the coefficient of variation, the more variable the data.

Source: Hunt & Kirkegaard (2011)

FALLOWING BENEFITS VARY

Growing season rainfall can be an important factor influencing the yield benefit from fallowing. The yield response to fallowing is generally lower in a wet year compared with a dry year. This may be associated with water availability becoming a less limiting factor and therefore the value of the fallow soil moisture declines, or it may be due to soil water use being increasingly limited by nitrogen. Therefore, having an adequate supply of nitrogen, either from fallowing or having an appropriate fertiliser program, is important to make the most use of fallow moisture (Sadras et al., 2012a).

falls during the growing season is higher and more reliable in the southern and western regions, the moisture retained by summer fallows can make a significant contribution to the yields of the following winter crops.

Hunt & Kirkegaard (2011) used crop modelling to estimate the contribution of summer fallow rainfall to grain yield of wheat in the southern and western regions, with the results shown in Table 5.2. Although the greatest benefit from stored moisture occurred at sites in NSW, summer fallow rainfall in WA, SA and Victoria also made significant contributions to yield. The variation in the benefit of summer fallow rainfall among the sites was also high; however, with the variability in WA being three times greater than in NSW, the benefit is less reliable.

A note on long fallows in the southern and western regions

Much of the work in the 1980s and 1990s that compared long fallows with more intensive systems concluded that the additional yield from the long fallow was not enough to offset the loss in production during the fallow. For example, Oliver, Robertson & Weeks (2010), who studied whole-farm grain production, found that production was reduced by long fallowing. However, this study did not include an economic analysis of the different rotations.

Long fallowing can reduce the impact of seasonal variation on yield and profit (Oliver et al., 2010; Ridge, 1986). A recent analysis for a site in north-west Victoria confirmed this (Cann et al., 2020); their analysis found that the inclusion of fallow improved cashflow over a 20-year period and reduced risk. The analysis suggested that using long fallows in low-rainfall areas may maintain profit and reduce risk. However, it is also important to note that the difference in profits is also affected by commodity prices and input costs and therefore the benefits of one system over another needs to be reassessed under different scenarios.

WHAT IS FALLOW EFFICIENCY?

Fallow efficiency is the proportion of rainfall that falls during the fallow period that is stored and retained for the next crop. The major cause of moisture loss is evaporation, but transpiration from weeds, drainage beyond the root zone and run-off also contribute to this loss.

The most common formula used to calculate fallow efficiency is given below, with the answer expressed as a percentage.

$$\frac{\text{Fallow efficiency} = (\text{PAW end of fallow} - \text{PAW start of fallow})}{\text{Rainfall received during fallow}}$$

To be effective, rain that falls during the fallow period needs to infiltrate below the zone of evaporation in the topsoil. This zone varies in depth with soil texture, being deeper in coarse (sandier) soils than in fine soils due to the greater porosity of sandier soils.

A rule of thumb of 25 per cent fallow efficiency is often used but caution is needed when applying this as there can be considerable variation. The factors that influence fallow efficiency are:

- initial **soil moisture** – dry start fallows generally have a higher efficiency than wet start fallows;
- the amount of **crop residue** during the fallow period – higher amounts of crop residues can improve fallow efficiency in the northern region;
- the **length** of the fallow – long fallows generally have lower fallow efficiencies than short fallows when compared in the same environment;
- the **type of crop** – work in the northern region indicates that the preceding crop can influence the amount of moisture stored and the fallowing efficiency;
- the size and frequency of **rainfall events** – over summer, soil water storage and fallow efficiency is lower when rain occurs as frequent, light showers. Less frequent but heavier showers can result in better infiltration of water below the evaporation zone; and
- **soil texture** – this effect seems to differ whether you are considering long fallows or short summer fallows: with long fallows, greater moisture storage and higher fallow efficiency occurs with fine textured soils (Oliver, Robertson & Weeks, 2010; French R., 1978). With short fallows, often the opposite seems to occur (Hunt & Kirkegaard, 2011) or there may only be minimal difference (Oliver et al., 2010).

Why does the depth of water storage matter?

The value of moisture accumulated during a fallow is not only influenced by the amount of moisture that is stored, but also the depth of storage. Water deep in the profile at sowing provides a higher WUE than growing season rainfall, so small increases in subsoil moisture during a fallow period can be very valuable for grain yield.

The WUE associated with subsoil moisture is referred to as the marginal water use efficiency. Marginal WUE values of up to 30 to 40kg/ha are possible in wheat. The value of this subsoil moisture will be greatest in seasons when the crop has a high yield potential and if water stress develops around flowering and early grain filling.

Paddock measurements and crop simulations have suggested that the greatest benefits of subsoil moisture are when the moisture is stored below approximately 1.2m and that the benefit of subsoil moisture diminishes in shallower profiles. This is because much of the water that is stored above one metre is used earlier in the season when the effect on yield may be less. The presence of subsoil constraints may also limit use of water deep in the profile.

Soil moisture probes can provide information on the depth of water storage and the potential benefit from marginal WUE.

Weed control during fallowing

Effective weed control is arguably the most important management practice influencing the storage of soil moisture over the fallow period. High weed growth in the fallow can reduce yields due to a reduction in soil water and mineral nitrogen. For example, two separate field tests at Wagga Wagga found that weeds reduced available soil water at sowing by 40 to 50 per cent (Zeleke, 2017; Verburg et al., 2012).

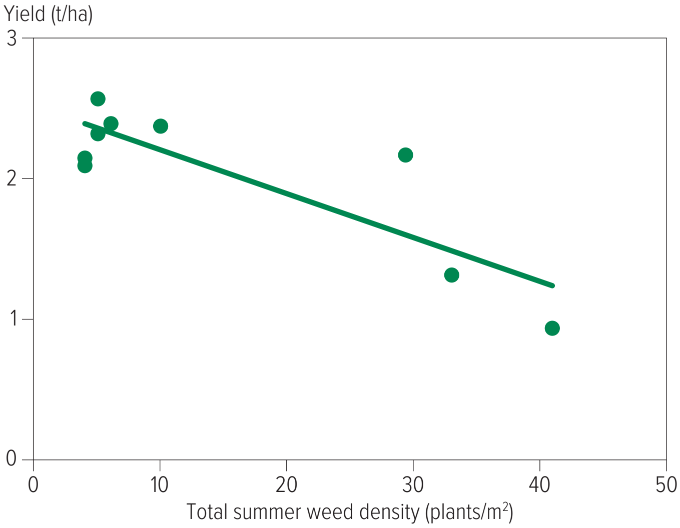
The magnitude of the loss will depend on seasonal conditions but can contribute to a reduction in yield. Several studies have shown strong reductions in yield caused by fallow weeds (Kohn & Cuthbertson, 1966; Osten et al., 2006), as demonstrated in Figure 5.2 from Hunt (2011) showing a yield decline of more than half depending on the density of summer weeds.

How does stubble management influence water storage?

The main effect of crop residues on soil moisture storage is to reduce run-off and increase infiltration, leading to increased soil moisture, rather than reduced evaporation during the fallow.

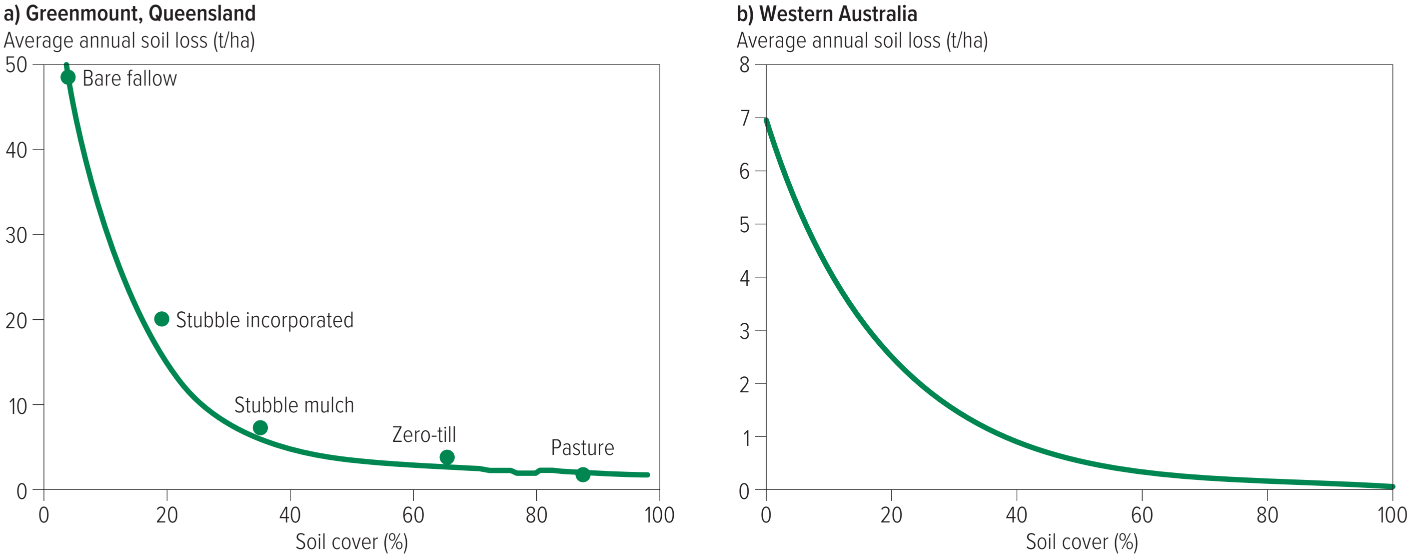
In areas where water erosion risks are high due to intense summer storms, the presence of crop residues reduces run-off, improves water infiltration and reduces erosion. Crop residues also reduce the severity of wind erosion. As a guide, 50 per cent or greater soil cover from crop residues will minimise the effects of water and wind erosion (Figure 5.3).

Figure 5.2: The relationship between summer weed density (common heliotrope and volunteer cereals) on 11 February 2008 and subsequent wheat grain yield in 2008 at Curyo, Vic.



Source: adapted from Hunt (2011)

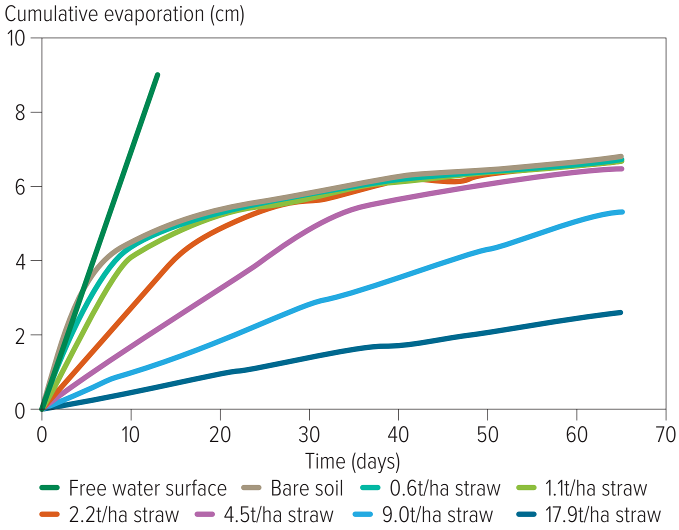
Figure 5.3: The relationship between soil cover and soil loss from erosion: a) mean annual water erosion on a sloping site at Greenmount, Queensland, and b) wind erosion over residue of lupin at a wind speed of 30km/h in WA.



Source: Thomas et al. (2007)

Source: adapted from Findlater, Carter & Scott (1990)

Figure 5.4: The effect of stubble load on the cumulative evaporation from column of moist soil and an evaporative potential of 0.7cm/day.



Source: adapted from Bond & Willis (1970)

The majority of water loss during the fallow period is from evaporation. However, stubble load has little effect on evaporative losses. Crop residues slow the rate of evaporation but under a prolonged period of high evaporative demand, there is little difference in total evaporation between different stubble loads. As shown in Figure 5.4, significant reductions in evaporative losses may only occur with dense stubble loads associated with high-yielding crops (for example, greater than 6t/ha).

The value of stubble will also be influenced by the pattern of rainfall during the fallow period, which will affect the depth of infiltration. Small showers of rain or rainfall events separated by a long time are quickly evaporated, even in the presence of stubble. For water to be captured effectively in the fallow period, water needs to infiltrate below the surface evaporative zone to the subsoil. This is achieved by consecutive falls of rain over short periods of time so infiltration overlaps between successive events and crop residues can help to improve water storage in these circumstances.

Although crop residues have little effect on evaporative loss of soil water during summer, the influence of stubble is greater when evaporative demand is low in autumn and early winter. In the winter-rainfall regions, the effectiveness of the more frequent falls of rain during autumn can be increased by the presence of crop residues. Being able to reduce evaporative losses at this time may improve the chances of early sowing of winter crops (Verburg et al., 2012).

How does stubble retention affect grain yield in the southern and western regions?

A range of trials across the southern and western regions has shown that yield responses to stubble management are often small and inconsistent, due mainly to the long period of drying over the summer months. For example, in the GRDC National Water Use Efficiency Initiative, more than 60 per cent of experiments showed no effect of stubble management on grain yield, 26 per cent showed a negative effect of stubble and only 11 per cent showed a positive effect. It was thought the negative effect of stubble was related to the tie-up of nitrogen by immobilisation.

How does stubble retention affect grain yield in the northern region?

In the northern region, improved storage of soil moisture with stubble retention translates to higher yields. Extensive trial work in Queensland over many years found that in no-till systems, soil moisture content at sowing was increased by 20mm and grain yield by 0.25t/ha on average, with the greatest benefits occurring in low-yielding years when moisture was limiting (Thomas et al., 2007).

Does grazing crop residues reduce soil moisture?

Grazing of crop residues generally has little effect on soil moisture storage and grain yield (Allan et al., 2016; Bell et al., 2011; Kirkegaard et al., 2014a). Increases in bulk density and reductions in infiltration rates following grazing have been recorded, but the effects are limited to shallow depths and are reversed by natural soil processes (for example, wetting and drying or biological activity) or by mechanical disturbance associated with sowing. Losses of crop residues during grazing are often small and livestock tend to flatten the stubble rather than consume large amounts. Damage to soil and a reduction in crop growth can occur with heavy grazing over long periods and when the soil is wet, but being aware of the risks can avoid damage to the soil.

Do cover crops affect water storage?

There has been increased interest in the use of cover crops to replace chemical or bare fallows where fallow efficiencies are low. A cover crop is a non-cash crop (either a monoculture or a mixture) that is grown prior to a cash crop but is terminated before it matures. The cover crop can be terminated by herbicide application or mechanically by rolling and crimping. Cover crops can be grown either in summer or winter, over part of the fallow period or to replace a cash crop. There are benefits of a cover crop that may help the productivity of subsequent crops, including helping to protect the soil from erosion, run-off or raindrop impact by increasing the amount of ground cover, improving soil organic matter, promoting nutrient cycling, reducing leaching of nitrate, acting as a disease break and, in some circumstances, improving moisture conservation.

In the northern region, maintaining high levels of ground cover is important to protect the soil from erosion, reduce run-off and improve infiltration. Cover crops can play an important role in achieving this when there is a lack of ground cover.

Trials in south-east Queensland have demonstrated that cover crops such as French millet or sorghum planted in spring and terminated after two to three months help maintain soil cover with little or no loss in plant-available moisture at sowing of the following winter crop. Early termination is critical to allow the soil moisture to be replenished late in the fallow period. This work has also demonstrated that cover crops can provide improved sowing opportunities by increasing soil moisture in the topsoil compared with a conventional fallow, due to reduced evaporation. A key factor in the success of cover cropping is sufficient rainfall to replenish soil moisture after the cover crop. When there is limited rainfall after the termination of the cover crop plant-available water can be reduced by the cover crop, resulting in low yields in the following crop.

There is less information about the benefits of cover crops in the southern and western regions. The value of summer cover crops is limited by the low and variable summer rainfall across the two regions, which will restrict biomass production and limit the benefits of organic matter and nutrient recycling. Recent work invested in by GRDC (project code AEA1812-001OPX) showed that yield benefits from cover cropping were strongly related to climate: improvements in yield and soil properties occurred more frequently in the high-rainfall areas whereas there were limited benefits from cover cropping in the low-rainfall areas and an increased risk (Collis, 2022; Farrell, 2022).

Winter cover crops can also be grown at the expense of a winter cash crop, but there may be little benefit from a winter cover crop unless it is replacing a winter fallow. For example, a nine-year trial at Cunderdin, WA (GSR = 214mm) found no benefits to crop productivity and reduced gross margins from a winter cover crop (Flower et al., 2017).

How does a previous crop affect stored soil moisture?

The crops grown in the previous years can have a significant influence on the growth and yield in the current crop mainly through the effects on the availability of water and nitrogen. Break crops can leave different amounts of moisture available at sowing of the following crop due to differences in root growth. Non-cereal break crops may also influence the ability of the crop to use residual soil moisture by improving root health through a disease break and by increasing the amount of residual soil nitrogen.

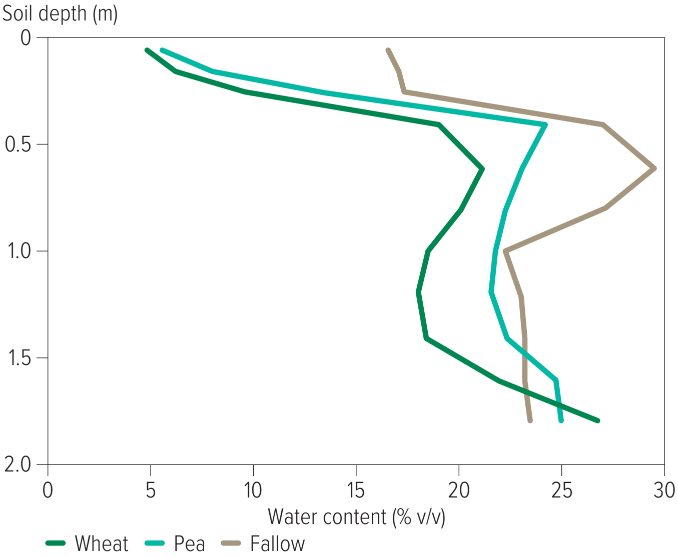
In the summer rainfall regions of the northern region, the previous crop can influence the efficiency of fallow water accumulation and the amount of stored moisture at the end of the fallow (Table 5.3). Fallows after a winter cereal have the highest efficiency whereas efficiencies after pulses are lower. The differences in fallow efficiencies relate to differences in ground cover and the rate of decomposition of the stubble as well as the influence of residual soil moisture after harvest.

Many experiments in eastern Australia have found that legumes tend to leave more residual soil moisture at harvest than winter cereals or canola (Figure 5.5). This is caused by differences in rooting depth and differences in the rate of senescence and water demand. Season length is also an important factor in determining residual moisture (Verburg et al., 2021).

However, these differences in residual soil moisture at harvest are not always translated to differences in soil moisture at sowing and to differences in grain yield, due to the lower fallow efficiency after pulses.

Differences in the legacy effects of summer crops have been measured. Cotton can leave the soil 20 to 30mm drier compared with maize or sorghum and this can result in lower yields after cotton compared with the summer cereals. In contrast, mungbeans tend to leave more residual soil moisture compared with summer cereals, but due to its poor ground cover the difference is diminished by the end of the fallow period and there may be no difference in yield (Bell et al., 2021).

Figure 5.5: Soil moisture profiles under wheat, pea and fallow at crop maturity at a site in southern NSW.



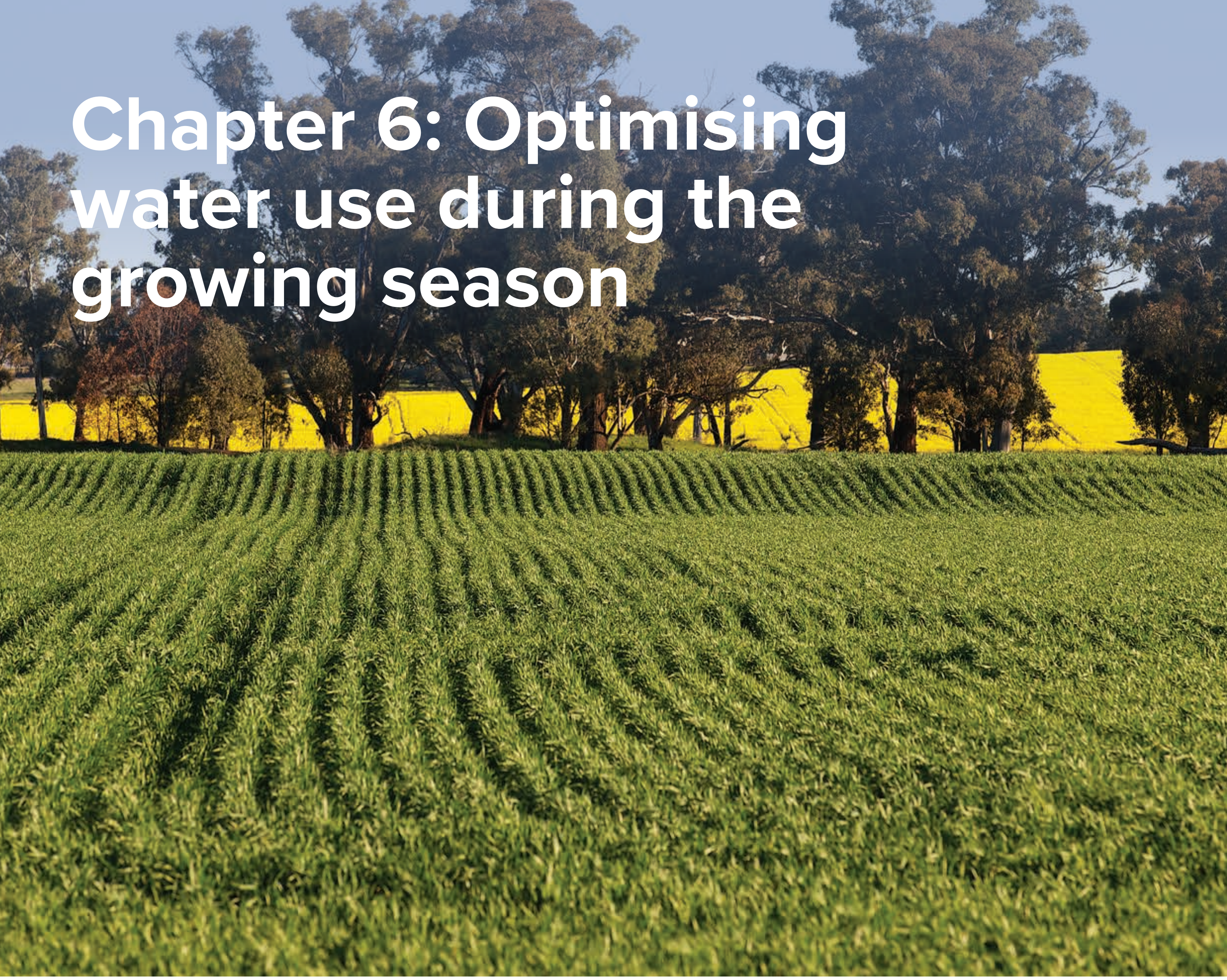
Source: adapted from Angus et al. (2015)

Table 5.3: Fallow efficiencies following different crops from trials in Queensland and central and northern NSW.

Previous crop	All fallows (%)	Short fallows (%)	Long fallows (%)
Winter cereals	30	34	21
Winter pulses	20	25	15
Sorghum	22	28	19
Canola	26	31	6
Cotton	16		16

Source: Erbacher et al. (2020)

Chapter 6: Optimising water use during the growing season



How does cultivar selection, sowing time and nutrition influence WUE?

CHEAT SHEET

- Selecting the right crop variety for the conditions can reduce limitations, reduce transpiration losses and improve crop establishment.
- Early sowing to allow the crop to flower during its optimal flowering window will optimise WUE and therefore yield.
- Limited nutrition will reduce yield potential, so optimum nutrition strategies will also optimise WUE.
- Narrow row spacings will generally improve WUE, except in certain low-rainfall conditions.

How do I match my variety to sowing time?

WUE, and therefore crop yield, will be maximised when crops flower in the optimal conditions (see Chapter 4). Knowing the optimal flowering window, you can choose the right combination of variety and sowing time that will meet that window and maximise WUE.

For example, GRDC-invested research in Central Queensland used VPD data to estimate the ideal flowering window for the region and back-calculated ideal sowing time for different varieties (Aisthorpe, 2021).

Many regional crop variety sowing guides provide a table showing optimal sowing time for different varieties to meet the optimal flowering window, which can assist growers in choosing varieties that suit their ideal sowing program.

What varieties will improve crop establishment?

Reliance on irregular rainfall for crop establishment can be reduced by sowing long-coleoptile cultivars deeper into soil moisture accumulated during a long fallow period (Flohr et al., 2018a; Flohr et al., 2018b; Hunt et al., 2019; Kirkegaard & Hunt, 2010; Rebetzke & Richards, 1999; Rebetzke et al., 2016).

This is common in the semi-arid United States Pacific Northwest where sowing 15 to 20cm deep into soil moisture is widely practised (Schillinger et al., 1998; Schillinger & Young, 2014; Wuest & Lutcher, 2013). Simulation of this practice in Australian conditions shows that fallow periods in rotation with early sown, long-season cultivars with long coleoptiles can provide a buffer against rainfall variability and increase yield by 0.5 to 1.2t/ha (Flohr et al., 2018a; Flohr et al., 2018b; Kirkegaard & Hunt, 2010).

Experiments in eastern WA including long coleoptile Mace$^{\phi}$, Magenta$^{\phi}$, LRPB Scout$^{\phi}$ and Yitpi$^{\phi}$ breeding lines, compared with commercial varieties Mace$^{\phi}$ and Scepter$^{\phi}$ and tall variety Halberd, demonstrated the benefits of new dwarfing genes in increasing coleoptile length and seedling emergence at sowing depths of up to 140mm (Table 6.1).

In the paddock over multiple seasons, Schillinger et al., 1998) found the best emerging cultivars had coleoptile lengths >100mm.

At the time of writing, long coleoptile wheat breeding lines have been provided to Australian breeders for testing and use in breeding, with the intention of commercially available long-coleoptile varieties being available in the future.

As an alternative to the new genotypes, some management practices with the existing cultivars can also favour long coleoptiles and crop establishment. For instance, cleaning and sizing seed to find the larger, plump seed will also assist in improving emergence when sowing deep or where there is potential for soil-crusting to impede seedling emergence.

How do I select the best sowing time to maximise WUE?

Arguably, time of sowing is the most critical management practice that will affect WUE and yield. There is an optimal period in which to sow, with many studies in a range of crops showing late sowing will reduce yields, yet sowing very early may have little benefit or reduce yields.

Delayed sowing beyond the optimum time reduces grain yields of wheat on average by 6.6 per cent per week. The optimum time of sowing is largely determined by the pattern of development of the crop and its effect on time of flowering. Therefore, the selection of variety will also affect sowing date responses, as mentioned in 'How do I match my variety to sowing time?

If there are opportunities to sow crops early in the growing season (for example, April to early May), varieties that develop slowly and flower late are used. Early sowing increases the effective length of the growing season and using varieties with longer patterns of development that take advantage of this improves the overall efficiency of water use. Conversely, with late sowing and a shorter effective growing season, early flowering varieties are more suitable.

Although the optimum sowing time for a particular location can be variable depending on the maturity type of a variety, the flowering window that provides the highest yields is generally more stable. For each variety, the optimum sowing date will be that which

Table 6.1: Grain yields and yield components for different wheat varieties and breeding lines sown deep at 120–130mm and shallow-sown at 40mm (in parenthesis). A subset of lines (Magenta$^{\phi}$18, Scout$^{\phi}$18, Yitpi$^{\phi}$18) were only sown in the deep sowing treatment.

Entry	Sowing depth	Grain yield (t/ha)	Number of heads (m^{-2})	Harvest index	Seed weight (mg)	Protein conc. (%)	Water productivity (kg/ha/mm)
Scepter$^{\phi}$	120–130mm	1.41	80	0.49	44	10.2	15.4
Scepter$^{\phi}$	40mm	1.86	121	0.45	39	9.2	19.3
Mace$^{\phi}$	120–130mm	1.25	76	0.49	42	10.4	13.7
Mace$^{\phi}$	40mm	1.95	149	0.44	38	8.4	21
Mace$^{\phi}$18^	120–130mm	1.8	137	0.45	39	10.6	19.8
Mace$^{\phi}$18^	40mm	1.87	174	0.41	34	10.2	20.6
Magenta$^{\phi}$18^	120–130mm	2.01	172	0.44	37	10.8	22.1
Scout$^{\phi}$18^	120–130mm	1.6	147	0.48	42	10.3	17.6
Yipti$^{\phi}$18^	120–130mm	1.68	132	0.42	38	11.4	18.4
Halberd (tall)	120–130mm	1.59	138	0.43	38	10.3	17.5

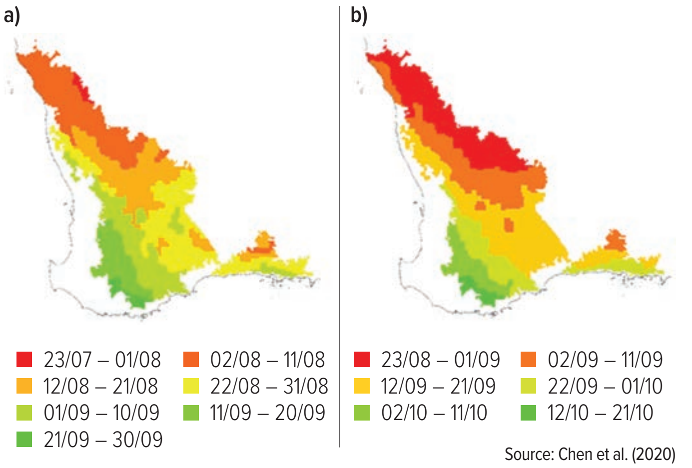
^Long coleoptile Rht18 selections

Source: adapted from Rebetzke, et al. (2021)

CASE STUDY: OPTIMAL FLOWERING WINDOWS IN WESTERN AUSTRALIA

GRDC-invested research by CSIRO estimated the start, end and duration of optimal flowering windows in wheat in 2020 for the WA wheatbelt. Figure 6.1 shows the start and end of the flowering window in different grain growing areas. Aligning your sowing date with variety selection so that flowering falls within these dates will optimise your yield potential.

Figure 6.1: a) The optimal opening date and b) closing date for flowering in wheat across WA regions as determined in 2020.



Source: Chen et al. (2020)

Table 6.2: Effect of fertiliser on grain yield, water use and water use efficiency of barley crops grown in two Syrian locations with different average annual rainfall (Jindiress = high rainfall 478mm, and Breda = low rainfall, 278 mm).

	Site and fertiliser treatment			
	Jindiress (high rainfall)		Breda (low rainfall)	
	Control	Fertilised	Control	Fertilised
Grain yield (t/ha)	3.26	4.61	1.51	2.01
Water use (mm)	331	356	235	239
Water use efficiency (kg/ha/mm)	9.8	12.9	6.4	8.4
Transpiration (mm)	188	232	76	96
Soil evaporation (mm)	143	124	159	143
Evaporation/evapotranspiration ratio	43	35	68	60

Source: adapted from Cooper et al. (1987)

causes the crop to flower during this optimum flowering window. The optimum flowering time is a compromise. On the one hand flowering needs to be late enough to avoid damage from frost and disease as well as produce adequate amounts of biomass to establish a high yield potential, but on the other hand early enough to minimise water stress, as measured by the lowest possible VPD.

Matching the time of sowing with the variety selection so that flowering occurs during the optimal flowering window is therefore an important management decision to improve yield and WUE.

GRDC has commissioned research into optimal flowering windows across Australia.

Late sowing reduces WUE for the following reasons:

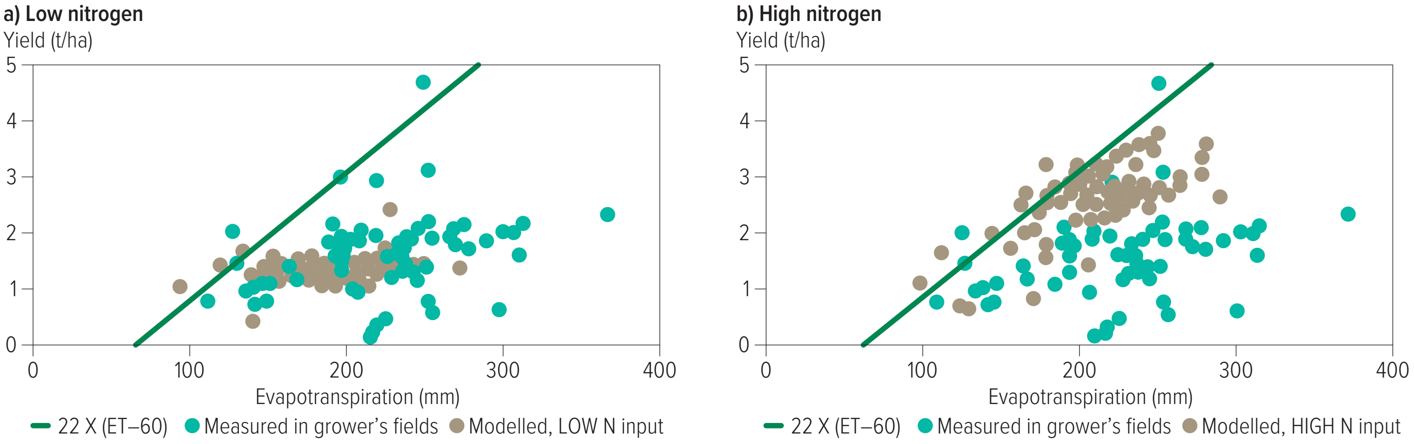
- delayed crop establishment;
- increased proportion of rainfall lost as soil evaporation;
- higher likelihood of heat stress; and
- reductions in biomass per unit water use associated with increasing VPD.

Is it important to align nutrition to water conditions?

Crop nutrition affects soil evaporation, crop biomass and root growth and canopy development. Table 6.2 shows the influence of fertilising on both WUE and yield.

Several studies indicate that nutrients play a critical role in interacting with water use and determining crop productivity (see Chapter 4) (Mazzarino et al., 1998). Nutrition is a costly input and risk management often leads to under-fertilisation (see Chapter 8) (Cossani et al., 2011; Monjardino et al., 2015; Monjardino et al., 2013; Roget & Sadras, 2003; Sadras et al., 2002; Sadras et al., 2016; Savin et al., 2015). In most cases, both nitrogen and water constrain crop production in low-rainfall environments where infertile soils are common and mineralisation is a small component of the nitrogen budget (Angus & Grace, 2017; Sadras et al., 2016). Deficient nitrogen levels restrict yields and deplete soil organic carbon, while excess nitrogen is economically wasteful and environmentally harmful, and in some cases can produce yield penalties (French & Schultz, 1984a; French & Schultz, 1984b; Sadras & Angus, 2006; Sadras & Lawson, 2011).

Figure 6.2: Measured (green symbols) and modelled (brown symbols) relationships between evapotranspiration and grain yield of wheat in the Mallee region of southern Australia under a) low and b) high supplies of nitrogen. The yield gap is the difference between the solid line and the actual and modelled yield shown at the points. Modelled yield using low inputs of nitrogen gives a similar result to the actual yields, with substantial yield gaps evident. Increasing the nitrogen inputs predicts a closing of the yield gap, showing that increasing N would bring the yield closer to the water-limited yield potential, demonstrating the interaction between nutrition and WUE.



Source: adapted from Sadras (2005)

The potential value of optimum nitrogen supply was illustrated in a study using crop simulation of more than 300 crops from the Yield Prophet® database.

Managing nitrogen so it was non-limiting to yield could potentially increase WUE by 12 per cent from 16.9kg/ha/mm with current grower practice to 19kg/ha/mm. Combining improved nitrogen nutrition with early sowing and high plant density increased WUE by a further 13 per cent to 21.4kg/ha/mm.

What is the optimal nitrogen application strategy?

Unless available soil nitrogen is very low, applications of nitrogen fertiliser can be deferred to later in the growing season without penalising grain yield. Figure 6.2 shows that not only can adding nitrogen improve yield and the efficiency of water use but strategic post-sowing applications can enhance this effect.

The strong interaction between moisture supply and nitrogen response and the desire to improve nitrogen use efficiency has seen a shift in nitrogen management to delayed or split applications of fertiliser from the conventional approach of applying the nitrogen at sowing.

As mentioned above, low nutrient availability reduces yield and WUE and increases the yield gap from the water-limited yield potential, which is currently approximately 24kg/ha/mm in southern Australia (Hochman et al., 2017; Sadras & Lawson, 2013).

The timing of supply of nitrogen can be used to manipulate canopy development, biomass production and water use. It can also be matched to the conditions of the growing season and provide greater flexibility in nitrogen management.

Some of the key principles to consider before using nitrogen to increase WUE can be summarised as:

- estimate the demand for nitrogen based on target yields and protein concentrations;
- estimate the soil-available nitrogen at the start of the season;
- monitor growing conditions, especially water availability through crop water status (for example, soil moisture monitoring (see Chapter 7); and
- adjust the timing of nitrogen applications to match supply of nitrogen to crop growth, targeting the critical yield-forming period leading up to flowering.

There are a range of tools growers can use to assist in planning a nitrogen strategy to maximise WUE, including the following:

- soil testing (see Chapter 2);
- PAWC characterisation (see Chapter 3);
- soil moisture monitoring (see Chapter 7); and
- tools and apps such as Yield Prophet® (see Chapter 7).

What is the best row spacing to optimise WUE?

Studies in wheat in a range of environments tend to show that increasing the row width will reduce yield and lower WUE. A series of experiments in Western Australia showed that there was an eight per cent decrease in yield for each 9cm increase in row width (Figure 6.3). Trials in Victoria and southern NSW found that maintaining row spacing at 30cm increased WUE by 6 to 13 per cent compared with 37.5cm row spacing in a wheat/canola sequence.

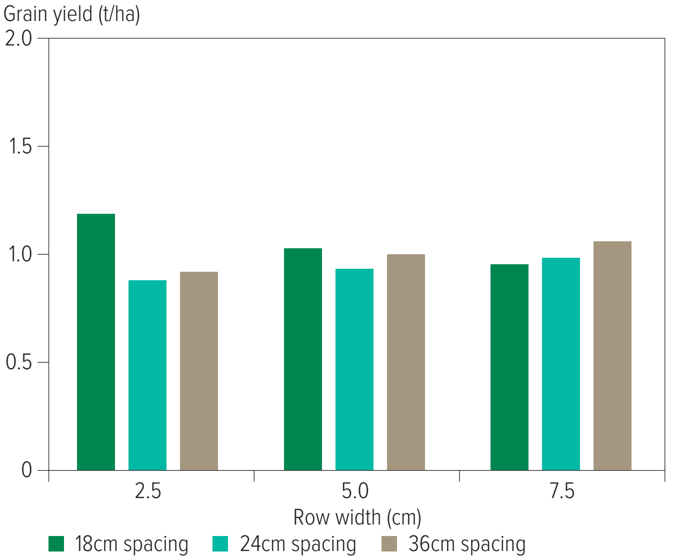
The causes of reduction in WUE are associated with higher soil evaporation as row width increases and the increased competition between plants within a row as row width increases.

Although increased row spacing can lead to higher soil evaporation and reduced WUE, the effect may not be important in all crops. For instance, in species with small canopies, altering row width has little effect on bare soil evaporation as the level of ground cover is low and minimally affected by row width (Sadras & McDonald, 2011).

In the case of pulses, grain yield responses to row width depend on species and seasonal conditions. However, in most cases there are either non-significant effects of row spacing or a reduction in yield with wider row spacing (Figure 6.4).

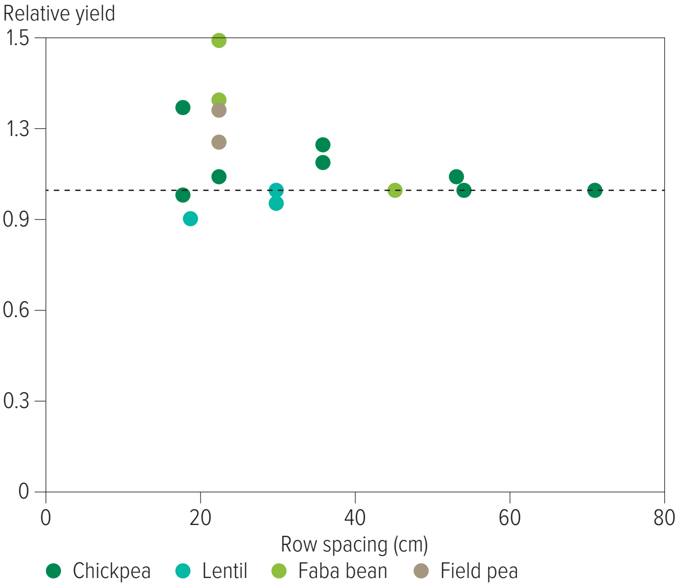
The selection of row spacing will therefore be a compromise between the potential reductions in WUE and the benefits of using wider rows in other aspects of crop management, such as weed and disease management, residue management and the ability to inter-row sow.

Figure 6.3: The effects of row spacing and the spread of seed within the row (row width) on the grain yield of wheat.



Source: adapted from Anderson et al. (2005)

Figure 6.4: Relative yield of chickpea, lentil, faba bean and field pea as consequence of changes in row spacing.



Source: adapted from Sadras & McDonald (2011)

If wide rows are preferable for other reasons, the reduction in grain yield may be mitigated by increasing the spread of seed within the row (seedbed utilisation), thereby reducing intra-row competition and minimising the yield penalty of wide rows (Anderson et al., 2005). This is shown in Figure 6.3 by the reduced penalty where 7.5cm row widths are used compared with 2.5cm widths.

Yield benefits, rather than penalties, are possible from wider rows in two specific situations: when crops rely on out-of-season rainfall or when the in-season rainfall is low. In both situations, the time taken for roots to grow out into the inter-row space rations the water use, preserving it for critical stages of development, and this benefit offsets the increase in soil evaporation (Scott et al., 2013).

Chapter 7: Using technology to improve water efficiency

What technology is available to maximise your rainfall?

CHEAT SHEET

- Technological tools are available to help improve growers' understanding of soil moisture, PAWC and spatial variability.
- Soil moisture monitoring is an invaluable tool to understand what is happening in the soil.
- A range of tools can be used to assess spatial variability including EMI surveys, NDVI and GRDC-supported apps.
- Soil moisture and spatial variability data can help with decisions on crop selection, variable-rate applications, fertiliser decisions, hay cutting and marketing.

Grain producers have numerous technologies that are available to assist with decision-making around soil water and its availability for producing crops and fodder. These technologies range from specific hardware that measures soil moisture to spatial mapping tools that can define soil types and water-holding capacity to apps that can model available water. Most of these technologies are specialised in that they are installed or delivered and supported by professionals.

IS SOIL MOISTURE MONITORING WORTHWHILE?

Although it is possible to estimate soil moisture based on experience and weather data, measured soil moisture can give a more accurate assessment, which improves the quality of information on which decisions are based. Measuring soil moisture with logging devices allows for data points to be collected and graphed and in turn examined so that historical information can assist with future projections of available soil moisture.

Soil moisture monitoring can give insights into the following questions:

- How deep has the rainfall or irrigation infiltrated over the course of a certain time?
- Where are crop roots actively extracting moisture from?
- How much residual moisture remains following crop senescence, that is, how much will be available for the next crop?

Key decisions made using soil moisture data include:

- when and what to plant based on how much stored soil moisture is available to emerging seedlings if there is only light rainfall post-planting;
- if stored soil moisture is low at seeding time, whether a crop with a lower CLL (see Chapter 3) should be considered, particularly in lower-rainfall areas;
- if soil moisture is at a reasonably high level deeper in the profile (>70cm deep), consider a crop type to extract that for late season grain fill;
- how likely a crop will achieve an economic response to a mid-season nitrogen application (see Chapter 6);
- as grain fill approaches, whether there is sufficient soil moisture for a target yield to be achieved;
- in high-rainfall regions, how close to saturation the soil profile is and potential issues with trafficability and crop degradation; and
- indications of likely grain quality issues (that is, screenings) and yield forecasting to help guide marketing decisions.

What is the best way to measure soil moisture?

Measuring depth

The key to implementing a moisture monitoring system is that the full root zone is captured in the monitoring. The rooting depth depends on a variety of factors including soil type, rainfall and crop selection. In some instances, physical barriers such as a hard rock layer or chemical barriers such as a boron layer can limit the rooting depth. Growers are advised to dig a profile pit and observe the depth to which crop roots have penetrated if they are unsure of their rooting depth range.

Regardless of the type of monitoring system chosen, a decision is required on how many sensors to install and at what depth through the root zone. A best practice approach is to measure at approximately 10cm-intervals through the entire root zone.

Capacitance probe

A capacitance probe contains multiple sensors, often at 10cm intervals, measuring soil moisture throughout the root zone. Most manufacturers of capacitance probes also have soil temperature sensors at each interval. The sensors use a process called frequency domain reflectometry or time domain reflectometry, which measures the electrical capacitance of the soil.

Capacitance probes need to be powered by a logging telemetry system. Typically, the capacitance probe is buried below the tillage depth out in the paddock and a cable is trenched back to a fence or laneway where the telemetry logger is situated. This way, the hardware is out of the way of machinery passes; it may also need to be protected from livestock interference with an enclosure.

When selecting a capacitance probe system, the user must decide what level of data collection and storage is required. The most simple, low-cost system will not have network connectivity and requires the user to plug into the logger and download the data on a laptop or via Bluetooth onto their phone.

For those growers who want to avoid downloading data, capacitance probes can be linked to an in-field telemetry unit that regularly transmits the data via a communication network to a hosting server. The data hosting organisation will often construct graphs of the data and growers can log onto a data hosting website to view their soil moisture trends at any time.

A capacitance probe system and telemetry unit can be purchased for approximately $4000.

If a telemetry system is installed with a capacitance probe, additional sensors can generally be added to the system. Many telemetry units have the capacity to add multiple additional sensors, including rainfall, temperature, wind speed/direction and relative humidity. These additional sensors complement a soil moisture probe as they can be used for monitoring weather conditions for the application of crop protection products, modelling disease risk, frost severity and fire behaviour risk at harvest time. Rain gauges can assist in gaining a comprehensive understanding of how the soil moisture and crops respond to rain.

In many cases, a grower will start with the purchase and installation of one soil moisture probe, which leads to the question of where the probe should be placed. If a weather station is part of the installation, often there are various elements to consider to get maximum value from the site.

Location

Soil moisture probes should be located:

- away from run-off water from a yard or track that could lead to increased readings that are not representative of the rest of the paddock;
- away from tree roots;
- accessible (within reason) from a track or fenceline in case the telemetry logger needs maintenance during the growing season;
- away from an area where there is high vehicle traffic or machine operations that may strike the telemetry unit;
- in a soil type that is representative of most of a farm. On farms with multiple soil types, it is preferable that a higher-yielding soil type is selected as these are the soil types that will typically give a greater return on investment in nutrition application; and
- if a weather station is included, at a site that is at least 100m away from trees, sheds and other obstructions so that wind speed and direction are not affected.

Some telemetry loggers will have the ability to plug in two or more soil moisture probes and have long cable runs (100m), which gives the ability to place a probe in adjacent paddocks that may have differing crop rotations or a different soil type such as dune/swale landscapes. This can also be a good way to share a site with a neighbour to reduce cost.

Interpretation of logged data from capacitance soil moisture probes can cause confusion for inexperienced users. There are many factors that affect infiltration and evapotranspiration in soils and sometimes the result on a soil probe graph can be counterintuitive to what a grower might expect.

EMI surveys: how can I understand variation across my property?

Electromagnetic imaging (EMI) soil surveys are performed with a device towed behind a ute or ATV that is used to map soil type change in a paddock. The data collected is then used to show variations in soil characteristics, which can delineate differences in PAW.

The device produces an electromagnetic signal that radiates through the soil. Conductive material in the soil will change the strength of this received signal that then shows areas of high and low conductivity in the paddock. This signal will bounce back and be detected by a receiver, with the strength varying based on the conductivity of the soil. Conductivity is driven by salinity, clay content and soil moisture so the resulting map needs to be examined to understand the soil factors at play.

Following an EMI survey, soil cores and sampling need to occur to interpret the results and establish what characteristics are driving the variability with conductivity. Methods for doing this will differ across the landscape and between service providers. Experienced providers will either classify zones and sample within these zones or, in some situations, it may be better to use a grid sampling pattern. The cost of soil sampling and analysis can be a restriction on obtaining a thorough analysis; more samples will provide a better picture of what is driving the conductivity variation but will also increase cost.

Soil core analysis can be performed to show the differences in sand/silt/clay percentages (particle size analysis) as well as other chemical constraints that may be present, such as salts. Service providers can use the analysis of soil cores to create zones of potential crop performance based on how much PAW may be available throughout the year. Having a soil moisture probe installed in differing soil zones based on EMI surveys can be a useful way to compare the differences in infiltration and evapotranspiration.

NDVI imagery: how can biomass information help make better decisions?

Normalised difference vegetation index (NDVI), and other remote sources of biomass imagery, has been shown to give a real-time picture of variations in crop growth by measuring the size and greenness of the canopy. With an increase in available satellite services and mobile app platforms to view current and historical NDVI images, growers are finding this layer of data to be useful for in-season decision-making.

NDVI and its related derivatives are driven by variations in crop greenness and biomass. There are multiple factors that can affect crop growth: poor germination, insect and disease pests, waterlogging, lodging as well as soil type characteristics that may be related to PAW and nutrient availability. If NDVI images are used for decision-making, then crop inspections to observe zones within the paddock are critical to understand the elements at play.

A grower can use NDVI imagery to define zones within a paddock that are affected by PAW, but this can only occur after crop scouting to confirm that there are no other factors impacting crop growth. Taking an NDVI image in a drier spring will likely show areas that are performing better due to increased access to soil water (for example, deeper loam) compared with areas that are not thriving due to less access to soil water (rocks, sand). Again, scouting and potentially soil sampling can confirm what is driving variability.

A step on from taking a single in-season NDVI image is to use multi-year images of a paddock and look at consistent patterns of variation. In many cropping regions of Australia, these historic images show regular patterns of crop growth and, as such, can be used to create crop yield performance maps when coupled with soil analysis to understand what is driving the variation.

Variable-rate technology: how can I make the most of soil water?

Variable application of seed and nutrition throughout the paddock has been adopted by many grain growers in Australia. There are differences across the country regarding the layers of spatial data that are used to create the application maps and there are many specialists to assist growers with creating these maps. Often, multiple layers of data are used to create the variable-rate application maps and may include EMI surveys, NDVI and historical yield maps.

As described in the preceding two sections, understanding what is driving soil type and crop biomass variation is critical before implementing a variable-rate application program. Where it is established that PAW content is driving variation in crop production zones, seed and nutrition rates can be matched accordingly.

What are some other useful tools to assist with decision-making?

Yield Prophet®

Yield Prophet® is an online crop production model designed by Birchip Cropping Group to present grain growers and consultants with modelled information about their crops, providing integrated production risk advice and monitoring decision support relevant to farm management. Yield Prophet® uses APSIM data to generate crop simulations and reports, with a fee charged per paddock.

A free tool, Yield Prophet® Lite, can provide basic modelling for growers to get started with using simulation tools.

Links: www.yieldprophet.com.au
www.yieldprophet.com.au/yplite

National Soil Moisture Information Processing System (SMIPS)

The National Soil Moisture Information Processing System (SMIPS) provides mapping predictions of daily available soil moisture to 90cm at a one-kilometre grid resolution. The daily soil water contents have been validated against a network of approximately 100 probes, mostly in south-east Australia. Further validation is ongoing.

In using the data, consider similar factors as documented for digital map predictions of DUL and LL in Chapter 3.

Link: shiny.esoil.io/SMIPS (turn off the Moisture Maps layer to navigate to a location of interest, then turn it back on)

National Variety Trials (NVT)

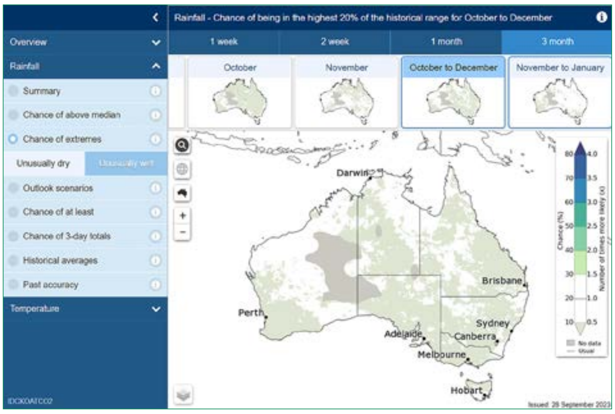
The GRDC National Variety Trials (NVT) program provides comparative information for commercially available grain varieties for 10 different grain crops across Australia. Growers can use the information from NVT, including regional variety sowing guides, to assess tolerance to different subsoil constraints, sowing windows and yield potential.

Link: nvt.grdc.com.au

What new forecasting products are available to help me assess climate risk?

The tools shown in Table 7.1 are all found within the Climate Outlooks tool on the BoM website.

Table 7.1: Recent products developed by the Bureau of Meteorology for growers.

DESCRIPTION	EXAMPLE
Forecast product **Chance of extremes** **Released November 2021** For these maps, ‘extreme’ has been defined as being among the driest, wettest, hottest or coldest 20 per cent of periods (weeks/months/seasons) from the climatological (historical) period (that is, deciles 1 and 2 (bottom 20 per cent) or deciles 9 and 10 (top 20 per cent)). The example shows an increased chance of wet conditions from October to December. **To access:** Choose ‘Chance of Extremes’ from the left hand menu.	**Extreme rainfall map.** This map shows the chance of having rainfall totals in the highest 20 per cent of the historical range (deciles 9 and 10) in the three-month period from October to December 2023. Issued 28 September 2023. **Grains industry example:** Top-dressing nitrogen, planning for disease management. 

DESCRIPTION

Operational product

Location-specific distribution bars

Released November 2021

These location-specific decile bars provide information for a single point. For example, the adjacent image shows that the chance of being very wet at Jabuk in 2022 had increased from 20 per cent to 55 per cent and the chance of being very dry decreased to five per cent.

Available for rainfall and maximum and minimum temperatures for the weeks, months and seasons ahead. This is one of the most popular products in consultation with producers and advisers.

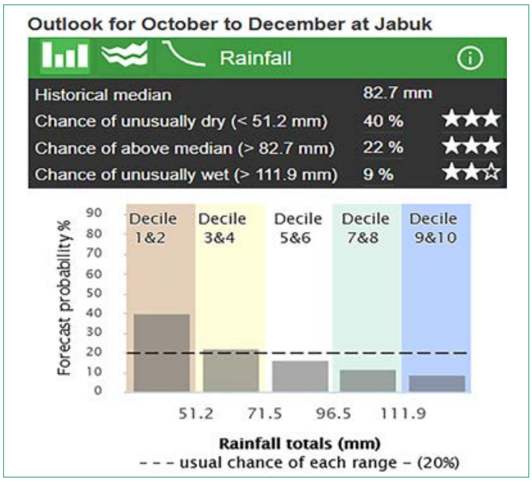
This gives a more complete picture of the forecast. An outcome in any one of the categories is still possible; however, there has been a revision in the odds that make it more likely that there will unusually wet conditions.

To access: Click on a location while viewing Climate Outlook maps.

EXAMPLE

Decile bars. Rainfall forecast in September 2023 for October to December in Jabuk in South Australian Mallee. The forecasts show the probabilities across five different decile ranges. The long-term average probability ('usual chance') for each category is 20 per cent.

Grains industry example: The increased chance of wetter deciles and decreased chance of drier deciles would increase confidence in top-dressing nitrogen-deficient paddocks. The 15 per cent chance of deciles 3 and 4 and 23 per cent chance of below median rainfall is a reminder of the downside risk.



Outlook for October to December at Jabuk

Historical median	82.7 mm	
Chance of unusually dry (< 51.2 mm)	40 %	★★★
Chance of above median (> 82.7 mm)	22 %	★★★
Chance of unusually wet (> 111.9 mm)	9 %	★★☆

DESCRIPTION

Operational product

Timeline Graph

Released June 2022

The third product to be released by the BoM is the Timeline Graph or Climagram. This produces location-specific time-series graphs showing the forecast of rainfall totals and maximum and minimum temperatures for the coming weeks and months. Past observations are also shown on the graph.

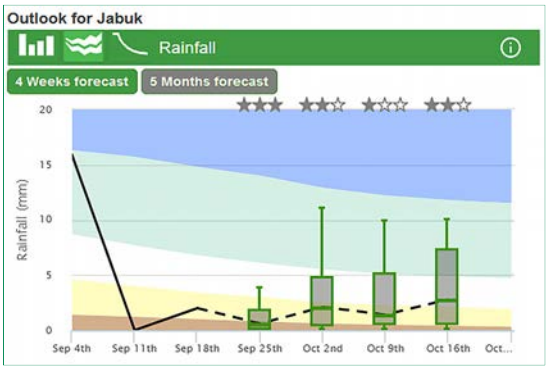
Insight from producers and advisers drove the creation of this product due to the strong desire to visualise the forecast as a time-series graph for a given location (rather than having to look at multiple maps). The forecasts of rainfall totals and temperatures (rather than departures from normal) facilitate flexibility for temperature/rainfall threshold-specific decisions.

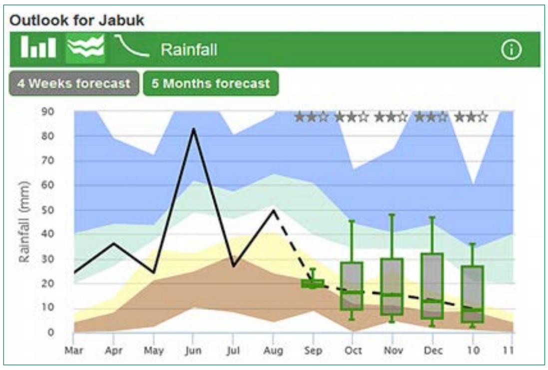
To access: While viewing a location-specific distribution bar, click on the icon underneath the location name.

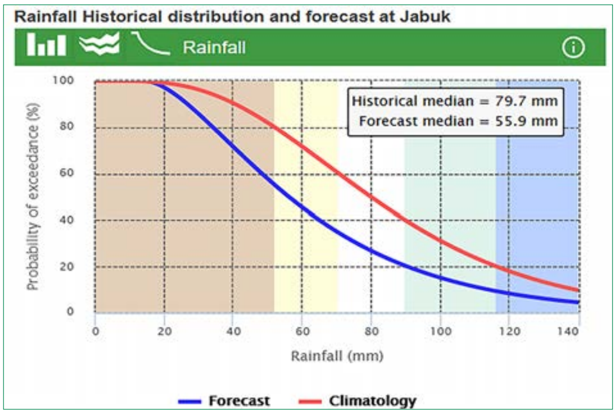
EXAMPLE

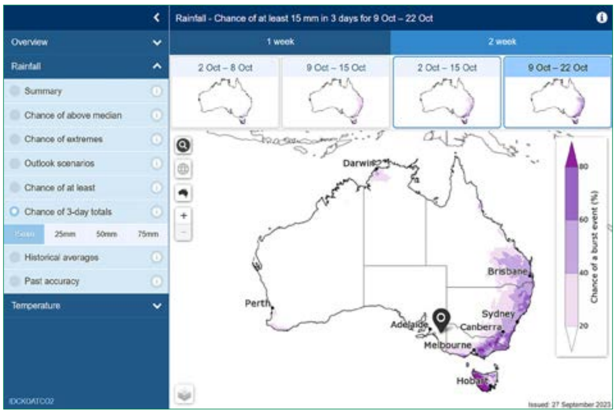
Climagram – rainfall outlooks for the coming weeks and months in Jabuk, September 2023. Time-series graph of observed (black solid line) and forecast (grey box plots) minimum temperature (y-axis) for consecutive weekly periods (x-axis) for Jabuk in SA Mallee. The box plots indicate the range in the expected outcomes from the forecasts. The coloured shading indicates the expected temperatures for that time of year (based on 1981–2010). The thresholds shown for the box plots and the shading are the 10th, 25th, 50th (median), 75th and 90th percentiles.

Grains industry example: This provides a forecast of wet and dry weeks and months. There is an indication that the dry July will be followed by a return to normal rainfall in August.





DESCRIPTION	EXAMPLE
Experimental product **Probability of Exceedance Graph** **Released June 2022** Probability of Exceedance (POE) graphs for rainfall were the fourth product chosen to be released by the BoM and are probably the most complex of the new tools. However, once understood, the overwhelming feedback was that this tool was valuable and would allow users to delve deeper into the forecast information. It forms part of a hierarchy of complexity of forecast tools. Insight from the producers in the reference groups indicated that for some users this information was too detailed, but for others, it could provide very useful input into their decision-making. **To access:** While viewing a location-specific distribution bar, click on the icon underneath the location name.	**Probability of Exceedance.** Example forecast for rainfall, showing the forecast (blue) and usual conditions (red) for October to December 2023 at Jabuk, SA. **Grains industry example:** A grower might set a threshold probability of exceedance for a set amount of rainfall to aid decisions on top-dressing or forward selling. The probability of exceedance graphs provide the likelihood of meeting this threshold. 

DESCRIPTION	EXAMPLE
Experimental product **Chance of three-day totals** **Released June 2022** The fifth product released by the BoM is the three-day rainfall accumulation (or burst) forecast, which is a map-based product and is available for multi-week forecasts (see adjacent image). The forecast product shows the likelihood (probability) of receiving a pre-selected threshold of rainfall over three consecutive days in the upcoming weeks or fortnights. **To access:** Choose ‘Chance of 3-day totals’ from the left hand menu.	**Three-day rainfall accumulation (burst) product.** A forecast map showing the probability of receiving an intense burst of rainfall over a short period of time in the fortnight 9–22 October 2023. **Grains industry example:** A grower might choose to spread urea before a rainfall burst or plan activities for a period with low rainfall. 

What apps can help manage soil water?

GRDC has supported the development of several apps to make it easier for growers to predict and maximise their soil water. These apps are free to use and can simplify the process of using soil water information to make informed decisions.

1. **CliMate: Climate analysis for decision-makers.** This app is designed for decision-makers who use soil water information along with probabilities of weather events to manage risk.
   Available for iOS and Android at climateapp.net.au
2. **SoilMAPP:** Provides access to national APSoil data as described in Chapters 2 and 3.
   Available for iPads at csiro.au/soilmapp
3. **Soil Water:** Estimates current and future soil water using BoM and local rainfall records.
   Available for iOS at soilwaterapp.net.au

CASE STUDY:
SOIL MOISTURE PROBES LEAD TO CONFIDENT DECISION-MAKING

Name: Matt and Danny Nihill
Location: Elmore/Runnymede, North Central Victoria
Farm size: 1100ha
Rainfall: 450mm
Soil types: Patches of brown self-mulching clays to duplex red soils

Since 2017, Matt Nihill and his cousin Danny have progressively invested in soil moisture and weather monitoring equipment across their farms to assist with management decisions.

"We started with soil moisture monitoring because we wanted greater control of some of the difficult decisions that determine profitability in dryland cropping," Matt said.

"The Victorian DPI has a soil moisture probe installed not far away from our farm but in a loamy soil, which is a very different soil type. While I found the information from the probe interesting, I knew it wasn't going to be very relevant to our heavier soil and red sodic subsoil."

Starting with two 120cm capacitance probes and telemetry systems in 2017, the Nihills expanded their systems to include paired probes across different soil types with 160cm probes to observe infiltration to a deeper profile.

With a range of soil and crop types, the data has been useful in understanding how deep rainfall events infiltrate into the subsoil and how this deep soil moisture is being used during grain fill.

"Since being installed, the soil moisture probes and weather stations have influenced a lot of our decisions," said Matt.

"For example, in 2018 we fallowed a heavy soil paddock for the first time in many years, based on low soil moisture, which gave us a great weed and disease break and in 2019 that paddock yielded 1.5t/ha more than the rest of the farm (see Chapter 5).

"In the same 2018 season, soil moisture data convinced us that cutting wheat for hay would be more profitable than leaving it for grain. On the flip side in 2022, the data gave us confidence to put in faba beans and canola instead of hay as break crops.

"In 2021, we applied a higher rate of late urea on our wheat, based on the moisture, and as a result we achieved higher grades than most local growers."

A key benefit has been monitoring for frost events.

"One season we had a late October frost that we didn't think was that bad, but the canopy sensor showed it was cold enough that damage was possible," Matt said.

Other benefits have included monitoring of canopy humidity to help with canola Sclerotinia fungicide decisions, choosing when to start and stop harvest for fire risk, and a later sleep-in on hay-baling days.

The Nihills have learned a lot about their soils and their capacity to support a crop through monitoring their soil moisture.

"We were surprised to learn how different the rooting depth can be in different soils," Matt said.

"We changed a couple of probes from 120mm to up to 180mm when we saw that our self-mulching soils would draw well beyond 120mm.

"In our sodic subsoils, I was pleasantly surprised to learn the roots could overcome difficult subsoil constraints and reach the 120mm sensor on a couple of occasions.

"In part, this finding encouraged us to try long season wheat and canola, to grow deep roots that can better cope with either waterlogging or dry conditions later in the season."

Along with soil moisture probes, the Nihills have used a range of tools to assess spatial variability including regular satellite NDVI, soil-type maps generated from soil grid sampling and subsoil maps.

"I've no doubt that having access to all this information has benefited the farm and helped me be a better agronomist," Matt said.

"It's that little extra confidence in decision-making that it brings to the table; confidence to chase yield potential when the going is good, and confidence to pull back or invest more in hay when it's dry."

Matt and Danny Nihill's weather station in North Central Victoria.

Photo courtesy Matt Nihill

Aerial photo of trenches showing where probes have been installed in two very different soil types.

Photo courtesy Matt Nihill

CASE STUDY:
TEN YEARS OF SOIL MOISTURE MEASUREMENTS PROVIDE CONFIDENCE

Name: **Jordan and Kylie Wilksch**
Location: **Yeelanna, Eyre Peninsula, SA**
Farm size: **3400ha**
Rainfall: **400 to 500mm**

Eyre Peninsula grower Jordan Wilksch was an early adopter of soil moisture probes back in 2009, which means he now has more than 10 years of soil moisture measurements to use in decision-making.

“We were interested to see what they would show us in regard to infiltration and how moisture was extracted out of the profile during grain fill,” Jordan said.

His years of experience with the data have taught him the cumulative benefit the data provides over multiple years.

“The data generated by soil probes can be useful in the first year they are installed, but the longer they are collecting data, the more valuable that data becomes,” he said.

“After a couple of years, we could see that the soil moisture probes could quantify how deep rainfall had infiltrated. After a couple more years, we gained confidence in how the data could show us where roots were active and how much moisture the crop was extracting from the profile during grain fill.”

He has been able to use the wide range of seasons to develop a good understanding of his soil’s PAWC, with the CLL being evident after seasons with dry springs and the DUL visible in years such as 2022, where soils were saturated. With these data points, Jordan now knows with a high level of confidence how much soil water there is in the profile across the year.

His journey has not been without challenges, leading to frustration with the early models.

“The reliability of the earliest soil moisture probes and telemetry systems was not great, but the more recent style of soil moisture probes is very reliable and gives consistent data year in year out,” he said.

The Wilkschs use the data for a range of decisions, including planting times, application of crop nutrition as well as giving a rough prediction of the crop yield potential based on soil moisture in spring.

“Particularly when coupled with a weather station, the data from the monitoring sites becomes an integral part of decision-making on our farm.”

Jordan and Kylie Wilksch’s soil moisture probe.

Photo source Leighton Wilksch.

Chapter 8: Managing risk

How to make tough decisions using uncertain weather forecasts

CHEAT SHEET

- Australian grain growers are faced with climate-risky decisions. The risks and rewards are often linked and growers must balance caution and optimism.
- Climate-risky decisions have always been informed by experience along with accessing the right advice. Growers today have more access to climate science and simulation modelling.
- The decision analysis technique is an established framework to handle uncertainty. In this chapter, we show how it can be used for nitrogen top-dressing.
- Australian grain growers are exposed to climate change, but they are also highly adaptable and can use skills from dealing with the variable climate for the early stages of climate change.

Why is climate risk management important?

Compared with most of their competitors, Australian grain growers face higher climate variability with less assistance from government. In recent years, the sharp increase in costs combined with volatile grain prices have made enterprises even more exposed to poor seasons.

At the same time, there is ongoing pressure to make the most of good seasons. Climate-risky decisions present a substantial challenge to Australian grain growers, but growers can draw on:

- their own experience;
- research, development and extension (RD&E) from field tests;
- historical climate records;
- access to output of simulation models; and
- frameworks such as the decision analysis technique.

The tactics to manage climate risk are the same tactics included in most best practice methods used by Australian grain growers. Examples include controlling weeds during fallows (see Chapter 5), stubble retention (see Chapter 5), optimum flowering windows (see Chapter 4), and maintaining good rotations (see Chapter 5). Beyond the paddock level, growers manage the risk of dry seasons with diversification on-farm (livestock and crops), off-farm and the use of income smoothing such as Farm Management Deposit Bonds.

All these practices tend to be good decisions to make whatever the coming season. That does not mean that the outcomes are insensitive to climate. The benefit of no-till and controlling fallow weeds will be more apparent in poor seasons than good seasons (see Chapter 5). But even though the outcome is sensitive to climate, uncertainty about the coming weather does not change the advice or decision. Therefore, these are not climate-risky decisions.

Key climate-risky decisions include:

- choosing the appropriate rate of nitrogen top-dressing;
- deciding when to buy or sell sheep;
- deciding the area to sow of a higher-risk crop;
- deciding whether to spray for foliar disease; and
- deciding whether to spend money on extra harvest resources such as labour or contract services.

Much of this chapter addresses climate risk management using the rate of nitrogen fertiliser on grain crops as an example.

How will historical data and climate science help me make decisions?

Historical data

Australian grain growers have long-term rainfall records that are the envy of most countries.

An example of the extensive historical record that shows the variability of growing season rainfall (April to October) for Wagga Wagga arranged as a time-series graph is presented in Figure 8.1. The year-to-year variability is clear, with the runs of good seasons and poor seasons, including the Millennium drought (2002 to 2009) and the difficult years of 2017, 2018 and 2019.

Deciles (Figure 8.2) are the language of climate risk used by many growers and agronomists, and categorises seasons into 10 groups based on how much rainfall occurs. For example, a decile 1 season features rainfall greater or equal to one out of 10 years, so is particularly dry, while decile 5 rainfall is equal to or greater than five out of 10 years, so is average. A season can be described as “a bit above average but not an exceptionally good season”, or a decile 7 season. Decile 7 immediately conveys that for that location, six years in 10 have been drier, one year in 10 has been similar and three years in 10 have been wetter. Deciles put a season in context and, as argued later in this chapter, they can also be used to look forward and inform climate-risky decisions.

Climate science

The history of European farming in Australia includes many unsuccessful attempts to find cycles and patterns in the droughts and floods. Rather than relying on cycles in the rainfall record, the science of seasonal climate forecasting has identified major climate drivers in patterns of sea surface temperatures such as El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). Figure 8.3 shows the same information as the growing season rainfall for Wagga Wagga as in Figure 8.1, but with the phase of drivers associated with wetter conditions (La Niña and IOD negative) coloured in shades of blue and phases associated with drier conditions (El Niño and IOD positive) in shades of red. Years with no strong climate drivers are coloured grey.

Many more experienced growers recall the drought of 1982, but only oceanographers and a few atmospheric researchers knew this was an El Niño. No one was aware in 1914 that the worst drought on record was an El Niño. By 2019, climate science had

Figure 8.1: Time series of growing season (April to October) rainfall 1900 to 2022 for Wagga Wagga.

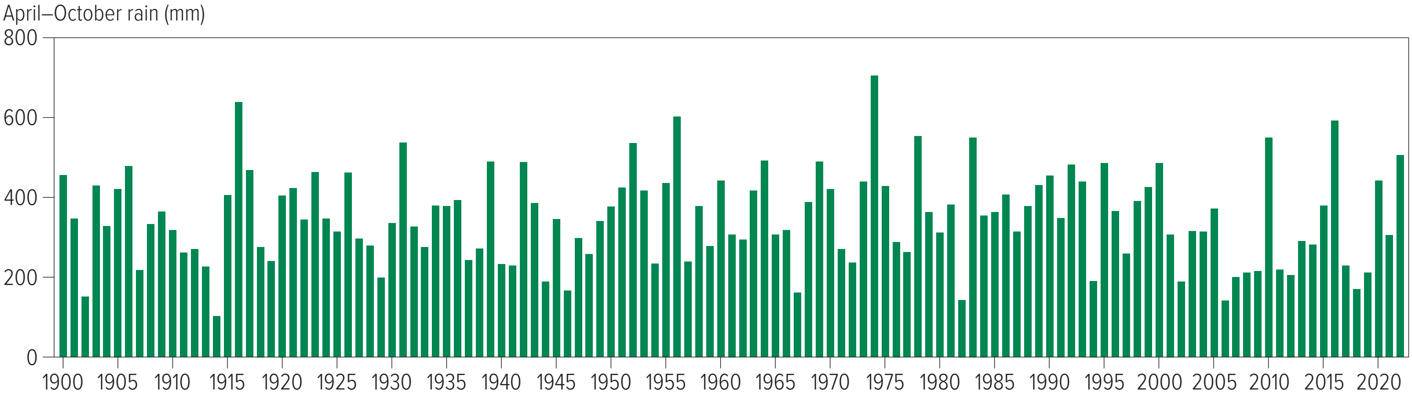


Figure 8.2: Data from Figure 8.1 (Wagga GSR) ranked from lowest to highest with deciles shown.

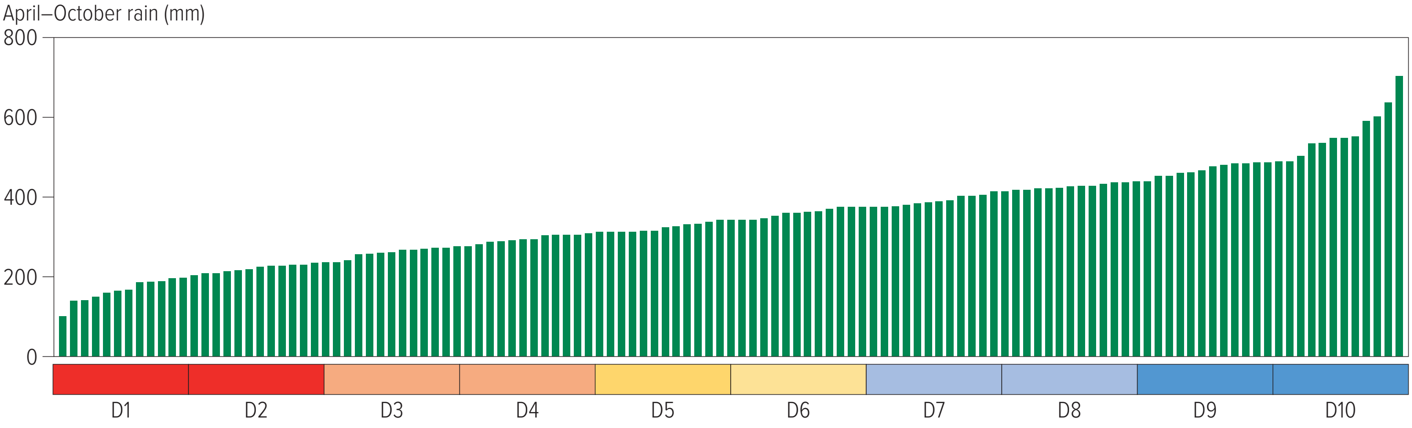


Figure 8.3: Data from Figure 8.1 coloured by phase of climate driver.

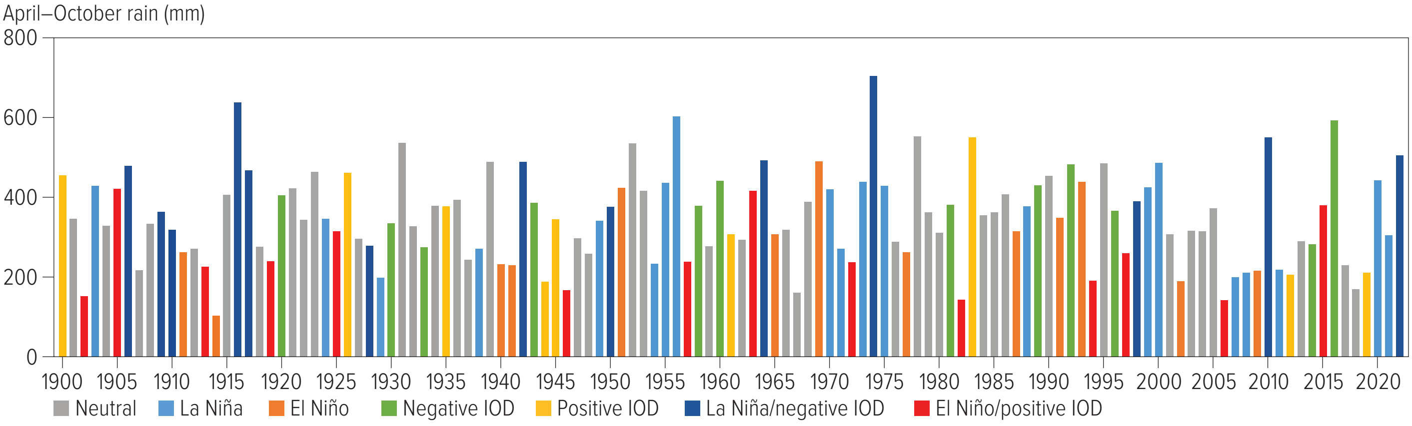
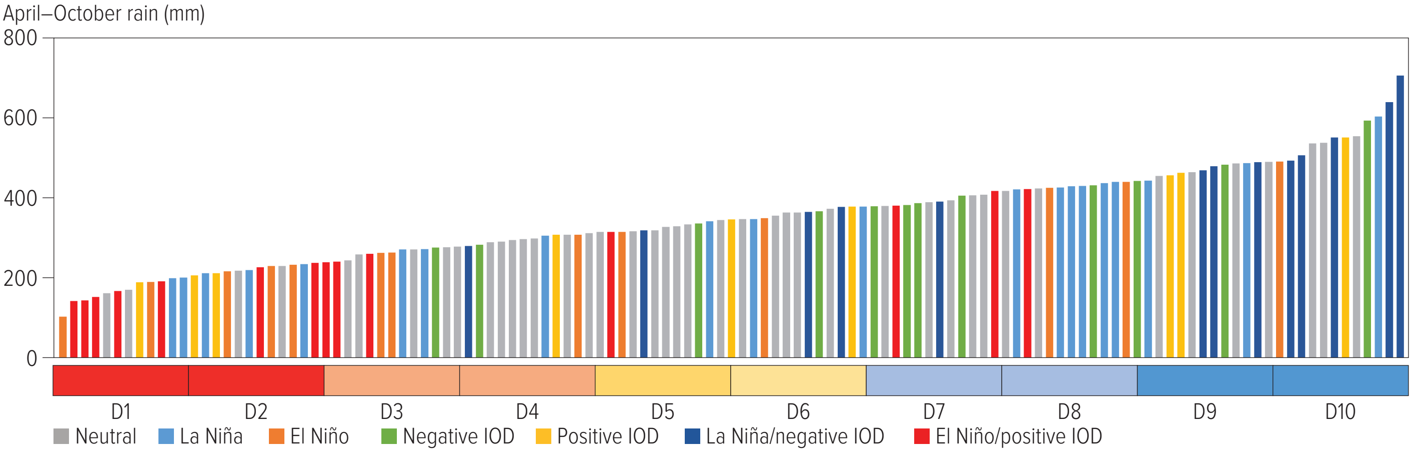


Figure 8.4: As per Figure 8.3 but ranked from lowest to highest. Bars coloured by phase of climate driver with deciles shown below.



become commonly communicated by the media. Many growers were aware that the dry conditions and bushfires in 2019 were linked to the strongest positive IOD on record and even more knew of the triple La Niña of 2020, 2021 and 2022.

Combining the two

Figure 8.4 shows Figure 8.3 sorted from the lowest to highest rainfall. There is a general pattern of more red at the dry end and more blue at the wet end, but it is noteworthy that there are some blue bars in the dry end and some yellow and red bars in the wet end. This graph also shows that it is a mistake to associate the years with no strong climate driver as average rainfall. The grey bars are scattered from the dry to the wet end.

The same data as Figure 8.4 can be presented in horizontal bars for a range of sites including Wagga Wagga (Figure 8.5). In all the years, there is an equal chance of decile 1 to decile 10. By definition, the chance of being in the driest two deciles is 20 per cent. In El Niño or positive IOD years, the odds at Wagga Wagga more than double from 20 per cent to 50 per cent. In La Niña years, the odds of being in the lowest two deciles reduce to less than 10 per cent and in the 25 negative IOD years, there have been no years as dry as the lowest two deciles.

There is a similar pattern of an increase in the chance of the wetter (blue) deciles in La Niña and negative IOD years and decrease in El Niño and positive IOD years. Figure 8.5 shows that the impact of ENSO and IOD are stronger in the northern and southern regions than the west. Although ENSO is often associated with the northern region, the shifts in the odds at Roseworthy in South Australia for the different climate drivers is quite similar to Dalby and Moree in the northern region.

Regions that have an impact from ENSO and IOD tend to have higher variability, but also higher predictability from seasonal climate forecasts.

Growers have contributed to improving climate forecasts

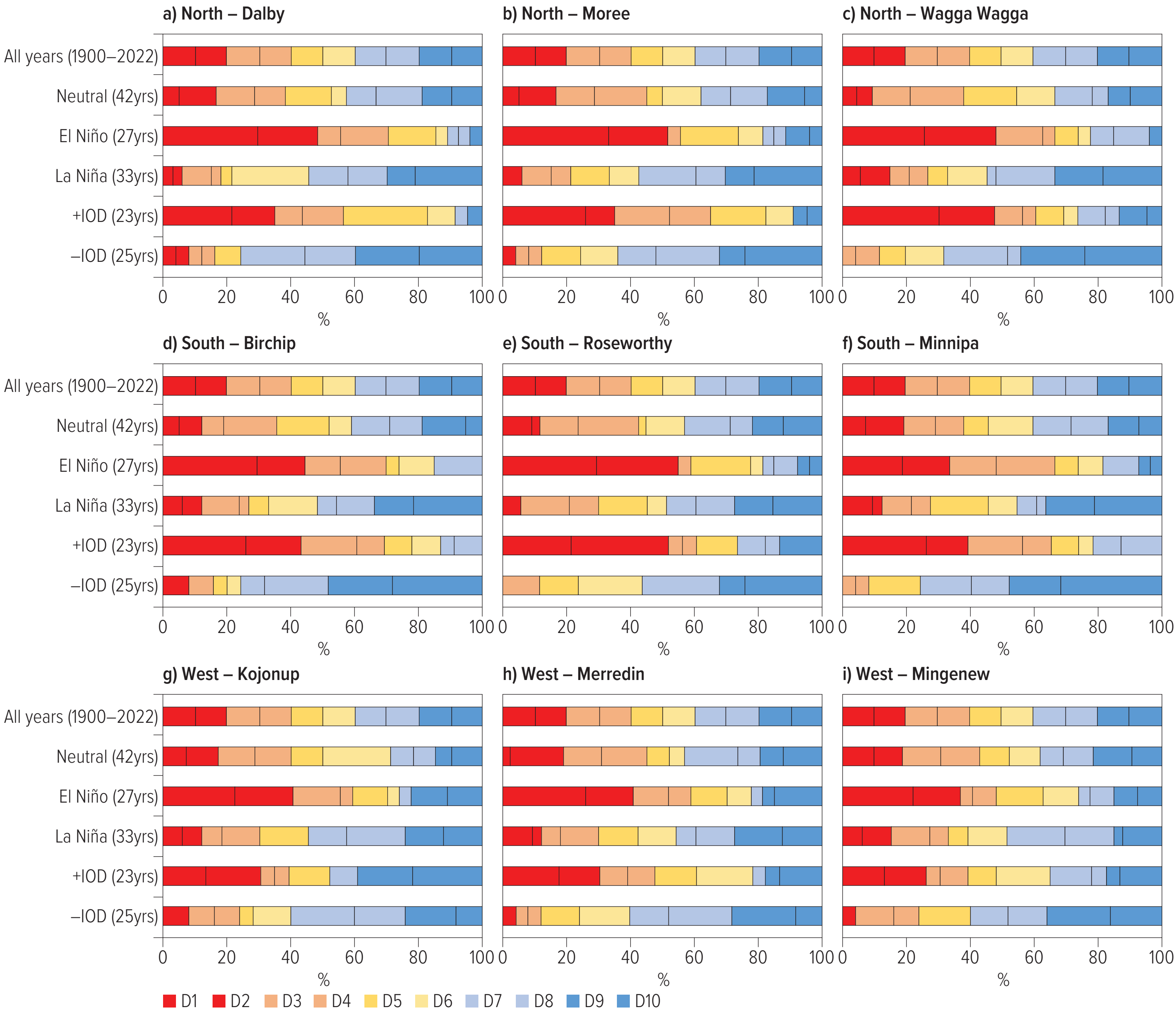
Until recently, seasonal climate forecasts from the BoM have only been expressed as the per cent chance of exceeding median rainfall or temperature. Grain growers have pointed out that there is a big difference between a season that is a few millimetres wetter or drier than the median and extremely dry or wet seasons; the middle deciles are easy to manage compared with the extremes. Forecasts of the chances of the driest or wettest, coldest and warmest two deciles have been developed as part of a recent project, ForeWarned is ForeArmed (FWFA), funded by the Australian Government Department of Agriculture, Water and the Environment's Rural R&D for Profit program with co-investment from 14 project partners including GRDC and SARDI. A grains industry reference group with GRDC panel members from each of the three regions and GRDC staff have reviewed products and provided feedback. See Chapter 7 for examples of the forecast products that were released in November 2021 and June 2022.

Seasonal climate forecasts will continue to improve along with the presentation and level of information. Nevertheless, there are theoretical reasons to believe that predictions at the seasonal time scale will never be as accurate as short-term weather forecasts. Seasonal forecasts will remain as shifts in probabilities with information based on an educated guess, which is challenging to use in decision-making. One way forward that we describe in the next section is to be clearer about the climate-risky decisions using the decision analysis technique.

How do I weigh up my options for an uncertain problem using the decision analysis technique?

Although they face a unique spectrum of risks, grain growers are not alone in having to make important business decisions with incomplete information. There is a long and ongoing history of research into the psychology and economics of judgement

Figure 8.5: Horizontal bars show the likelihood of being in each decile for different climate drivers.



and decision-making under uncertainty. There are many ways to approach decision-making, but the applied economic discipline of the decision analysis technique is a tested framework to map out a decision and to adjust assumptions to explore the long-term risks and returns.

The decision analysis technique can help to clarify what choices are available and to think through the range of outcomes for each choice. Slowing down and thinking through the logic of a decision is a way to minimise a problem and identify the major sources of uncertainty and the value of information to reduce this uncertainty. This process can improve the conversations between growers and experts about the choices they face and how this interacts with the variable climate. A principle of decision-making under uncertainty is to distinguish between a good decision (made with the best available information) and what turned out to be a lucky or unlucky decision. The decision analysis technique is an effective way to pull together what is known at the time, including what we know about the uncertain climate.

The decision analysis technique involves the following key steps:

- **problem formulation:** clearly define the decision required and the objectives that need to be considered;
- **identification of options:** identify all possible options. For example, different rates of fertiliser or whether to sell or buy sheep;
- **identification of uncertainty:** identify the source of uncertainty. For example, the rainfall decile;
- **assessment and measurement of outcomes:** determine and, where possible, quantify potential outcomes for each alternative and uncertainty. For example, this may be the yield, or the profit that would result from each decision in different eventual deciles;
- **probability assessment:** based on the probabilities of the different deciles, assess the most likely result from each option. As an example, see the next section (How can I manage nitrogen fertiliser as a climate-risky decision?); and
- **decision:** based on the assessment, and your risk tolerance, make your decision.

In the following section, we apply the decision analysis technique to the climate-risky decision of nitrogen top-dressing.

How can I manage nitrogen fertiliser as a climate-risky decision?

This section demonstrates how climate forecasts can be incorporated into the decision of how much nitrogen to apply to a crop. Using the above steps in the decision analysis technique, the problem formulation would be: Should I add a high or low rate of nitrogen to a wheat crop? The options and uncertainty are well defined as the nitrogen application rate and the rainfall decile.

A key aspect of the decision is to accept that regret is unavoidable when making decisions in an uncertain world. It can be useful to mentally weigh the regret of caution (missing out on an opportunity) against the regret of optimism (applying more nitrogen than was needed that year). Most of us struggle to juggle four futures in our head, but this is easy to do on paper or a spreadsheet. Figure 8.6 presents a simple decision tree for the nitrogen decision. This decision will be influenced by an accurate forecast indicating the chance of above and below-average rain.

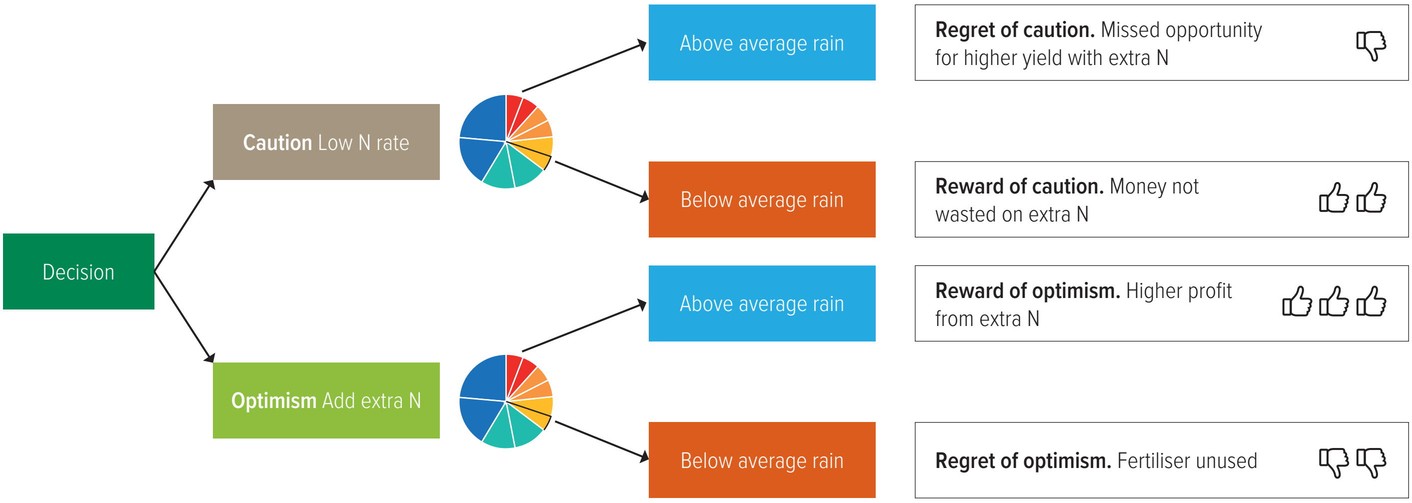
Applying the decision analysis technique to nitrogen as a risky decision

Obviously, we would prefer to know exactly how the season will finish so that we know what decile to aim for. Instead, we are presented with a risky decision and can take a cautious approach aiming for below-average rainfall and be under-fertilised for deciles 6 to 10 or to take an optimistic approach and aim for above-average rainfall and be over-fertilised in deciles 1 to 4.

Seasonal forecasts are improving, but they remain an uncertain area of science and therefore we need to consider the consequences of a false alarm or the failure to warn of dry conditions.

To proceed through the decision analysis technique, we must assess and measure the outcomes for high or low fertiliser rates at different deciles.

Figure 8.6: Simple decision tree identifying options and outcomes for nitrogen fertiliser on wheat.



Assessing and measuring outcomes for a single decile

Although an active area of research, much is known about the response of grain crops to nitrogen under Australian conditions (see Chapter 4). The results of past research have been applied in practice through nitrogen budgeting using the robust simple rule of 40kg N required per tonne of wheat. The 40kg N rule is based on one tonne of wheat removing about 20kg N, assuming the nitrogen fertiliser recovery is about 50 per cent. When nitrogen cost approximately $1 per kilogram, the payoff from investing $40 as fertiliser on a wheat crop for an extra tonne of grain was an excellent investment.

Even when the cost of urea is high relative to the price of wheat, there are positive returns on investment of about 50 per cent fertiliser recovery (Table 8.1). For example, if urea is $1500 per tonne and wheat is $300 per tonne, at 50 per cent efficiency there is $2.30 return for every $1 invested. As grain growers are aware, the risk lies in lower fertiliser recovery. This risk has an impact on grower returns. The GRDC National Paddock Survey showed that one of the main reasons for low water use efficiency was growers being too conservative with the supply of nitrogen.

Fertiliser recovery and nitrogen carryover also need to be considered. Low spring rainfall reducing crop demand for nitrogen is the most common reason for low fertiliser recovery on most soils in most of the grainbelt. Low nitrogen fertiliser recovery can also occur due to loss from volatilisation at application or leaching and denitrification in wet seasons on some soils, but these losses are rare and usually negligible in the widespread nitrogen budgeting approach.

Nitrogen fertiliser recovery is usually calculated as recovery in the year of application. The strong evidence of at least some of the unused nitrogen being available for subsequent years (Smith et al., 2019; Meier et al., 2021) can lead to a situation where recovery might be 30 per cent in year one and 20 per cent in year two (Hagen & Bell, 2022).

Accounting for the carryover can be complicated by considering different loss pathways, and the chance that a dry year might be followed by a run of poor seasons.

The implication of nitrogen carryover for the downside risk of nitrogen is an important consideration that we will return to later in this section.

Table 8.1: Benefit:cost ratio for a combination of nitrogen costs, wheat prices and N fertiliser recovery. Any value equal to or below 1 is in bold and represents a breakeven point or a loss. The application rate of $10/ha is not included in these figures.

		Increased N cost →												
Urea $/t		450	1000	1500	2000	$ Urea/ $ wheat	N fertiliser recovery							
N $/kg		$0.98	$2.17	$3.26	$4.35		5%	10%	20%	30%	40%	50%	60%	70%
		Wheat price $/t					Benefit:cost ratio ($ return for $ invested in N)							
Decreased price of wheat ↓	1t wheat = 1t urea	**450**	**1000**	**1500**	**2000**	1.0	1.2	2.3	4.6	6.9	9.2	11.5	13.8	16.1
		375	833	1250	1667	1.2	**1.0**	1.9	3.8	5.8	7.7	9.6	11.5	13.4
		321	714	1071	1429	1.4	**0.8**	1.6	3.3	4.9	6.6	8.2	9.9	11.5
		281	625	938	1250	1.6	**0.7**	1.4	2.9	4.3	5.8	7.2	8.6	10.1
		250	556	833	1111	1.8	**0.6**	1.3	2.6	3.8	5.1	6.4	7.7	8.9
	2t wheat = 1t urea	225	500	750	1000	2.0	**0.6**	1.2	2.3	3.5	4.6	5.8	6.9	8.1
		205	455	682	909	2.2	**0.5**	**1.0**	2.1	3.1	4.2	5.2	6.3	7.3
		188	417	625	833	2.4	**0.5**	**1.0**	1.9	2.9	3.8	4.8	5.8	6.7
		173	385	577	769	2.6	**0.4**	**0.9**	1.8	2.7	3.5	4.4	5.3	6.2
		161	357	536	714	2.8	**0.4**	**0.8**	1.6	2.5	3.3	4.1	4.9	5.8
	3t wheat = 1t urea	150	333	500	667	3.0	**0.4**	**0.8**	1.5	2.3	3.1	3.8	4.6	5.4
		141	313	469	625	3.2	**0.4**	**0.7**	1.4	2.2	2.9	3.6	4.3	5.0
		132	294	441	588	3.4	**0.3**	**0.7**	1.4	2.0	2.7	3.4	4.1	4.7
		125	278	417	556	3.6	**0.3**	**0.6**	1.3	1.9	2.6	3.2	3.8	4.5
		118	263	395	526	3.8	**0.3**	**0.6**	1.2	1.8	2.4	3.0	3.6	4.2
	4t wheat = 1t urea	113	250	375	500	4.0	**0.3**	**0.6**	1.2	1.7	2.3	2.9	3.5	4.0
		107	238	357	476	4.2	**0.3**	**0.5**	1.1	1.6	2.2	2.7	3.3	3.8
		102	227	341	455	4.4	**0.3**	**0.5**	**1.0**	1.6	2.1	2.6	3.1	3.7
		98	217	326	435	4.6	**0.3**	**0.5**	**1.0**	1.5	2.0	2.5	3.0	3.5
		94	208	313	417	4.8	**0.2**	**0.5**	**1.0**	1.4	1.9	2.4	2.9	3.4
	5t wheat = 1t urea	90	200	300	400	5.0	**0.2**	**0.5**	**0.9**	1.4	1.8	2.3	2.8	3.2

Measuring outcomes across all deciles

Climate is a major source of uncertainty, but thanks to the use of deciles and robust nitrogen budgeting rules we can reduce the uncertainty and calculate the risk.

Nitrogen budgeting is widespread, but generally it is commonly applied to only a single target yield. Growers often aim for decile 3 if cautious, decile 7 or 8 if very optimistic, or decile 5 for the average. Instead, making the risky decision can be helped by considering the regret of caution (aiming for decile 3 and the season is decile 7) and the regret of optimism (aiming for decile 7 and the season is decile 3).

Figure 8.7a shows the water-limited and nitrogen-limited yield across deciles of rainfall for a particular medium-rainfall site. Each site will have a different line for the water-limited yield depending on the starting soil water and rainfall and a different nitrogen-limited yield depending on starting soil nitrogen. This graph is effectively the nitrogen budget repeated for each decile. The water-limited yield (blue line) increases from less than 1t/ha in a poor season to more than 5t/ha in a good season. In the low-rainfall zone, these numbers might be adjusted to 0.5t/ha to 4t/ha and in high rainfall 4t/ha to more than 9 to 10t/ha.

In Figure 8.7a, the nitrogen-limited yield (green line) is the same as the water-limited yield under very dry conditions, but wetter than decile 1. There is an increasing gap between the yield without nitrogen fertiliser (nitrogen-limited yield) and with adequate additional nitrogen fertiliser (water-limited yield). The gap between the water and nitrogen-limited yields is the source of the risky decision. The table below the graph shows the gap between the two lines as wheat yield and as fertiliser requirement. Figure 8.7b is a case with much higher starting soil nitrogen, in which the nitrogen-limited yield tracks the water-limited yield except for the wettest deciles.

A grower faced with Figure 8.7a has a climate-risky decision of how much nitrogen fertiliser to use, whereas the grower who has improved soil fertility through a successful legume pasture phase (Figure 8.7b) is unlikely to add any fertiliser. That does not mean that the grower growing a crop after a pasture phase is indifferent to how the season turns out; they will still face disappointment in a poor season, but they do not face the regret of optimism, compared with the grower who applied nitrogen. Where the chance of regret is limited, the decision becomes less risky.

Probability assessment

The representation of nitrogen application as profit per hectare of each decile is a powerful way to assess the risk and return.

Growers and agronomists can develop the nitrogen profitability curves shown in Figure 8.8 using the method shown in 'How to develop your nitrogen profitability curve' (page 55) for a particular site to assist with the decision on how much fertiliser to apply.

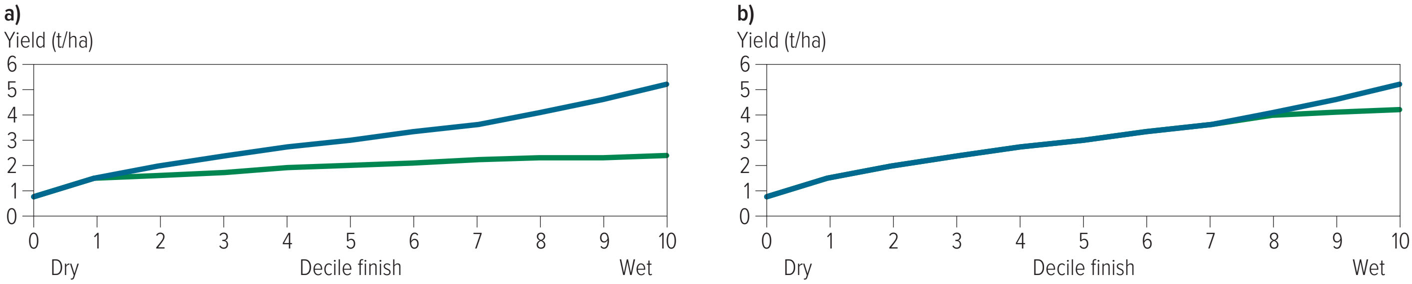
The top graph in Figure 8.8 presents the nitrogen profitability curve from aiming for a decile 3 season (green line) or decile 7 season (brown line) if the odds of all deciles are equal. The average profit of all deciles is $238/ha if aiming for decile 7, compared with $149/ha if aiming for decile 5. However, aiming for decile 7 increases the losses in very dry seasons, so a risk-averse grower may prefer the $149/ha with less risk. The middle and lower graphs in Figure 8.8 present the same information, but shifted left or right for seasons where the odds of each decile are not even.

A forecast for only 30 per cent chance of exceeding the median, for example an El Niño type forecast, shifts the curve to the right. The profit outcome for a given decile is unchanged; a forecast does not influence the outcomes, only changes the likelihood.

This forecast extends the downside and narrows the upside of aiming for decile 7. Under these assumptions, aiming for decile 7 leads to a probability weighted average return of $157/ha compared with $119 for decile 3, so more profitable, but much closer, and therefore growers may not consider the upside worthy of the increased risk.

A forecast of 70 per cent chance of exceeding the median (for example, a negative IOD or La Niña) shifts the curve to the left, increasing the likelihood of the wetter deciles. The probability weighted average return per hectare is much higher for all strategies under the increased chance of wetter conditions. Unsurprisingly, the higher rate of nitrogen is even more beneficial.

Figure 8.7: a) Stylised water and nitrogen-limited yield for different deciles of spring rainfall. Starting soil nitrogen about 64kg N/ha (1.6 x 40kg N/ha). b) As per a) except for a site with high starting soil nitrogen where the green line tracks the blue line for most deciles.



a)

	0	1	2	3	4	5	6	7	8	9	10
WL yield	0.8	1.5	2.0	2.4	2.8	3.0	3.3	3.6	4.1	4.6	5.2
NL yield	0.8	1.5	1.6	1.7	1.9	2.0	2.1	2.2	2.3	2.3	2.4
Gap	0.0	0.0	0.4	0.7	0.9	1.0	1.2	1.4	1.8	2.3	2.8
N req	0	0	16	28	36	40	48	56	72	92	112

b)

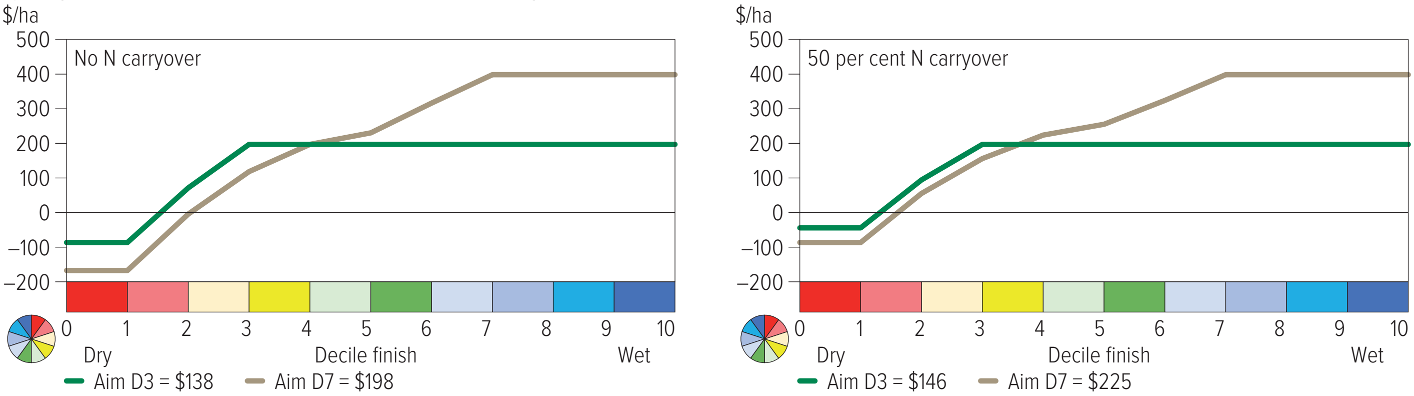
	0	1	2	3	4	5	6	7	8	9	10
WL yield	0.8	1.5	2.0	2.4	2.8	3.0	3.3	3.6	4.1	4.6	5.2
NL yield	0.8	1.5	2.0	2.4	2.8	3.0	3.3	3.6	4.0	4.1	4.2
Gap	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.5	1.0
N req	0	0	0	0	0	0	0	0	4	20	40

Any nitrogen budgeting exercise requires an assumption of in-crop mineralisation (depending on the soil and organic matter). An approximate rule is soil nitrogen mineralisation (kg N/ha) = soil organic carbon (%) x growing season rainfall (mm) x 0.15. Some researchers exclude in-crop soil nitrogen mineralisation from the calculation as the nitrogen will have to be replaced in future seasons.

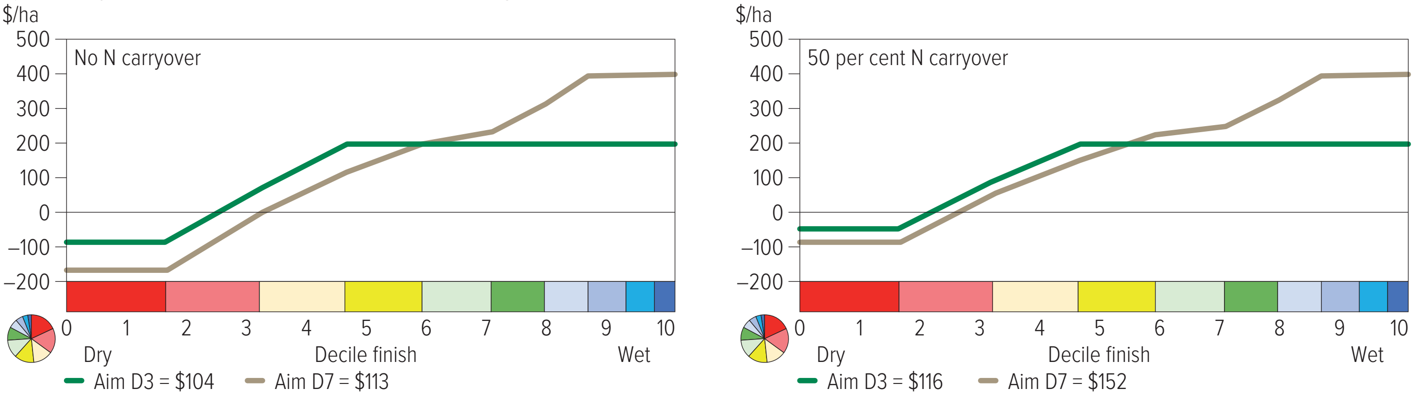
Source: Peter Hayman

Figure 8.8: Profit by deciles curves when taking more cautious choice of decile 3 (28kg N/ha) or more optimistic choice of decile 7 (60kg N/ha). Top row using long-term climate odds, second row El Niño type seasonal outlook (30 per cent chance of exceeding the median) and bottom row a La Niña type seasonal outlook (70 per cent chance of exceeding the median).

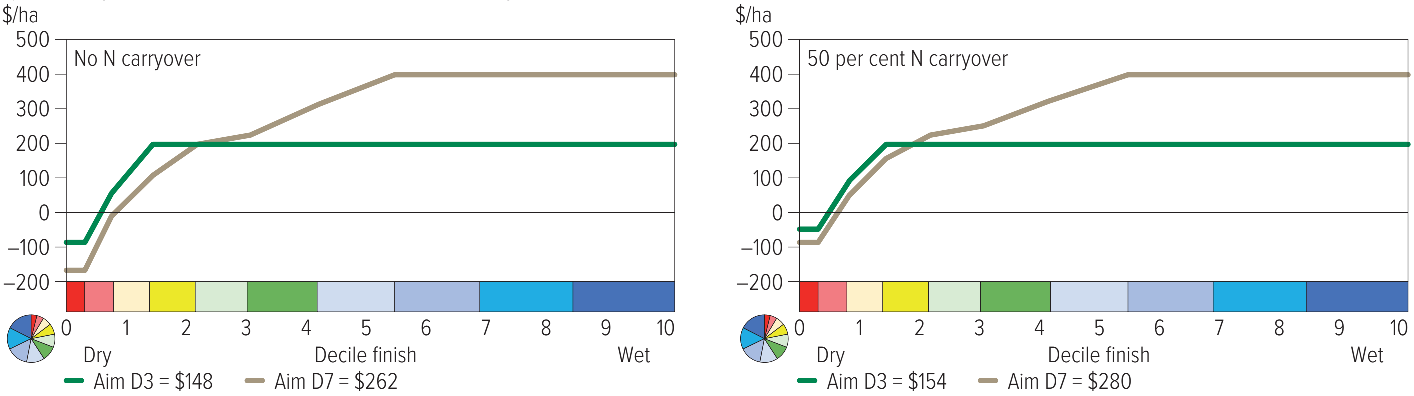
a) Long-term climate odds: 50 per cent chance of exceeding median.



b) El Niño type forecast: 30 per cent chance of exceeding the median.



c) La Niña type forecast: 70 per cent chance of exceeding the median.



HOW TO DEVELOP YOUR NITROGEN PROFITABILITY CURVE

Step 1: Create a water-limited yield and nitrogen-limited yield curve

The first step is to develop your own version of Figure 8.7.

Yield Prophet® provides access to the sophisticated cropping system model APSIM with a version of the water-limited and nitrogen-limited yield. Alternatives to Yield Prophet® include Yield Prophet® Lite, or many growers and agronomists have their own nitrogen budgeting spreadsheets (see Chapter 7).

Any grower or agronomist who calculates a nitrogen budget for a paddock has calculated at least one set of the blue (and green) dots in Figure 8.7.

By repeating yield modelling for deciles 1, 3, 5, 7 and 9, growers can re-create Figure 8.7.

Step 2: Model your nitrogen scenarios

The next step is to model the outcome for a given rate of nitrogen in dry deciles, average deciles and wet deciles. The example in Figure 8.9 is a scenario where the grower is fertilising at 60kg N/ha, aiming for a decile 7 year (with a 1.5t/ha gap between the nitrogen limited yield of 2.2t/ha and the water-limited yield of 3.7t/ha).

Dark green indicates nitrogen used by the crop, light green indicates unused nitrogen and brown indicates the extent of under-fertilisation or missed opportunity of nitrogen that could have been used in the seasons with a wetter finish. In this scenario, the carryover of N is set at zero.

At decile 7 we are matching the N demand of 60kg N/ha with N supply of 60kg N/ha. The grower is over-fertilising in the year of application for deciles 1 to 6 and under-fertilising in deciles 8 to 10.

The kg N/ha axis can then easily be converted to a nitrogen fertiliser budget (Figure 8.10), assuming a given price of urea ($650/t) and wheat ($350/t).

Step 3: Account for carryover nitrogen

The previous step ignored the effects of unused nitrogen that is carried over to the following season. A simple approach to account for carryover is to use the nitrogen budget to calculate the excess nitrogen for each decile and let the user assign a carryover factor from zero to 100 per cent.

These numbers can be informed by experimental work and modelling that investigates the recovery of nitrogen in subsequent years. In the example in Figure 8.11 it is set at 50 per cent, which is a conservative estimate. It is also worth noting that carryover nitrogen has no impact on wetter deciles as all the nitrogen is used.

Figure 8.11 shows the same scenario aiming for decile 7 and applying 60kg N/ha, but now we assume 50 per cent of unused nitrogen is carried over (shown in orange).

Figure 8.9: Nitrogen use model, aiming for decile 7 and applying 60kg N/ha, assuming no nitrogen carryover. Light green is unused N, green is N used by the crop and brown is the N that could have been used in the wetter decile finishes.

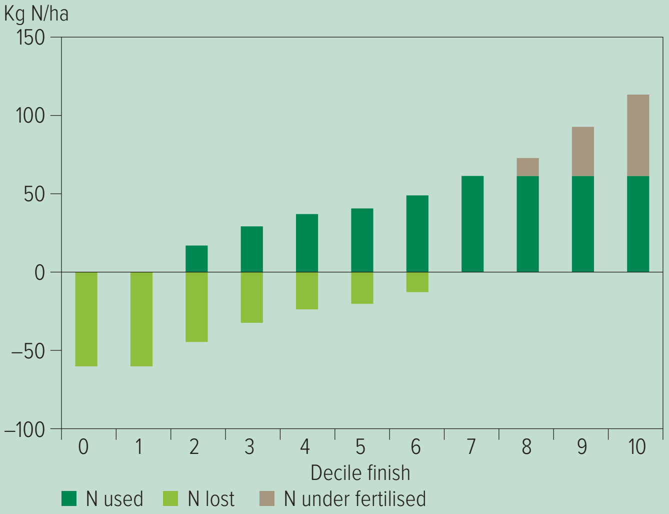


Figure 8.10: Nitrogen value for the same scenario (decile 7 target, 60kg N/ha applied) based on $650/t urea price, $350/t wheat price and assuming no carryover of nitrogen.

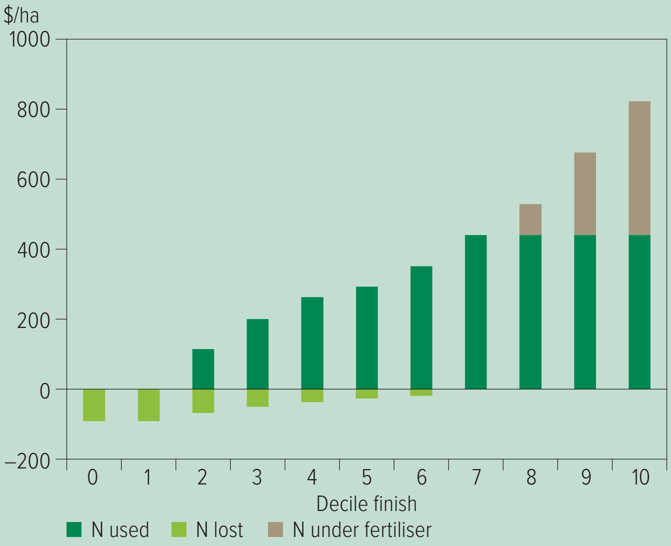
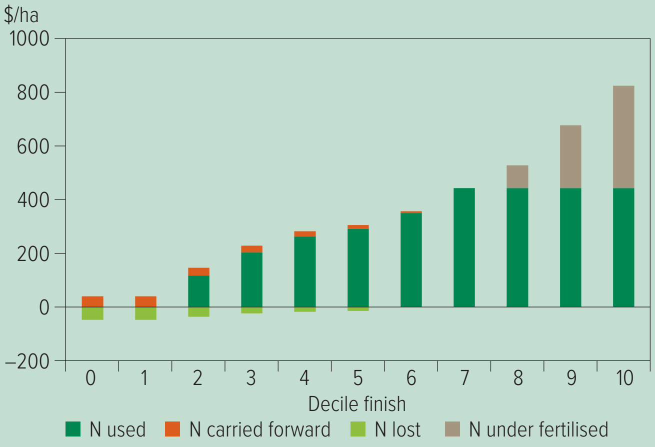


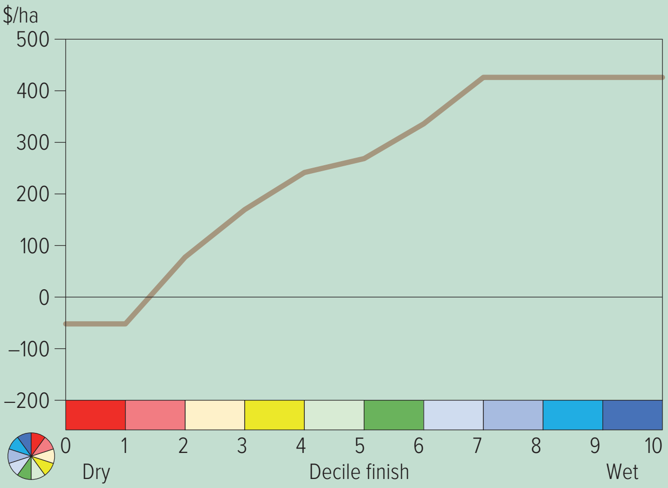
Figure 8.11: Nitrogen value model for the same scenario (60kg N/Ha applied, urea $650/t), but now assuming 50 per cent of unused N is carried over to the following season. N carried forward is orange, light green is unused N, green is N used by the crop and brown is the N that could have been used in the wetter decile finishes.



Step 4: Weigh the risks

Based on the yield potential of each decile (step 1), and the nitrogen use value (step 3), along with an assumption for the price of wheat, a profitability curve can now be developed for each decile. For this example of a 60kg N/ha application, with an assumption of $350/t wheat price and $650/t for urea, we see the resulting profit for each decile (brown curve; Figure 8.12).

Figure 8.12: Nitrogen profitability curve for the same scenario as Figure 8.11 (60kg N/ha applied, urea $650/t, 50 per cent carryover) converted to profit at a wheat price of $350/t.



How do I manage risks in a changing climate?

Common questions from grain growers about climate change range from the more general “What is climate change?” to the more localised “What are the likely changes to temperature and rainfall in my region?” and the practical question of “What will the impacts be and how can we address them?” These three questions are answered below.

What is climate change and how does it differ from climate variability?

Climate variability is the year-to-year changes in seasonal conditions due to the internal forcing of the climate system such as El Niño–Southern Oscillation (ENSO) or Indian Ocean Dipole (IOD).

Climate change is a longer-term trend due to external forcing that comes from astronomy (distance from the sun), volcanoes and changes to levels of greenhouse gases. Human-induced climate change or the enhanced greenhouse effect refers to the changes in the radiative properties of the atmosphere due to human activity. Earlier reports of the Intergovernmental Panel on Climate Change (IPCC) stated that the warming of the climate system was unequivocal. The fifth assessment report states that “Human influence on the climate system is clear” and that there is a 95 to 100 per cent probability that human influence was the dominant cause of global warming in the past 50 years. The attribution of the cause of warming increases confidence in the trend and indicates that the future depends on choices made by the global community.

A simple but powerful analogy used by the climate scientist Stephen Schneider is to consider a vulnerable system (such as a grain crop) being impacted as a sandcastle with waves (climate variability) and tides (climate change). After droughts, fires, heatwaves or floods, the question is often posed as to how much can be attributed to climate change (the tide) and how much to climate variability (the wave). It is almost always the wave that destroys the sandcastle, but on a rising tide the waves do more damage.

What are the projected changes in temperature and rainfall at my location?

As part of the National Drought Initiative, CSIRO and BoM have been funded to produce the Climate Services for Agriculture tool. This tool provides historical data (1961–2020), seasonal forecasts (one to three months) as well as future climate projections based on the 15 years before and after 2030, 2050 and 2070 for a given location.

The Climate Services for Agriculture tool, now called My Climate View, can be access at myclimateview.com.au. My Climate View provides Australian growers and farmers with tailored insights into the changing climate in their region.

How can I adapt to reduce the downside risks and find the opportunities?

The vulnerability of a natural or managed system to climate can be considered as the difference between impact and adaptive capacity (Figure 8.13). In this simple diagram, the impact of climate is the result of exposure and sensitivity. A high-value horticultural crop in a glasshouse is sensitive to climate but not exposed, whereas a slow-growing rangeland shrub is exposed but less sensitive. Recent seasons have highlighted that the grains industry in Australia is both exposed and sensitive to adverse climatic conditions such as drought, frost and heat. In a managed system such as cropping, adaptive capacity includes the varieties, equipment, chemicals and know-how in dealing with the variable and changing climate. Impressive crops produced under difficult circumstances in recent years show the high degree of adaptive capacity within the Australian grains industry.

In Table 8.2, the broad concept of climate change is broken down into components of seasonal heat, extreme heat, frost, seasonal rainfall, extreme rain events and changes to CO_2 levels. This allows comment on the level of confidence from climate science on the exposure, confidence on crop science on sensitivity, and agronomy on management (Hayman et al., 2019).

There are some changes, such as an increase in mean temperature, where the confidence from both climate science on projections and agricultural science on impacts is high. This contrasts with changes to rainfall where the confidence in the projections is lower, but the impacts on cropping of changes to rainfall are well understood. The interaction between these six aspects of climate change is important but uncertain. For example, elevated CO_2 is likely to partially offset some of the impacts of a decline in rainfall, but it is less clear how a drier but CO_2 enriched future will respond to a heat wave.

Grain farming is risky and climate change will make it riskier. Grain growers have a vested interest in policies that reduce greenhouse gases. Some grain growers are asking how they can reduce emissions and recognising that policies to reduce emissions in Australia and key markets represent both downside risks and upside opportunities.

Figure 8.13: Vulnerability is determined by impacts and adaptation. See Turner et al., 2003 for review and critique of frameworks.

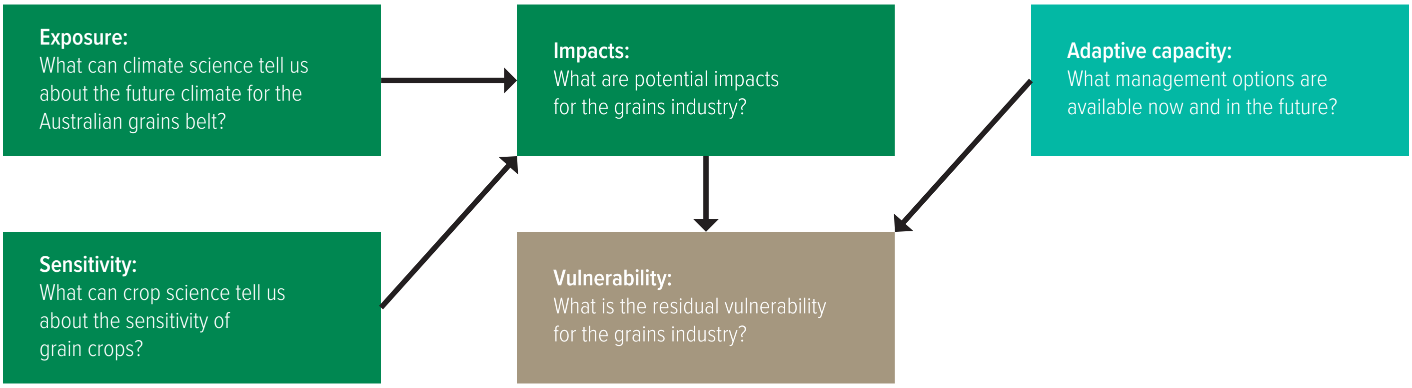


Table 8.2: Vulnerability to components of climate change (seasonal heat, extreme heat, frost, seasonal rainfall, extreme rain events and changes to carbon dioxide levels) based on the framework from Figure 8.13.

1. Increased mean temperature	
Confidence from climate science (Exposure)	**Very high.** The Australian grain belt, like the rest of Australia, has warmed and is expected to warm in the future. Because more inland regions are drier, they are expected to warm faster than regions closer to the coast. The greatest trends in warming across most regions have been in spring; this may be partly due to a decline in spring rainfall.
Confidence of impact from crop science (Sensitivity)	**High** confidence that the rate of crop development will increase. This faster development can be beneficial in very dry years but will reduce yields in wetter years. When there is sufficient water, the biomass of winter crops will increase in cooler months and regions. Higher temperatures contribute to a modest increase in potential evapotranspiration. Hot conditions can contribute to more challenging conditions for crop emergence. Increased mean temperature will change the weed and disease spectrum.
Management options (Adaptive capacity)	Understanding the drivers of crop development can be used to better match varieties to the climate. In a warmer world, slower-maturing varieties will develop more quickly. GRDC is funding ongoing work on measuring and modelling the phenology of cereals and pulse crops in the current and future climates. This analysis includes the interaction of water stress with the timing of heat and frost events. Stubble retention will reduce evaporation and keep the seedbed cooler. CSIRO and GRDC are investigating the role of long coleoptile wheat varieties.
Residual vulnerability	**Low to medium** vulnerability to warming over coming decades providing grain growers have access to crops with appropriate development. Vulnerability to warmer seasons will be greatly increased if growing season rainfall declines and warming is associated with heat waves.
2. Changes to heatwave frequency and intensity	
Confidence from climate science	**High** confidence that in a warmer world the weather patterns that bring heat to the grain belt will result in more intense heat waves. Confidence is lower on how the weather patterns that set up the hot spells will change.
Confidence of impact from crop science	**Moderate** understanding of the impact of heat on different phenological stages and thresholds for different crops grown in the field and how these impacts are modified by soil moisture. There is ongoing R&D investigating the impact of heat spells at critical stages of cereals and pulses.
Management options	Optimising the flowering time of available winter crops and breeding crops that can tolerate high heat loads.
Residual vulnerability	**High vulnerability** to an increase in spring heat events for all dryland winter crops but especially pulse crops. Spring heat events are more damaging when combined with low soil moisture. In cooler-than-normal springs WUE tends to be higher than expected. This suggests moderate heat events might be imposing a cost in most years.
3. Changes to frost frequency and intensity	
Confidence from climate science	**Low** – a perceived paradox that, despite warming, the frequency and intensity of frost has increased in some regions of the southern and western grain belt. This may be simply due to dry springs or other drivers related to synoptic patterns. It remains unclear whether this trend is due to decadal variability or increased greenhouse gases. The more rapid crop development due to warmer conditions can contribute to frost risk.
Confidence of impact from crop science	**Moderate to low** – although the impact of extreme frost at critical times can be obvious, the exact link between minimum temperature recorded in the Stevenson screen and damage to crops is noisy. Frost damage is poorly represented in simulation models.
Management options	Understanding the frostier parts of the landscape and matching land use (e.g., livestock on river flats). Using the small amount of variation in frost susceptibility between wheat varieties and greater variation between winter crops (e.g., barley as less susceptible than wheat). If sowing early (e.g., in April) selecting a longer-season variety, delaying flowering by sowing time and variety choice seem to be ineffective because of the damage from heat and drought.
Residual vulnerability	Although there is less confidence on the likelihood, there is **high vulnerability** to any increase in frost severity and frequency for many parts of the grain belt. Agronomists working with frost-affected growers refer to both a direct cost of frost damage and an indirect psychological impact on decision-making.
4. Changes to seasonal rainfall	
Confidence from climate science	**Moderate** confidence in drying in western and southern winter growing season, especially spring. **Lower** confidence for other seasons and regions.
Confidence of impact from crop science	**Very high.** There are extensive studies, many of them underpinning other chapters in this manual, that provide a good basis for understanding water productivity of major crops. Growers and agronomists are highly aware of the impact that the timing and amount of rainfall has on yield and profitability.
Management options	More effective storage of water prior to the growing season and then using the water as efficiently as possible by matching sowing time and cultivar to the environment. The impact of dry autumns can be partially offset by sowing part of the cropping program into dry soil. Grain growers have improved their water use efficiency using summer weed control, stubble retention and timely sowing. Some growers are using seasonal climate forecasts to adjust their operations.
Residual vulnerability	**Very high vulnerability.** Although grain growers are highly skilled at managing low-rainfall environments, the ongoing profitability of enterprises relies on capturing good seasons and is strongly affected by drier seasons. In medium to higher-rainfall parts of the southern grains belt, a substantial increase in drier-than-average growing seasons would greatly reduce confidence in management of input levels. Drier conditions would also reduce the amount of higher return and higher risk broadleaf crops.

Table 8.2 (Continued)	
5. Changes in the intensity of rainfall	
Confidence from climate science	**High.** A warmer atmosphere contains more energy and will hold more water. This leads to intensification of the hydrological cycle, which further increases variability. There is lower confidence in changes to weather systems that bring high or low intensity of rainfall.
Confidence of impact from crop science	**High** confidence in the impacts of changes to daily intensity. Low-intensity falls (< 5mm) tend to be inefficient as most of the rainfall wets the surface and is lost in evaporation. A moderate increase in intensity will improve efficiency of soil water gains. An increase in large falls (>20mm) is likely to lead to runoff and erosion and cause problems for operations such as sowing and harvest.
Management options	Stubble retention and other erosion management, especially on sloping sites. Many grain growers are using short-term weather forecasts to plan operations. This planning leads to improved efficiency and reduces the likelihood of runoff of agricultural chemicals.
Residual vulnerability	**Lower vulnerability** in southern and western regions than the northern region as southern and western regions are starting from a lower level. There are risks to water erosion but these can be managed with stubble retention, which has high levels of adoption and co-benefits of reducing wind and water erosion risk and increasing productivity.
6. Elevated levels of carbon dioxide	
Confidence from climate science	**Very high.** Future emissions depend on policy and technology. Although the exact concentration is difficult to predict, there is high confidence that future levels will be higher than present.
Confidence of impact from crop science	**High** for growth and yield of crops but **lower** for longer-term cropping systems (soil C and N) and grain quality components, e.g., protein and its various end use requirements. The growth rate of weeds, pests and disease will also change with elevated CO_2.
Management options	Changes in CO_2 cannot be considered separately from temperature and water supply, and together plant breeding advances cultivars suitable to present day conditions by default. In the future, there is likely to be deliberate selection of varieties that respond more positively to elevated CO_2. Monitoring changes to pests and disease and revising nutrition will be essential.

Glossary

APSIM – an agricultural crop production model to simulate growing conditions.

Available water capacity (AWC) – a crop-independent approximation of PAWC using the DUL and the LL, instead of the DUL and the CLL.

Co-limitation – simultaneous limitation of yield by multiple resources.

Crop lower limit (CLL) – the minimum soil moisture content at which a crop can extract water. If the soil is drier than this limit, the crop cannot access the remaining moisture. The CLL varies with soil and crop type.

Decile – categorisation of seasons based on how much rainfall occurs, with each decile responding to one out of 10 seasons. Decile 1 is wetter than one out of 10 seasons , decile 5 is average, decile 10 is wetter than 10 out of 10 seasons.

Drained upper limit (DUL) – the maximum amount of water a soil can hold before running off or draining. The DUL is a function of soil and is independent of crop type.

Dry start fallows – defined by Fischer (1987) in terms of the soil moisture at the start of the fallow period. A dry start fallow occurs after the harvest of a previous crop when the soil moisture content is low. This occurs with short fallows in winter rainfall areas. The aim is to allow rainfall that occurs over the fallow period to infiltrate and be stored for the following crop.

Electromagnetic imaging (EMI) – measures and maps the electrical conductivity of soil. As the conductivity is influenced by soil moisture, salt and clay content, this imaging technology can identify variations in soil type.

El Niño–Southern Oscillation (ENSO) – a global climate-driver relating to the variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean. There are three phases: neutral, El Niño, and La Niña. During an El Niño phase, Australia typically experiences reduced rainfall, and during a La Niña, Australia typically experiences increased rainfall (see Chapter 8).

Evapotranspiration – the loss of water from the plant through transpiration as well as water lost through evaporation from the plant surfaces and soil. This represents the total water used by the plant.

Fallow – a period when the paddock is kept free of plant growth by cultivation (cultivated fallow) or the use of herbicides (chemical fallow). There are multiple types of fallow (for example, short and long fallow, and wet start and dry start fallow). These types are described in this glossary.

Fallow efficiency – the proportion of rainfall that occurs over the fallow period that is stored in the soil and available for the following crop. The fallow efficiency is affected by the amount of rainfall that infiltrates into the soil and the losses from run-off, evaporation and drainage over the fallow period.

GSR – growing-season rainfall

Indian Ocean Dipole (IOD) – a global climate-driver relating to the variation in sea surface temperatures in the western Indian Ocean. When the IOD is positive, Australia tends to experience reduced rainfall, and when the IOD is negative, Australia tends to experience increased rainfall (see Chapter 8).

Long fallow – a longer period that replaces a crop with a period of fallow; therefore, a paddock is left out of production for a growing season. The length of the fallow will depend on the cropping system (for example, winter cropping in the southern and western regions and summer/winter cropping in the northern region). In winter cropping areas, a long fallow is greater than six months and starts in the previous winter or spring period; in the northern region, a long fallow may be longer and last up to 18 months.

Lower limit (LL) – estimates of CLL developed in laboratory conditions that respond roughly to CLL except at lower root depths.

Marginal WUE – the additional yield potential from additional water input.

Normalised difference vegetation index (NDVI) – measures the 'greenness' of a crop through the difference in reflection of red and infrared light. A very green crop will reflect little red but a lot of infrared light, while a less green crop will reflect less red and more infrared.

Parent material – the source of sediments or type of rock in which the soils are formed.

Plant-available water (PAW) – the current amount of water available to a particular crop, equal to the current soil moisture content minus the CLL.

Plant-available water capacity (PAWC) – the soil's capacity to retain and release water or, in other words, the maximum amount of water a particular crop can extract from a particular soil, equal to the DUL minus the CLL. For a more comprehensive definition, refer to Chapter 3.

Short fallow – a shorter period of fallow between consecutive crops. A summer fallow occurs in winter cropping areas between the harvest of one winter crop and the sowing of next year's winter crop.

Stomata – specialised cells in the surface of leaves that control the rate of transfer of carbon dioxide and water in and out of the plant.

Transpiration – crop growth depends on photosynthesis, which involves the uptake of carbon dioxide (CO^2) through the stomata. The stomata open and close to allow CO^2 uptake and water loss. This water loss is known as transpiration.

Vapour pressure – a measurement of the number of water vapour molecules in the air. The maximum amount of water vapour that can be contained in a parcel of air increases exponentially with temperature. The maximum value of vapour pressure corresponds to 100 per cent relative humidity At 100 per cent relative humidity, the vapour pressure is at its maximum (measured in hectopascals or kilopascals (hPa or kPa)). Most of the time, however, the air in the atmosphere is not saturated.

Vapour pressure deficit (VPD) – the difference between the current vapour pressure and the saturated (100 per cent humidity) vapour pressure.

Water use – the total amount of water used to grow the crop during the season, and includes evapotranspiration, run-off and deep drainage. Under rain-fed farming systems, water use can be estimated using the following equation:

$$\text{Water use (mm)} = \text{(soil water at sowing – soil water at maturity) + in-crop rain}$$

This method assumes only minimal losses by run-off, drainage and lateral water movement.

Water use efficiency (WUE) – the amount of grain produced per unit of water use, usually measured in kilograms per hectare (kg/h) of grain per millimetre of growing-season rainfall. WUE indicates the farming system's effectiveness in using water. This key concept is extensively covered in Chapters 4 to 6.

Wet start fallows – defined by Fischer (1987) in terms of the soil moisture at the start of the fallow period. A wet start fallow commences after soil moisture has accumulated, with the aim of minimising losses and retaining stored soil moisture. This occurs, for example, with long fallows in winter rainfall areas when the fallow starts at the end of winter or early spring.

Yield Prophet® – an online interface to allow growers to access the APSIM model and support on-farm decision-making.

Useful resources

PAWC

- *Estimating Plant Available Water Capacity*, 2013, GRDC manual by Lawrence Burk and Neal Dalgliesh. URL grdc.com.au/resources-and-publications/all-publications/publications/2013/05/grdc-booklet-plantavailablewater
- APSoil: URL apsim.info/apsim-model/apsoil
- Soil and Landscape Grid of Australia: URL esoil.io/TERNLandscapes/Public/Pages/SLGA
- SoilMapp:
  - Android: URL play.google.com/store/apps/details?id=au.csiro.soilmapp&hl=en_US
  - Apple: URL itunes.apple.com/au/app/soilmapp/id578173447

Marginal WUE

For studies on marginal WUE, Marley & Littler (1989a), Incerti, Sale & Oleary (1993), and Latta & O'Leary (2003) are all good resources.

Nitrogen cycling

There are two publications that cover nitrogen cycling and the effects of crop rotations on soil nitrogen in considerable detail:

- Cox & Strong (2015) *The Nitrogen Book. Principles of soil nitrogen fertility management in southern Queensland and northern NSW farming systems*. Queensland Government.
- Unkovich et al. (2020) *A Nitrogen Reference Manual for the Southern Cropping Region.* GRDC. URL grdc.com.au/resources-and-publications/all-publications/publications/2020/a-nitrogen-reference-manual-for-the-southern-cropping-region

Summer weed management

GRDC published a comprehensive reference manual on summer weed management: *Summer fallow weed management – a reference manual for grain growers and advisers in the southern and western grains regions of Australia*. URL https://grdc.com.au/GRDC-Manual-SummerFallowWeedManagement

Optimal flowering windows for your location

These are some GRDC resources to help you work out the optimal flowering window for your location:

- Central Queensland GRDC Research Update on optimising wheat maturity and sowing date. URL grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2021/11/optimising-wheat-maturity-x-sowing-date-sweet-spots-for-flowering-in-cq
- *Ten Tips for Early Sown Wheat – Victoria, SA and southern NSW*. URL grdc.com.au/ten-tips-for-early-sown-wheat
- *What are the optimal flowering periods for wheat across Western Australia and how will they change with potential climate change?* URL grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2020/03/what-are-the-optimal-flowering-periods-for-wheat-across-western-australia-and-how-will-they-change-with-potential-climate-change
- State government crop variety sowing guides can also provide location-specific information on optimal flowering windows.

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