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Water use efficiency of grain crops in Australia: principles, benchmarks and management

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INTRODUCTION

Water availability is a major constrain for production of grain in Australia, and improving water use efficiency is a primary target of growers, breeders, and agronomists. This publication reflects the Grains Research and Development Corporation's commitment to improving water use efficiency through projects under the GRDC Water Use Efficiency Initiative, which bring together growers, farming systems groups and researchers across Australia.

The aim of this publication is to provide decision makers with tools to understand and improve water use efficiency in rainfed systems where water deficit is a perennial problem. Yield limitations imposed by excess water are beyond the scope of this publication.

Chapters 1 and 2 set the scene and provide an overview of biophysical and agronomic principles underlying crop growth, yield, capture of resources and water use efficiency. Readers can skip these chapters if their primary interest is guidelines to improve crop water use efficiency. However, understanding the principles is a powerful means to help determine our own solutions for specific combinations of soil, climate, technology and finance of particular farms. Readers are encouraged to take up the challenge of the two opening chapters.

Chapter 3 provides guidelines for benchmarking wheat water use efficiency using the French and Schultz approach with two parameters: soil evaporation and maximum yield per unit water use. Location-specific parameters are presented that account for the main climate drivers and nitrogen supply. The chapter highlights the trade-off between nitrogen use efficiency and water use efficiency that is critical in decision making. The consequence is that maximising water use efficiency may require nitrogen rates that are too costly, too risky or environmentally unsound. Hence the need to target water and nitrogen use efficiency collectively, rather than individually. This is particularly important with high fertiliser prices relative to grain prices.

Chapter 4 gathers information from diverse Australian environments to summarise the effects of cropping practices on crop growth and yield, water use and water use efficiency. The principles outlined in Chapters 1 and 2 are used to interpret crop responses to practices including fallowing, crop rotation, planting arrangement (sowing rate and row spacing), crop nutrition, variety selection and precision agriculture.

CHAPTER 1
Crop growth and yield: physiological principles

The aim of this chapter is to discuss the two key principles that are behind the determination of yield in grain crops:

- capture and efficiency in the use of resources; and
- critical windows for grain yield determination.

These principles will help us to:

- understand the influences of soil, climate and variety on yield;
- be better informed on effective crop management.

Capture and efficiency in the use of resources driving crop growth

Figure 1 shows how crop biomass is driven by:

- the capacity of roots to capture water and nutrients, chiefly nitrogen and phosphorus (black arrow in Figure 1);
- the capacity of canopies to capture radiation and carbon dioxide used in photosynthesis (green arrow in Figure 1); and
- the efficiency of the crop to transform resources (water, nutrients, radiation, carbon dioxide) into dry matter (red arrow in Figure 1).

Dashed lines in Figure 1 highlight how environmental factors, such as ambient temperature or soil salinity, modulate the rate of capture of resources and the efficiency in the transformation of resources in plant biomass.

Crop growth and yield depends on the ability of crops to capture above-ground and soil resources, and on the capacity of crops to transform these resources into biomass.

Figure 2 illustrates the relationship between crop growth and the capture of resources. As the season progresses and roots and canopies expand, the crop captures more soil and above-ground resources. A straight line represents increasing growth with increasing resource capture. The black line represents an unstressed crop and the red line represents a stressed crop producing less biomass. Stresses such as deficit of nutrients or soil compaction reduce growth through two processes:

- reducing the amount of resources captured by the crop (horizontal arrow in Figure 2); and
- reducing the efficiency in the use of resources. The vertical arrow in Figure 2 indicates the reduction in growth for the same amount of resource captured; this means lower efficiency.

As a rule of thumb, shortage of resources (drought, nutrient deficit) and soil constraints (compaction, salinity, alkalinity) reduce crop growth by reducing the capture of resources, rather than efficiency in the use of resources.

For example, control wheat crops established in compacted Mallee soil and crops where subsoil compaction

FIGURE 1 How crop biomass is driven

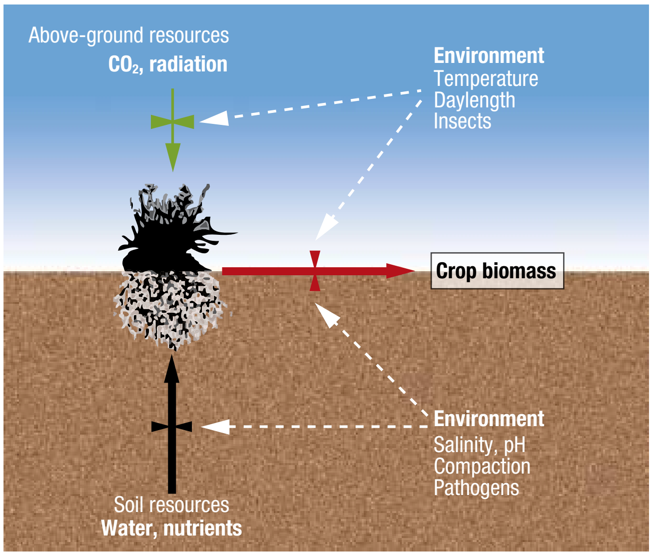
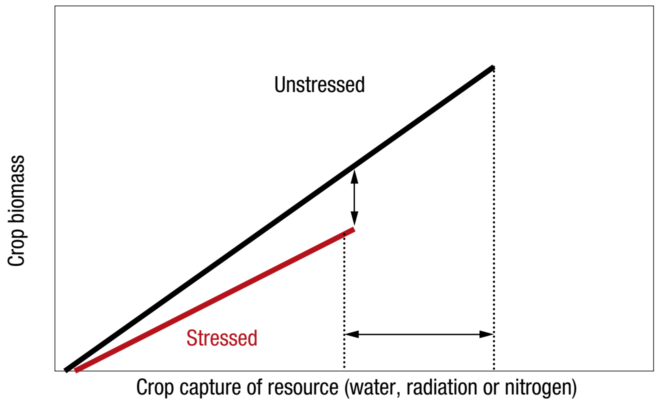


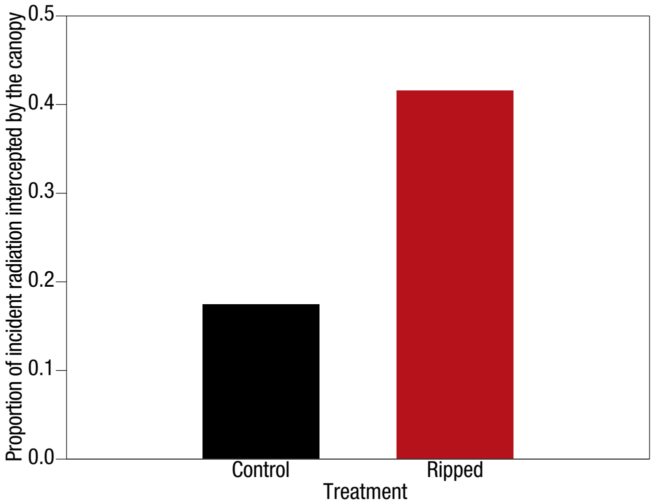
FIGURE 2 The relationship between crop growth and the capture of resources



was relieved by deep tillage were compared. The size of both the canopy and root system was seriously reduced in compacted soil, as show in Figure 3. Canopies and roots were therefore less able to capture resources, and this accounted for most of the reduction in growth. Compaction reduced peak leaf area index, resulting in reduced radiation by 40 per cent. Capture of water by the crop, measured as transpiration, was similarly reduced from 110 to 60 millimetres, whereas biomass per unit transpiration was largely unaffected, at about 58 kilograms per hectare per millimetre. The next chapter will discuss further the stability or otherwise of water use efficiency.

FIGURE 3 Effects of subsoil compaction on the canopy and root systems of wheat crop at Caliph, South Australia

View of the untreated control, where compaction dramatically reduced ground cover, and deep-ripped treatment.



Proportion of radiation captured by control and ripped crops.

Compaction reduces root growth and capacity for water uptake.

Root system of crops where soil compaction was alleviated with deep-ripping.

SOURCE: Sadras et al. (2005)

Annual crops have typical 'windows' when yield is more sensitive to stresses

The production of biomass is proportional to the amount of water, radiation and nutrients captured by crops (see Figure 2). However, the step from biomass to grain yield also depends on the occurrence of stresses during critical windows when kernel set and kernel size are determined. For most annual crops, these windows have been identified, as illustrated in Figure 4. For wheat, the critical window for kernel set is between stem elongation and shortly after flowering. In practical terms, this window for typical Australian crops comprises the 30 to 40 days before 10 days after flowering.

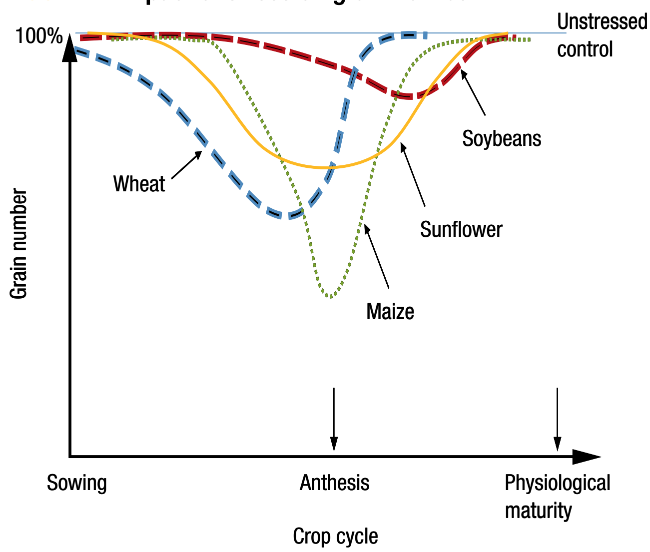
Grain number is reduced when stress occurs in critical developmental windows. Compared to unstressed controls, which produce 100 per cent the (potential) number of grains (horizontal line), stressed crops have severe depressions in grain set when stressed at critical windows. Stress before or after this window has little effect on yield.

This window shows two critical processes in action. First, the wheat plant overproduces florets and then it kills an amount of florets leading to the potential kernel set at the end of this critical window (see Figure 5). The rate of flower mortality is higher under poor environmental conditions.

Second, over the same developmental window, the plant sets an upper limit for grain size. For example, elevation of temperature by 5°C over ambient between booting and anthesis can reduce maximum kernel size of winter cereals by about 20 per cent. By the end of this developmental window, the maximum yield of the crop, defined in terms of number and size of kernels, is pretty much defined. For this reason, stresses such as frost, high temperature, water deficit or low radiation in this critical window will have a direct effect on yield. Crop management is, to a large extent, the ability to shift this window out of harms way by manipulating sowing date and cultivar choice, as discussed in Chapter 4. Flowering time is indeed the most important attribute of crop adaptation.

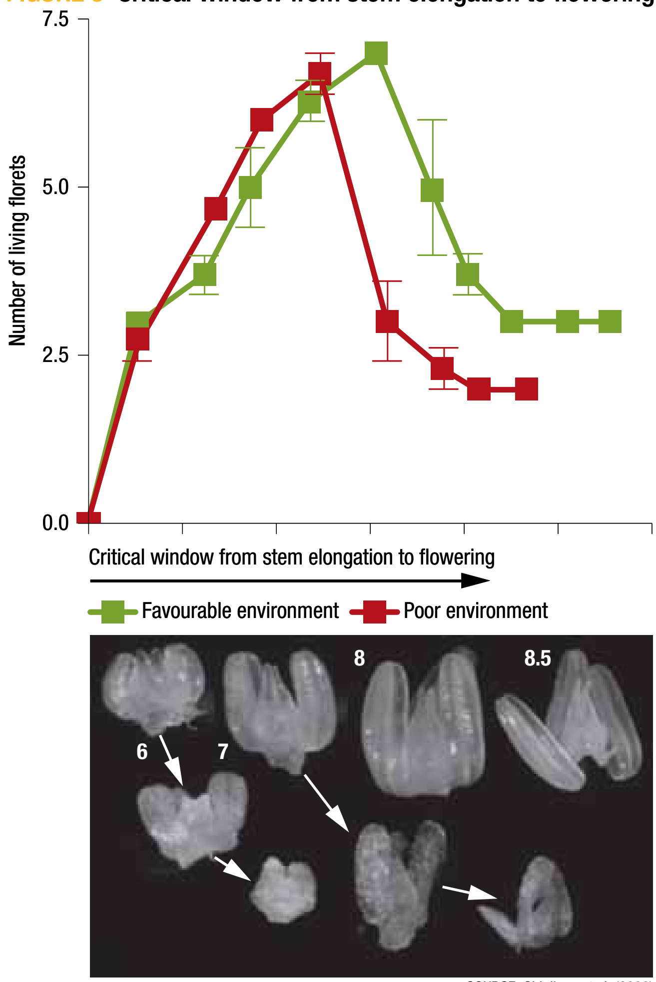
During the critical window between stem elongation and shortly after flowering, the wheat plant defines the number of live florets that set a ceiling for grain number and yield. The process of floret mortality is under genetic control and responds to the environment: the plant will kill more florets in a poor environment. The inset image under Figure 5 shows the fate of florets leading to either viable florets, and eventually grain, or sterile florets (white arrows).

FIGURE 4 Impact of stress on grain number



SOURCE: Calviño and Monzon (2009)

FIGURE 5 Critical window from stem elongation to flowering



SOURCE: Ghiglione et al. (2008)

CHAPTER 2
Water use efficiency: climate and crop drivers

Crop biomass and grain yield depend on photosynthesis. Photosynthesis involves the uptake of carbon dioxide (CO_2) through stomata, which are pore-like, specialised cells in the surface of leaves (see Figure 6).

However, open stomata required for CO_2 uptake are an open gate for water loss. There is a tight trade-off between uptake of CO_2 and water loss, and this explains the close link between crop production and water use. Vapour pressure deficit (see Box 1), nitrogen supply and seed composition are the main drivers of water use efficiency, and understanding their influence helps understanding of the effects of management decisions such as crop choice, sowing date and fertiliser rate.

In this chapter, the physiological basis of the link of water use efficiency with vapour pressure deficit, rainfall pattern, nitrogen supply and seed composition is presented. Chapter 3 uses these principles to derive location-specific benchmarking parameters accounting for nitrogen supply. Chapter 4 utilises these principles to discuss management practices to improve water use efficiency.

FIGURE 6 Stomata in the leaf surface are pore-like cells that open and close in response to environmental signals. Arrows represent fluxes of carbon dioxide and water.

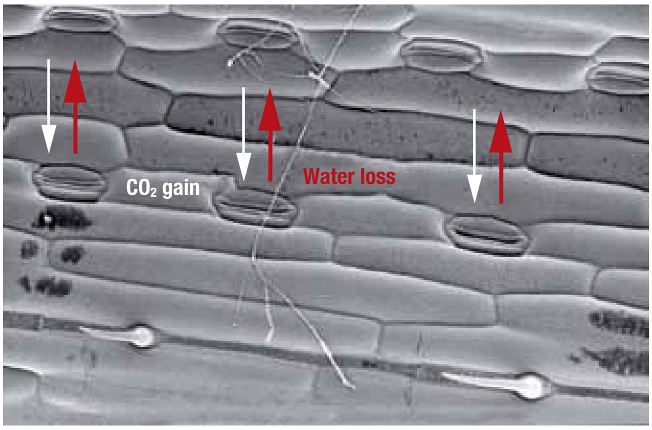


IMAGE: University of Bath, UK

Water use efficiency and vapour pressure deficit

Liquid water moves from soil to root, and from root to shoot. Water passes from liquid to vapour in leaf cavities just below the stomata and moves out through the stomata into the air surrounding the leaf. The rate of water loss from leaves is proportional to vapour pressure deficit, which is the driving force behind crop transpiration.

Vapour pressure deficit has a large impact on water loss and little direct impact on CO_2 uptake. With high vapour pressure deficit the ratio of CO_2 uptake and water loss drops dramatically. For this reason, biomass and grain yield per millimetre of water use drop with increasing vapour pressure deficit, as illustrated in Figure 7.

Figure 7a shows biomass per unit transpiration of early-sown barley was 47kg/ha per mm compared with late-sown barley that only produced 30kg/ha per mm. In Figure 7b, transpiration is corrected by vapour pressure deficit and the differences between first and second seeding date

BOX 1

VAPOUR PRESSURE DEFICIT

The maximum amount of water vapour that can be contained in a parcel of air increases exponentially with temperature, as shown by the red curve in the figure at right. This saturation curve corresponds to 100 per cent relative humidity and is expressed in kilopascals (kPa), as in weather reports. Most of the time, however, the air is not saturated. The blue 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 arrows show the vapour pressure deficit, which is the gap between actual and saturated. Vapour pressure deficit integrates the effects of temperature and humidity and is therefore a more robust measure of air dryness than relative humidity.

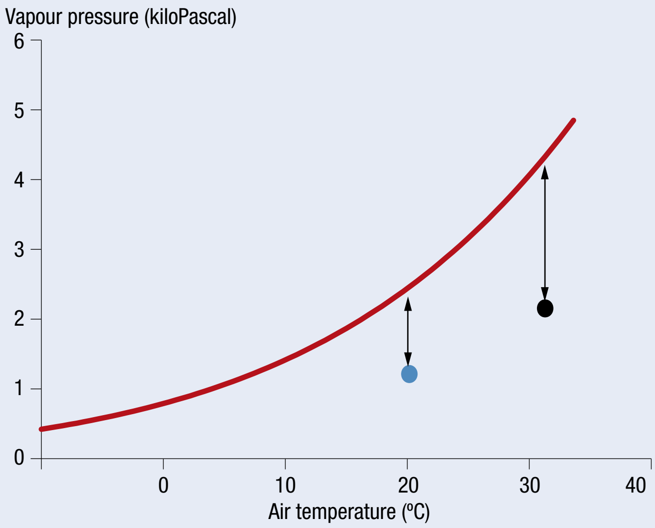
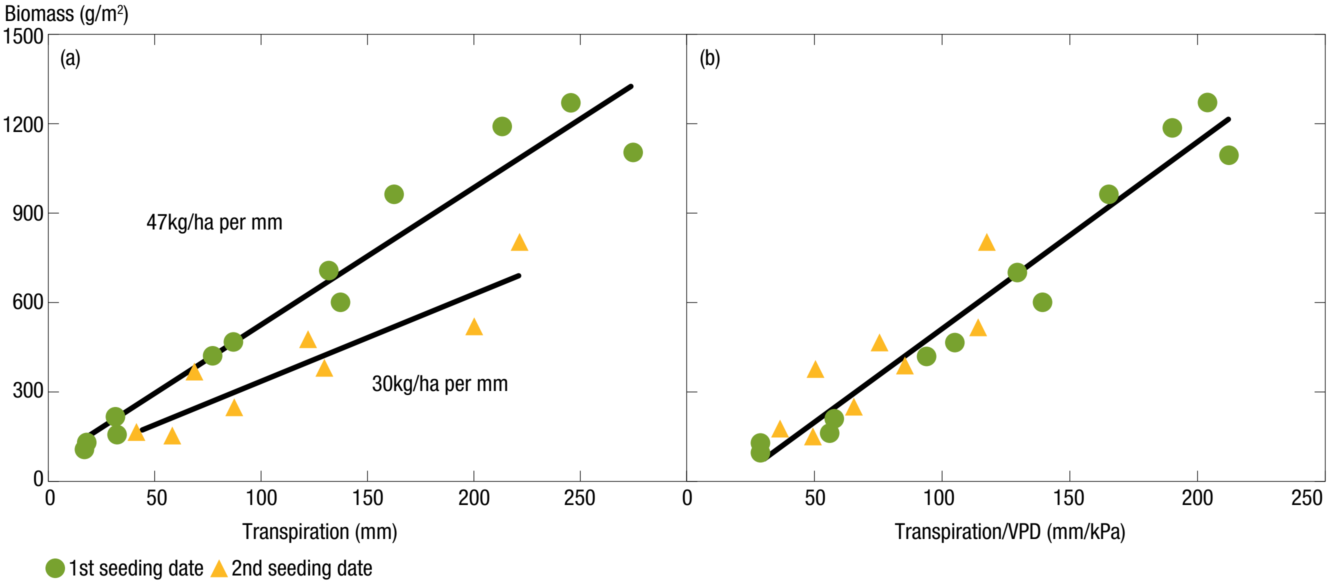


FIGURE 7 Biomass and transpiration of early-sown barley



(a) Biomass per unit transpiration of early-sown barley (represented by green circles) was 47kg/ha per mm compared with late-sown barley (yellow triangles), which only produced 30kg/ha per mm.
(b) When transpiration is corrected by vapour pressure deficit the differences between 1st and 2nd seeding date disappeared.

SOURCE: Kemanian et al. (2005)

disappeared. This explains the greater biomass productivity per unit water of early-sown crops.

In Australia, vapour pressure deficit at the critical window around flowering of typical wheat crops increases northwards and inland, as shown in Figure 8. Other things being equal, grain yield per millimetre of water used is lower in locations and seasons with high vapour pressure deficit.

The French and Schulz parameter – 20kg/ha per millimetre – was originally derived under South Australian conditions. This parameter would overestimate yield per millimetre in northern NSW and central Queensland, where the corresponding vapour pressure is higher, and may probably underestimate yield per millimetre in regions with lower vapour pressure deficit, such as south-west Western Australia and Tasmania. Chapter 3 presents estimates of this parameter for a range of locations and discusses further the impact of vapour pressure deficit.

Water use efficiency and rainfall patterns

Seasonality and size of rainfall events influence crop water use efficiency. In the southern and western grain-growing regions, rainfall is winter-dominant, whereas in the northern region it is summer-dominant. There is a transition zone in central NSW in particular with no clear seasonality. Superimposed on this pattern, rainfall is dominated by small events (< 5mm) in the southern and western regions and larger events are characteristic of the northern region.

These features of rainfall mean that soil evaporation, favoured by winter rainfall and small events, is the main unproductive source of water loss in southern and western regions. For a given soil type, run-off and deep drainage are more likely where large rainfall events dominate.

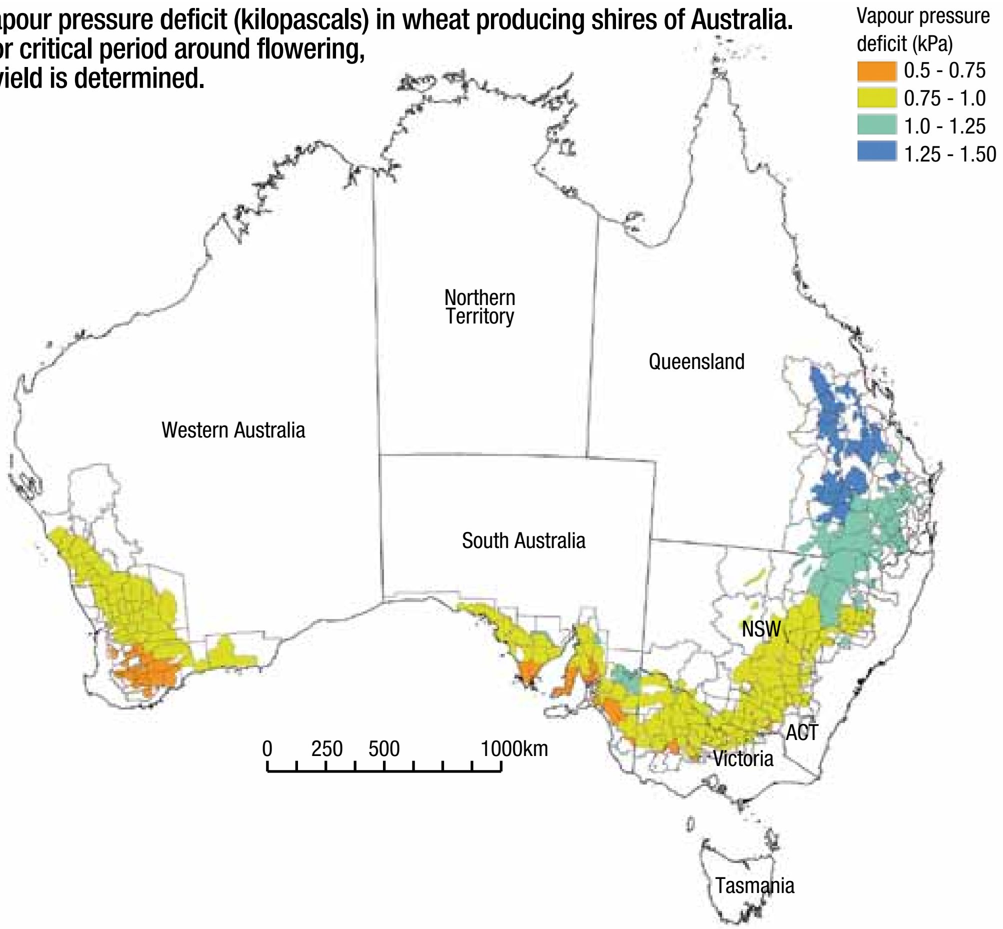
Collectively, vapour pressure deficit and rainfall patterns are the main climate determinants of location-specific water use efficiency. These are integrated in benchmarking estimates presented in Chapter 3.

Table 1 Effects of nitrogen fertilisation on yield and water use efficiency of canola in the Victorian Wimmera. Note that increasing fertiliser rate improves yield per unit water use at the expense yield per unit of nitrogen

Nitrogen rate (kg N/ha)	Grain yield (t/ha)	Shoot dry matter (t/ha)	Water use (mm)	Soil evaporation (mm)	Dry matter per unit water use (kg/ha.mm)	Yield per unit water use (kg/ha/mm)	Yield per unit nitrogen fertiliser (kg grain per kg N)
0	1.6	5.2	307	128	17.1	5.3	
70	2.5	8.8	349	112	25.3	7.1	35.3
140	2.5	8.7	344	91	25.2	7.3	17.9
210	2.8	9.5	335	87	28.4	8.4	13.4

SOURCE: Norton and Wachsmann (2006)

FIGURE 8 **Vapour pressure deficit (kilopascals) in wheat producing shires of Australia. Values are for critical period around flowering, when grain yield is determined.**



SOURCE: Doherty et al. (2010)

Water use efficiency and nitrogen availability

Nitrogen-deficient soils reduce water use efficiency. First, a nitrogen-deficient crop will have impaired photosynthesis; hence, above-ground dry matter per unit transpiration will drop. Figure 9 shows consistent reductions in above-ground dry matter per unit transpiration up to 50 per cent of well-fertilised controls.

Second, nitrogen deficiency reduces the ability of the crop to capture soil water and increases soil evaporation in association with a smaller canopy and root system.

Table 1 illustrates the multiple effects of fertiliser on growth, yield and water use of canola in the Victorian Wimmera. Under the particular conditions of this experiment, fertiliser increased yield from 1.6 to 2.8 tonnes per hectare. This was achieved with an increase in water use of 28mm and a substantial reduction in unproductive soil evaporation of 41mm. Dry matter per unit of water use increased from 17 to 28kg/ha per mm and grain yield per unit water use from 5.3 to 8.4kg/ha per mm with high nitrogen rate. The gain in water use efficiency is achieved at the expense of reduced yield per unit of nitrogen fertiliser.

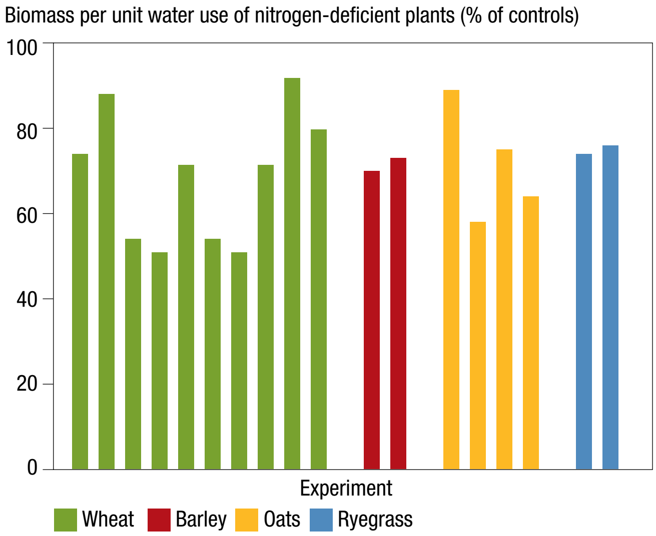
The nitrogen-driven trade-off between water and nitrogen use efficiency is universal; it has been documented for wheat, rice, maize, canola and forage grasses, among other crops. An important consequence of this trade-off is that the achievement of high water use efficiency may require nitrogen rates that are too costly, too risky or environmentally

Table 2 Difference in yield and water use efficiency of cereal and oilseed crops

Season	Water regime	Crop	Water use (mm)	Yield (t/ha)	Yield per unit water use (kg/ha per mm)
2000-01	Rainfed	Wheat	237	2.05	8.6
	Rainfed	Canola	252	1.19	4.7
2001-02	Rainfed	Wheat	337	4.18	12.4
	Rainfed	Canola	256	1.75	6.8
2001-02	Irrigated	Wheat	401	6.04	15.1
	Irrigated	Canola	387	3.44	8.9

SOURCE: Norton and Wachsmann (2006)

FIGURE 9 Biomass per unit water use of nitrogen-deficient plants



Nitrogen deficit reduces above-ground dry matter per unit water use in crops. Each bar is from a single, independent experiment. The magnitude of the reduction in dry matter per mm water depends on the severity of nitrogen deficit. SOURCE: Brueck (2008)

unsound.

Water use efficiency and seed composition

The trade-off between leaf photosynthesis and water loss is rather robust: there is not much difference between crop species, except for maize and sorghum, which have a higher photosynthesis per unit water loss than small grain crops.

However, the conversion efficiency of sugar into grain ranks cereals > pulses > oilseeds. This reflects the differences in energy content of the seed: one gram of starch (dominant component of wheat or barley grain) requires 1.2g of raw sugar; 1g of protein in pulses requires 1.62g of sugar; and 1g of fat in oilseeds requires 2.7g of sugar.

A plant can therefore produce twice as much starch as fat using the same amount of raw sugar from photosynthesis. This explains the large difference in yield and water use efficiency of cereal and oilseed crops, as illustrated in Table 2. Cereals have a much greater water use efficiency than oilseed crops. This reflects the low energy cost of starch relative to fat as main products stored in grain.

CHAPTER 3
Benchmarking wheat water use efficiency: accounting for climate and nitrogen

Owing to its simplicity and solid foundation, the benchmarking approach of French and Schultz is widely used in Australia. This approach relates grain yield to either seasonal rainfall or crop water use. A rainfall-based benchmark is easier to apply, but would bias estimates if initial soil water or residual soil water at harvest are large.

We therefore favour an approach based on water use calculated as seasonal rainfall plus the difference in soil water content between sowing and harvest.

In this chapter, location-specific parameters for benchmarking wheat water use efficiency for crops grown with a wide range of nitrogen supply are presented.

French and Schultz parameters: expected effects of climate and nitrogen

The model of French and Schultz has two parameters. One is the slope of the line representing the best yield for a given water use. Originally, this slope was estimated as 20kg/ha per millimetre. This slope accounted for varieties and management practices typical of the late 1970s and was limited to South Australian environments.

The second parameter is the water use for zero yield, which is interpreted as unproductive soil evaporation. This parameter is usually set to 110mm, but French and Schultz highlighted a rainfall-dependent value and proposed a rule of soil evaporation as 60 per cent of the seasonal rainfall.

More recent research has shown that size of rainfall events, rather than total rain, drives soil evaporation. In the northern region for example, where rainfall is summer-dominant with typically large events and crops depend primarily on stored soil water, soil evaporation is well below the 110mm used as a reference in southern locations.

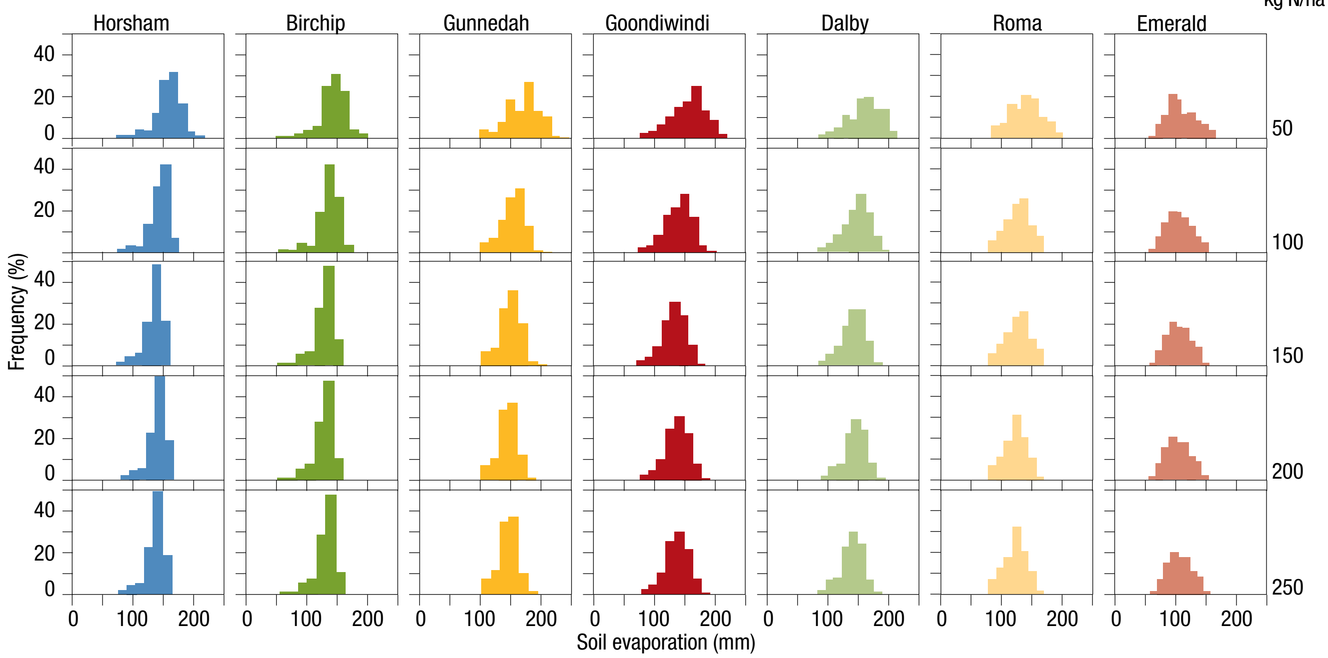
The approach of French and Schultz has known limitations; for example, it does not account for timing of rainfall. As demonstrated in Chapter 1, the critical window around flowering is particularly important for grain set and shortage of water in this window causes large reductions in yield and water use efficiency.

The notion of a single parameter representing maximum yield per unit water use and a single parameter representing soil evaporation is a simplification. Both parameters have large season-to-season variation, as illustrated in Figure 10 for soil evaporation.

Nonetheless, it is important to make this point: the original model of French and Schultz is sound, provided its limitations are understood and, very importantly, the right parameters are used.

Using the principles outlined in Chapter 2, the effects of

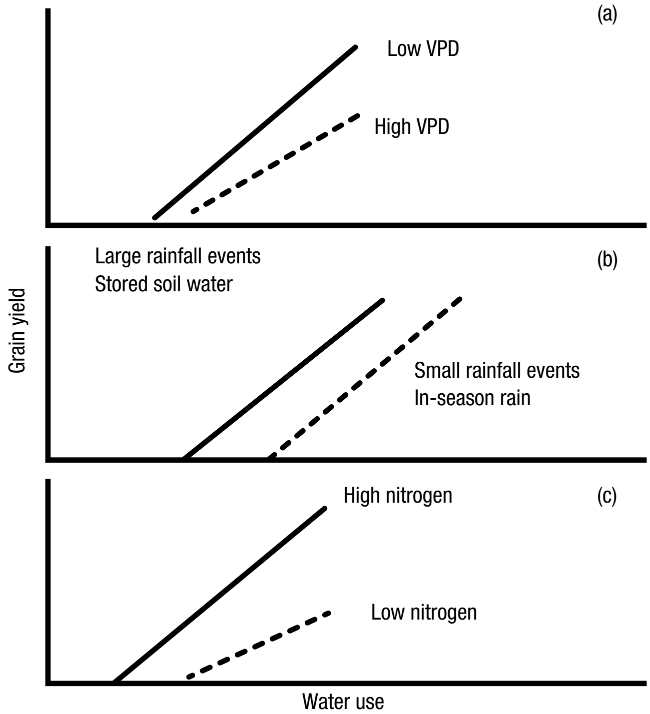
FIGURE 10 Frequency distribution of soil evaporation in a south–north transect from Horsham, Victoria, to Emerald, Queensland for wheat crops grown with a wide range of nitrogen supply



Note how soil evaporation is greater in southern locations with dominance of small rainfall events and a greater proportion of total water use derived from in-season rainfall. Also note how soil evaporation increases with nitrogen deficit. Data from simulations with APSIM model and long-term climate records.

SOURCE: Sadras and Rodriguez (2010)

FIGURE 11 Influence of climate and nitrogen supply in the parameters of the French and Schultz benchmark



(a) Reduction in slope with increasing vapour pressure deficit (VPD). Vapour pressure deficit 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.

climate and nitrogen on the parameters of the French and Schulz model can now be discussed.

First, the slope of the line decreases with increasing vapour pressure deficit (see Figure 11a).

Second, soil evaporation is greater in locations and seasons with a dominance of small rainfall events and where a greater proportion of total water use is derived from in-season rainfall (for example, in the southern region), as opposed to locations with a dominance of stored soil water and large rainfall events (for example, the northern region) (see Figure 11b).

Third, nitrogen deficit reduces the slope and increases soil evaporation (see Figure 11c).

These predictions are based on the principles of crop physiology and agronomy outlined in Chapters 1 and 2 and have experimental support. Importantly, there is a nitrogen-driven trade-off between water use efficiency and nitrogen use efficiency (see Table 2).

In summary, the model of French and Schultz can be applied with some confidence, but it is necessary to be aware of how the parameters change with climate and agronomic factors. Keeping these limitations in mind, the maximum yield per unit water use and soil evaporation parameters for 43 locations across the Australian wheatbelt have been derived as a practical tool for benchmarking wheat water use efficiency (Figure 12).

The APSIM model with long-term climate records and characteristic soils for each location was used in

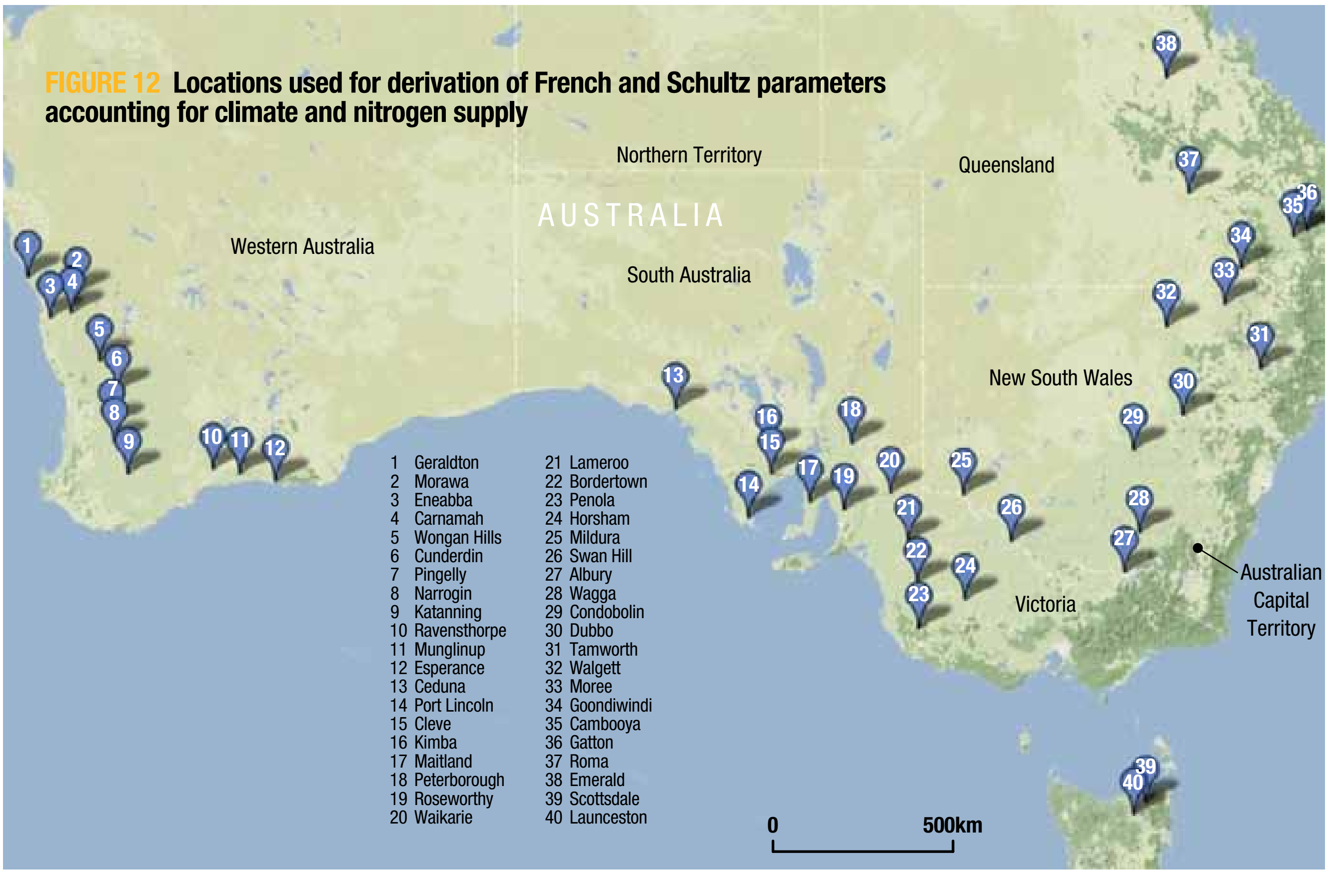
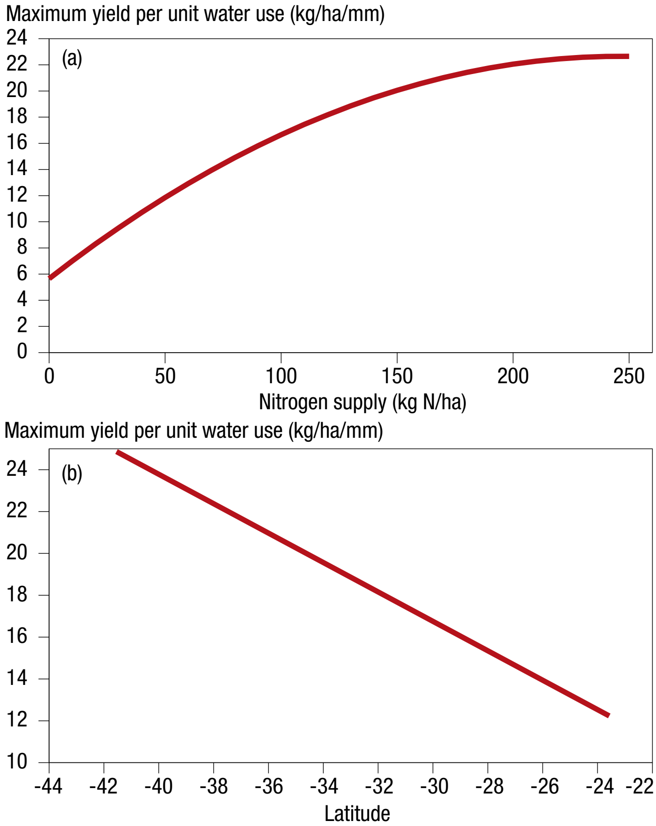


FIGURE 12 Locations used for derivation of French and Schultz parameters accounting for climate and nitrogen supply

FIGURE 13 **Maximum yield per unit water use as a function of (a) nitrogen and (b) location**



These curves were derived from simulations with the APSIM model using characteristic soils and long-term climate records for 43 locations, in combination with a broad range of initial soil water content and nitrogen availability.

combination with a broad range of initial soil water content and nitrogen availability.

Estimating maximum yield per unit water use by location and nitrogen

A three-step procedure to derive the 'slope' parameter representing maximum yield per unit water use accounting for nitrogen and location is proposed.

Step 1

Use the curve in Figure 13a to account for the effect of nitrogen on maximum yield per unit water use.

For severely limited crops (nitrogen supply < 50kg nitrogen per hectare), maximum yield per unit water use would be about 5 to 6kg grain/ha/mm. For crops with abundant nitrogen supply (N supply > 200kg N/ha), the parameter approaches 22 to 24kg grain/ha/mm. For intermediate nitrogen supply, maximum yield per unit water supply can be estimated graphically using this curve.

Step 2

Use the line in Figure 13b to correct for location.

For a latitude of –41.5° (Launceston, the southernmost location in this study), maximum yield per unit water use would be about 24 to 25kg grain/ha/mm. For a latitude of –23.5° (Emerald, the northernmost location), maximum yield per unit water use would be about 12kg grain/ha/mm. For intermediate locations, maximum yield per unit water supply can be estimated graphically using the line in Figure 13b.

Step 3

Select the lowest value from steps 1 and 2.

For example, to estimate the maximum yield per unit water use for Dalby (latitude = –27.1°) with intermediate nitrogen supply (100kg N/ha), the location correction would return 14.7kg/ha/mm and the nitrogen correction would return 16.6kg/ha/mm. Select the lowest value, 14.7kg/ha/mm, as a benchmark for this combination of location and nitrogen supply.

Estimating soil evaporation as a function of location and agronomy

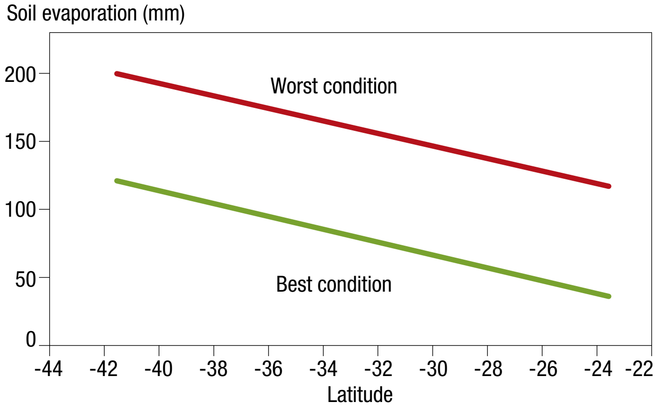
Soil evaporation is extremely variable, as illustrated in Figure 10.

It depends primarily on the pattern of rainfall and crop ground cover. High frequency of small rainfall events increases the proportion of rain lost as soil evaporation. Reductions in leaf area development caused by factors such as diseases, nutrient deficiency or soil compaction (see Figure 3) increase the proportion of rainfall lost through soil evaporation.

Assuming a single soil evaporation parameter to benchmark water use efficiency is therefore a very coarse simplification and possibly the main source of error in estimating water use efficiency using the French and Schultz approach.

Here it is proposed to use two boundary functions to

FIGURE 14 **Soil evaporation of wheat crops as a function of latitude and agronomic and environmental conditions**



'Best' conditions to achieve low soil evaporation include good nutrition and large proportion of total crop water use accounted for stored soil water.
'Worst' conditions leading to high soil evaporation include N deficiency and a large proportion of total crop water use accounted for by in-season rainfall, particularly small events.
These lines were derived from simulations with the APSIM model using characteristic soils and long-term climate records for 43 locations in combination with a broad range of initial soil water content and N availability.

represent the maximum and minimum soil evaporation as a function of latitude and general growing conditions (Figure 14). Under favourable conditions – for example, agronomy favouring rapid ground cover and a large fraction of seasonal crop water use derived from stored soil water – soil evaporation would range from 120mm in southern locations to 35mm in northern locations as rainfall shifts from winter to summer-dominant.

Under poor conditions – for example, poor agronomy and nutrient deficiency and a large fraction of seasonal crop water use derived from in season rainfall – soil evaporation would range from 200mm in southern locations to 120mm in northern locations.

Estimates of soil evaporation can be derived directly from Figure 14.

CHAPTER 4
Crop management, water use and water use efficiency

The amount and distribution of rainfall are major factors influencing crop water use. While farmers have no control over rainfall, by using different management practices they can affect how much of the rainfall is used by the crop and how efficiently it is used. Water use efficiency of crops is variable and while some of the variation in water use efficiency is caused by environmental factors, such as soil type, vapour pressure deficit and the timing of rainfall events, much of the variation is due to the management of the crop.

A number of studies in southern Australia have shown that growing season rainfall, while important to yield, only explains a small proportion of the variation in grain yield, indicating there is potential for significant improvements in water use efficiency by improved management. As water use efficiency is defined as yield (or biomass) per millimetre of crop water use, in broad terms management practices that produce high yields will increase water use efficiency and management practices that improve profit will increase the economic water use efficiency (dollars per millimetre of crop water use).

While this chapter will concentrate on the effect of management on productivity and water use efficiency, the profitability of the practices to improve water use efficiency needs to be considered. Also, in many experiments crop water use and water use efficiency are not measured, but improvements in water use efficiency (or at least rainfall use efficiency or water productivity) can be inferred from the changes in yield or biomass.

Management practices are often tailored to suit local patterns of rainfall and water availability and are reflected in regional differences in sowing rates, fertiliser management, row spacing and time of sowing. In northern regions for example, where winter crop yields depend on the amount of moisture in the profile at sowing rather than in-season rainfall, crops are often managed to curtail early vigour to manipulate water supply later in the growing season.

Conversely, in the southern and western regions where rainfall is winter-dominant, improving early crop vigour and biomass production prior to anthesis is often an effective means of increasing yield and water use efficiency.

Despite regional variations in crop management, there is an underlying theme to managing yield and water use efficiency in rainfed systems.

High yields will be achieved by maximising the capture and storage of rainfall and subsequent extraction of available soil water, increasing the efficiency at which available moisture is used and minimising the severity of drought stress during key developmental stages of the crop (see Figure 4). This can be achieved directly by altering the pattern of growth and water use through practices such as variety selection, time of sowing and sowing rate, or indirectly by minimising the effects of weeds and disease that either compete for soil moisture or which limit the ability of the crop to use available soil water or its use efficiency.

In many case there are interactions between different management practices, such as variety selection and time of sowing, which if not matched carefully can limit yields and water use efficiency.

Fallowing

Fallowing captures out-of-season rainfall and can increase the amount of water available for crop growth. Soil mineral

Table 3 Water use efficiency based on total biomass (WUEdm) or grain yield (WUEgy) of different crops. Water use efficiency is based on the biomass or yield per mm of crop water use. Values are mean and range.

Crop	Region	WUEdm (kg/ha.mm)	WUEgy (kg/ha.mm)	Source
Canola	Victoria	24.0 (17.1-28.4)	6.8 (4.7-8.9)	Norton and Wachsmann 2006
Canola*	NSW		13.4	Robertson and Kierkegaard 2005
Chickpea	Western Australia	16.0 (11.1-18.3)	6.2 (2.6-7.7)	Siddique et al. 2001
Lentil		12.7 8.5-16.7)	6.7 (2.4-8.5)	
Lupin		17.3 (9.3-22.3)	5.1 (2.3-8.3)	
Faba		24.2 (18.7-29.6)	10.4 (7.7-12.5)	
Pea		26.2 (17.6-38.7)	10.5 (6.0-15.9)	
Vetch		18.2 (13.4-22.4)	7.5 (5.6-9.6)	
Chickpea	Tel Hadya, Syria	13.7 (9.4-18.1)	3.2 (2.1-5.2)	Zhang et al. 2000
Lentil		8.7 (5.0-14.2)	3.8 (1.9-5.5)	
Wheat	South Australia	36.1 (21.2-53.1)	15.9 (9.2-23.2)	Sadras et al (unpublished)
	SE Australia		9.9 (max =22.5)	Sadras and Angus 2006

* based on simulated estimate of crop water use

nitrogen can also increase under fallows by mineralisation.

Fallowing is very important for winter crop production in the northern cereal zone where rainfall shows a strong summer incidence. In the southern and western regions fallowing is generally less important, but its value is greatest in low-rainfall environments and on fine-textured soils.

A survey of farms in the Mallee region of NSW, Victoria and South Australia found the average amount of soil moisture in the top metre of soil at sowing was 154mm (range 32 to 330mm) and this contributed to 16 per cent of the variation in yield. An additional 6kg/ha was produced for each millimetre of additional stored moisture. In an earlier study, in the 1960s in South Australia, using cultivated fallows, the mean increase in soil moisture after a 9 to 10-month fallow was 9mm (maximum 38mm) on sandy soils and 38mm (maximum 125mm) on fine-textured soils. The proportion of rainfall retained by fallowing (also referred to as fallowing efficiency) can be small, typically of the order of 20 per cent but frequently less.

However, retaining stubbles on the fallow and controlling summer weeds may help to reduce water loss from the fallow and improve fallow efficiency, although the value of stubble retention depends on soil texture and rainfall. On sandy soils, there may be little benefit from stubble retention on water capture over summer and in some cases standing stubble may enhance evaporative losses.

In contrast, on clay soils in southern Australia fallow efficiencies up to 40 per cent have been measured with retained stubbles. The ability to retain summer rainfall may also depend on the size of the rainfall events, with the benefit of stubble retention being low at both low and high rainfall during the fallow period. Small amounts of rain may evaporate quickly irrespective of the presence of stubble, whereas high rainfall that exceeds the evaporative demand may allow soil moisture to accumulate in both the presence and absence of stubble.

Where soils have subsoils with physical and/or chemical barriers to root growth, the additional moisture stored by the fallow may not be completely used by the crop. In a five-year study in the Victorian Mallee, 64 per cent of the stored moisture was used by the subsequent crop, although this ranged from 23 to 100 per cent. Improving the ability of crops' roots to grow into the subsoil and access moisture would improve overall benefits of fallowing.

While fallowing efficiency is often low, leading to small increases in available soil moisture and crop water use, the benefits of this moisture can still be high. A long-term study on cultivated fallow in South Australia in the 1960s found the average water use efficiency for dry matter production of wheat was 18.3kg/ha per mm after fallow and 15.9kg/ha per mm in non-fallow, and the corresponding values for grain yield were 6.1kg/ha/mm and 5.1kg/ha/mm. While the farming systems have changed considerably since this work was completed, the results are consistent with recent measurements on the use of subsoil moisture that found moisture stored in the subsoil can be used very efficiently.

Work in southern New South Wales has indicated that the conversion of subsoil moisture to grain can be up to 60 kg

Table 4 The effect of previous crop on the initial soil moisture and mineral nitrogen levels, grain yield of wheat and rainfall use efficiency in the Mallee region of South Australia and Victoria

Previous crop	Initial soil moisture (mm)	Initial soil mineral N (mg/kg)	Grain yield (kg/ha)	Rainfall use efficiency (kg/ha/mm)
Grain legume	149	14.7	2320	12.0
Fallow	169	22.0	1990	13.3
Pasture	154	12.6	1840	9.3
Cereal	130	9.8	1590	9.1

The data are the averages of a survey of 72 commercial wheat crops in the region.

Source: Sadras et al (2002)

Table 5 Mean yield loss of wheat when sowing is delayed past the optimum date, grouped according to the maximum yield recorded in the experiment

Yield category (t/ha)	Number of data sets	Mean maximum yield (t/ha)	Yield loss per week (mean ± std deviation)	
			%	kg/ha
<1.50	3	1.1	5.9 ± 3.89	61 ± 51
1.50–2.00	5	1.7	8.2 ± 5.8	139 ± 98
2.00–3.00	15	2.3	7.8 ± 4.8	178 ± 109
3.00–4.00	8	3.3	8.7 ± 4.4	285 ± 129
4.00–5.00	9	4.3	4.5 ± 1.7	197 ± 77
>5.00*	9	6.2	4.0 ± 1.7	239 ± 118
Average			6.6	198

* Includes some irrigated trials

This data was derived from experiments conducted in NSW, Victoria, SA and WA, the majority of which were conducted between 1972 and 2008.

grain/ha/mm compared to a reference 20kg grain/ha/mm for growing-season rainfall. Thus, small amounts of additional moisture may result in significant improvements in yield. The value of subsoil moisture over a wider range of soils and environments needs to be evaluated.

Crop species

There are intrinsic differences in the water use efficiency of crops (Table 3). Wheat is more water use efficient than grain legumes or canola whether considered in terms of total biomass production or grain yield. The reasons for the differences can be explained by the agronomic and physiological characteristics of the crops. Differences in the composition of the grain (see Chapter 2) partially explain the higher yield per unit water use of wheat compared to oilseed crops and pulses. Furthermore, canola and the grain legumes are grown at lower plant densities and/or have less vigorous seedlings than wheat, features that will contribute to greater early losses of moisture from soil evaporation and hence lower water use efficiency. The amount of winter growth made by the crop will be an important factor in determining the crop water use efficiency. Grain legumes also divert some of the sugars produced from photosynthesis to support nitrogen fixation in the root nodules, which would also reduce water use efficiency.

Crop rotations

Water use efficiency is most commonly considered for individual crops and often the focus is on management of the crop during the current growing season to improve water use efficiency.

However, management in the preceding years can be important to water use efficiency by influencing the amount of available soil moisture, the amount of soil nutrients – especially nitrogen – the severity of root and foliar disease and the level of weed competition, as illustrated in Table 4. Long-term management can also improve the physical, chemical and biological properties of the soil, which will enhance root growth.

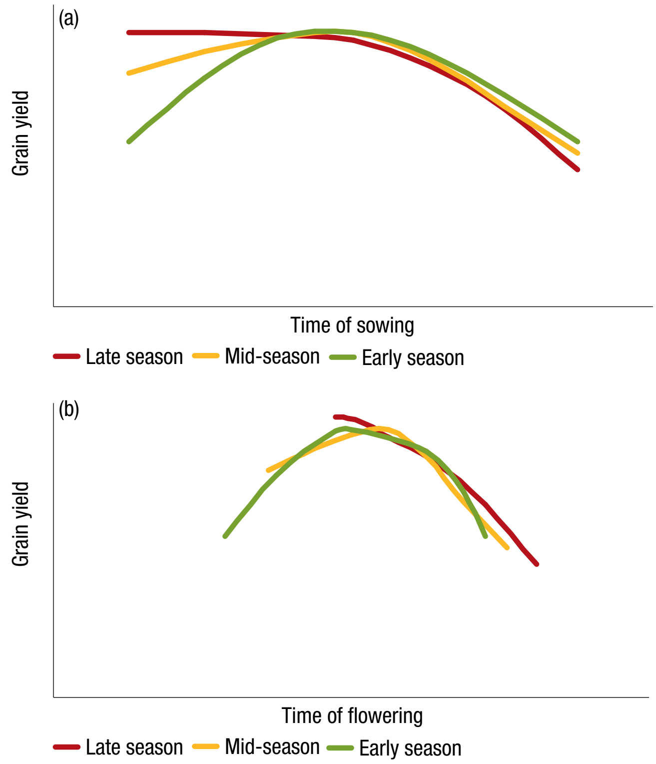
Including legumes in the crop rotation is an effective way of improving water use efficiency through improvements in available nitrogen and reducing disease incidence. Measurements of water use efficiency in rotation experiments show consistent increases in water use efficiency when wheat is grown after a legume (see Table 4).

In Western Australia, growing wheat after lupins increased total water use by 11 per cent (168mm compared to 186mm) and water use efficiency by 26 per cent (10.0kg/ha/mm compared to 7.9kg/ha/mm) compared to continuous wheat.

In Queensland, sowing wheat after chickpeas increased water use efficiency by a similar amount (27 per cent), compared to continuous wheat (11.7kg/ha/mm compared to 9.2kg/ha/mm). In this example, the increase in water use efficiency was related to the pre-sowing soil nitrate rather than differences in soil moisture.

Similarly in the Mallee region of south-east Australia,

FIGURE 15 Time of sowing and flowering window in wheat maturity and yield



A generalised response to (a) time of sowing and (b) time of flowering in winter cereal varieties differing in maturity. Yields are shown on a relative scale to illustrate the general trends with sowing time and actual grain yields will vary among the different maturity types, i.e. late, mid-season or early.

improving the available soil nitrogen as well as better disease and weed management by growing wheat after a grain legume, increased the rainfall use efficiency of wheat (see Table 4). In a long-term rotation trial at Tarlee in South Australia, average water use efficiency ranged from 3.0kg/ha/mm for continuous wheat up to 6.8kg/ha/mm for wheat grown after faba beans with supplementary nitrogen.

Time of sowing

Responses to sowing time

Arguably, time of sowing is the most important management practice that will affect water use efficiency and yield.

Many studies in a range of crops have shown late sowing will reduce yields, although sowing very early may have little benefit or reduce yields, leading to an optimum sowing period. Delayed sowing beyond the optimum time reduces grain yields of wheat on average by 6.6 per cent per week (Table 5).

The optimum time of sowing is largely determined by the pattern of development of the crop and its effect on time of flowering and therefore the selection of variety will also affect sowing date responses.

If there are opportunities to sow crops early in the growing season (for example, April to early May) varieties that develop slowly and are late flowering are used. Early sowing increases the effective length of the growing season and using varieties

Table 6 Yield, water use and water use efficiency of rainfed wheat crops sown at different times in regions with winter-dominant rainfall

Site	Sowing date	Grain yield (kg/ha)	Total water use (mm)	Water use efficiency (kg/ha/mm)
Kimba, SA	20 May	1500	226	6.6
	1 June	1340	268	5.0
	Change (%)	–11	19	–24
Turretfield, SA	22 May	2520	435	5.8
	7 June	2020	422	4.8
	29 June	1280	396	3.2
	Change (%)	–49	–10	–45
Minnipa, SA	11 May	2420	242	10.0
	5 June	1920	239	8.0
	28 June	1540	219	7.0
	Change (%)	–36	–10	–30
Werribee, Victoria	May	4305	305	14.1
	June	4193.5	292	14.3
	July	3280	259.5	12.6
	Change (%)	–25	–15	–11
Tel Hadya, Syria	November	2400	308	7.8
	December	2300	289	8.0
	January	1600	272	5.9
	Change (%)	–34	–11	–25

SOURCE: French and Schultz (1984), Connor et al (1992), Oweis et al (2000)

with 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.

Late-flowering lines in general will provide higher yields from early sowing, while early-flowering varieties may provide higher yields from late sowing.

While 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 (Figure 15).

For each variety the optimum sowing date will be that which 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 the effects the drought and heat stress.

Therefore, sowing decisions should perhaps be viewed in terms of when the crop will flower rather than when the crop can be sown. Selecting a variety to match to a time of sowing so that flowering occurs during the flowering window is therefore an important management decision to improve yield and water use efficiency.

Water use and water use efficiency

Time of sowing generally has a small effect on total crop water use but can have a marked effect on water use efficiency.

This is illustrated in Table 6, which shows that the response of water use to sowing date is between –10 per

Table 7 Estimates of crop evapotranspiration (ET) and its components transpiration (T) and soil evaporation (Es) at different locations in the cereal zone

Site	ET (mm)	T (mm)	Es (mm)	Es/ET (%)
Merredin, WA	154	70	84	55
Merredin, WA	164	92	72	44
Wongan Hills, WA	303	183	119	39
Werribee, Victoria	300	156	144	48
Rutherglen, Victoria	399	259	140	35
Tamworth, NSW	477	365	112	23
Narayen, Queensland	192	165	27	14

SOURCE: Yanusa et al. (1993), Perry (1987), Connor et al. (1992), Angus et al. (1980), Doyle and Fischer (1987) cent and +19 per cent, in comparison to responses of water use efficiency between –24 and –45 per cent.

The highest water use efficiencies are consistently achieved when the crop is sown at the optimum time.

Late sowing reduces water use efficiency for a number of reasons: delayed crop establishment and increased proportion of crop evapotranspiration lost as soil evaporation, higher likelihood of heat stress and reductions in biomass per unit water use associated with increasing vapour pressure deficit, as described in Chapter 2.

Table 6 also shows that the water use efficiency of the crop mirrors that of yield more closely that total water use: the optimum sowing date results in optimum water use efficiency.

This is an important point when considering the most appropriate combination of variety and sowing date. Sowing a variety at a time that is either too early or too late for its maturity type will reduce yield and water use efficiency, but may not greatly affect total water use.

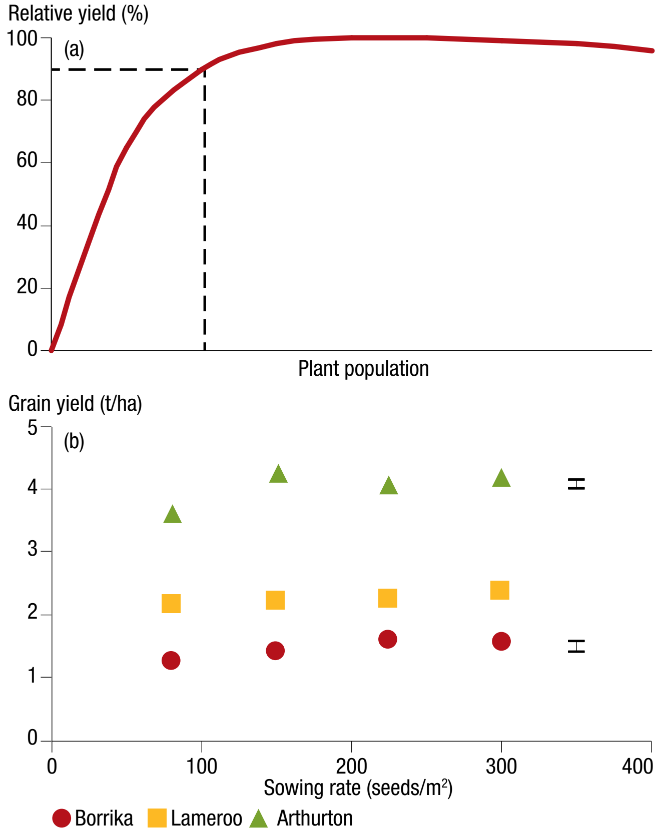
Planting arrangement

Plant density and row spacing determine the spatial arrangement of plants in crops. This affects the rate of early growth, the degree and timing of canopy closure and consequently the pattern of water use during the growing season. The degree and timing of canopy closure affects the proportion of crop water use lost as soil evaporation and thus influences water use efficiency. In areas with winter-dominant rainfall a large proportion of the total crop water use occurs as evaporation from bare soil under the crop. The amount of soil evaporation is proportional to the degree of ground cover by the crop canopy. Bare soil evaporation from the crop can represent 50 per cent of total crop water use (Table 7), most of which occurs during the early stages of crop development. However, the relative loss from soil evaporation declines as rainfall shifts from a winter-dominant to a summer-dominant pattern (Table 7). Reducing soil evaporative losses can improve water use efficiency by channelling more moisture through transpiration, which directly contributes to growth and yield.

By affecting the early growth of the crop, plant arrangement also affects the evapotranspiration during the pre-anthesis period and the balance between pre- and post-anthesis water use. High rates of crop growth during winter without adequate spring rainfall can induce high levels of drought stress in crops, limiting yield and lowering water use. Therefore, the best combination of sowing rate and row spacing is influenced by the amount of available moisture and the distribution of rainfall.

While sowing rates and row spacing are often considered as separate management practices, they do interact to affect yield, water use and water use efficiency. Crops are communities of plants that compete among themselves for growth resources, chiefly water, nutrients and light (see Figure

FIGURE 16 Curves showing typical response to sowing rates in cereals



(Top) A generalised response to sowing rate showing the initial increase in yield to an optimum sowing rate (shown as dashed line) above which there is little change in yield.
(Bottom) Examples of sowing rate responses in Schooner barley at three sites. Error bars for Borrika and Arthurton are LSD (5%). There was no significant effect of plant density on yield at Lameroo.

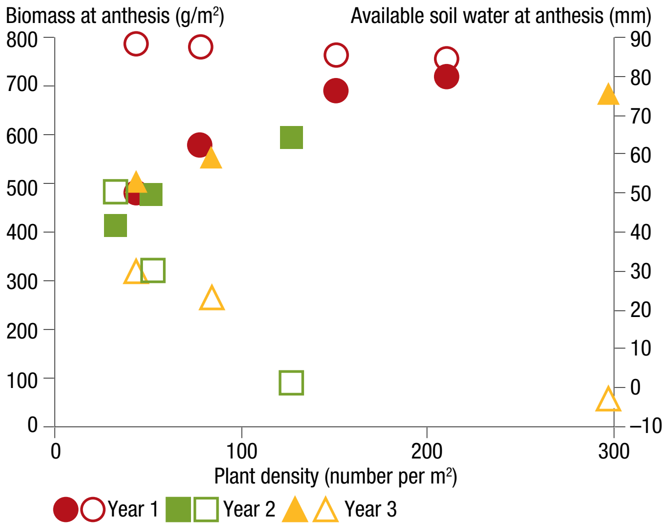
SOURCE: Jefferies and Wheeler (1993)

Table 8 Water use efficiency for biomass production in rainfed spring wheat at four times during the growing season

Time (days after sowing)	Sowing rate (kg/ha)		
	50	100	150
	(kg/ha/mm)		
71	5.0	9.5	13.0
96	22.5	25.5	25.0
112	27.0	34.0	34.0
166 (maturity)	42.5	45.0	42.0

SOURCE: van den Boogaard et al. (1996).

FIGURE 17 **The effects of plant density on biomass production (closed symbols) and available soil moisture (open symbols) at anthesis in three successive years**



The crops were grown after a summer fallow and had 130mm, 113mm and 123mm available soil moisture at sowing in years 1, 2 and 3 respectively and 240mm, 161mm and 188mm rainfall between sowing and anthesis in years 1, 2 and 3 respectively.

SOURCE: Doyle and Fischer (1987)

16). The degree of interference between plants is minimised when they are grown on a square arrangement, rather than a rectangular arrangement. This means that as sowing rates are increased, ideally the row spacing should be reduced to minimise the rectangularity of the plant arrangement and to reduce the intra-row competition. Conversely, as the row spacing is increased, without any adjustment to plant density, the degree of crowding within the row increases and the level of competition within the row increases.

While both plant density and row spacing can affect water use and grain yield, there may be other agronomic reasons for selecting a particular combination, such as the need to use wide rows to improve sowing into stubble, to assist with disease and weed management in crops or in frost management. Therefore, the final decision is often a compromise between the need to achieve high yield with the appropriate sowing rate – row spacing combination – and the desire to maintain crop residues (and the attendant benefits that accrue from this practice) and the need to undertake routine operations for sowing, pest management and weed control.

Sowing rate

Sowing rate can alter water use efficiency by influencing early crop vigour, and the pattern of water use before and after flowering. High sowing rates increase the initial crop growth rate and rate at which the crop canopy develops. A

Table 9 **The effects of row spacing on the grain yield and water use efficiency of wheat in a range of environments**

Location	Crop	Row spacing (cm)	Grain yield (kg/ha)	Water use efficiency (kg/ha/mm)
Morocco	Durum wheat	12	4020	9.5
		24	3380	8.0
		12	2310	7.8
		24	1620	5.5
Canada	Winter wheat	9	1585	9.9
		36	1455	9.4
Western Australia	Wheat	9	884	5.7
		18	792	5.1
		27	1008	6.7
	Wheat	9	1508	8.5
		18	1558	8.4
		27	1594	8.4
		36	1586	8.4
Syria	Winter wheat	17	1710	9.3
		30	1240	7.2
South Australia	Wheat	18	2946	13.9
		36	2753	12.8
		54	2277	10.8
Southern NSW	Irrigated wheat	17	4770	
		30	4870	
		45	4370	

SOURCE: Karrou (1998), Tompkins et al. (1991), Yanusa et al. (1993), Eberbach and Pala (2005), Stapper and Fischer (1990) consequence of increased early vigour is that the amount of water evaporated from the soil under the crop is reduced, increasing the amount available for transpiration and improving water use efficiency. However, the effect tends to diminish as the season progresses as the differences in the growth rates and canopy development among the different sowing rates narrow (see Table 8).

Most crops have considerable plasticity in their growth and can compensate for variation in plant density and row spacing. At low densities, plants can produce more tillers or branches, increasing biomass production and yield per plant, which compensates for a lower plant population. Consequently, yield can vary relatively little over a wide range of plant densities (Figure 16).

The ability to express this level of compensation is likely to be related to other environmental factors that promote growth such as water and nutrient availability. Yields are low at very low plant densities and increase to an optimum value. The optimum plant density is very broad or "flat" for cereals and pulses, and much sharper in maize.

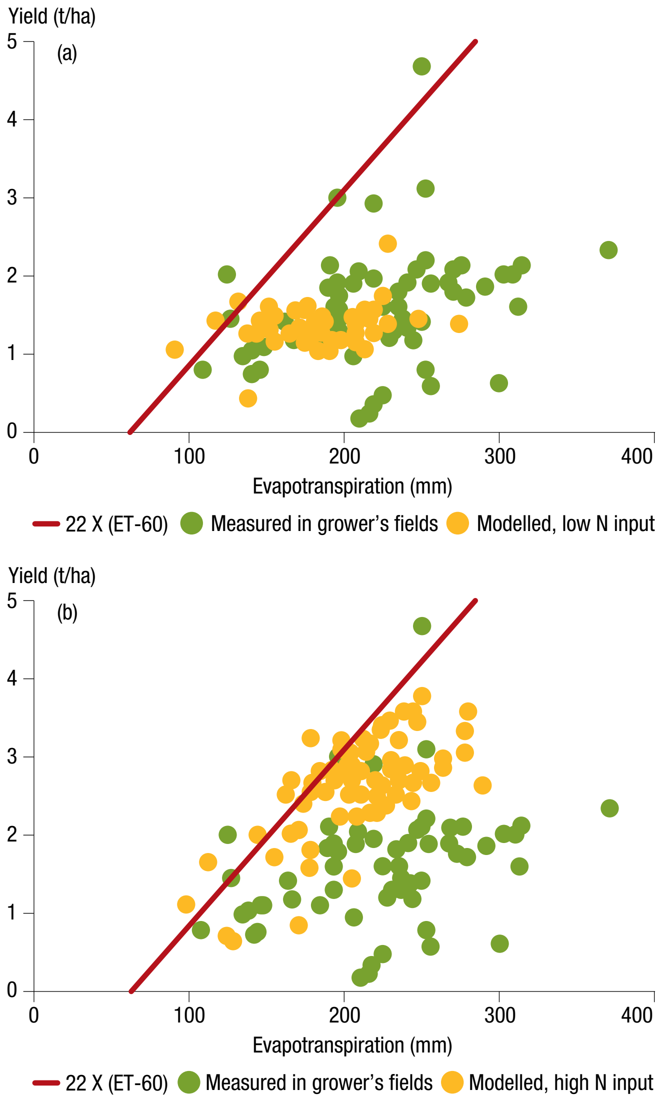
The optimum plant density is affected by the amount of available moisture as well as the ability of the crop to compensate for changes in plant density. For example, the optimum sowing rate can be lower with early sowing as plants can grow more vigorously and have a longer growing season.

There can be considerable site and season variation in the optimum plant density. In general, the drier the environment, the lower the optimum plant density. This is related to the effects of sowing rates on the patterns of water use during the growing season. High plant densities can increase the rate of water use early in the growing season, which may deplete soil moisture reserves and induce severe drought stress later in the growing season. Using lower plant densities in low-rainfall regions or in regions where crop water use depends on soil moisture reserves at sowing, helps to partition water use between the pre-flowering and post-flowering periods more effectively. This effect is illustrated in Figure 17 for wheat grown at a site with summer-dominant rainfall. Higher sowing rates increased biomass production and reduced the available soil moisture at anthesis, especially in the two years with low rainfall. In these two years, high sowing rates exhausted soil moisture by anthesis which reduced yield and water use efficiency. Similar responses may also occur in winter rainfall areas with below-average winter rainfall or in low rainfall areas.

Row spacing

Studies in a range of environments with wheat crops tend to show that increasing the row width will reduce yield and lower water use efficiency (Table 9). A series of experiments in Western Australia showed that there was an 8% decrease in yield for each 9 cm increase in row width. Reductions do not occur in every instance and often there are only small or no differences in yield as row spacing is widened. The causes of reductions in yield and water use efficiency are associated with increases in loss of moisture from soil evaporation as row width increases and the increased level of competition among plants within a row as row width increases. The effect may be greater when row width increases and high plant sowing rates are maintained, leading to a high degree of crowding in the row. The reduction in grain yield may be mitigated by increasing the spread of seed within the row (seed bed utilisation), thereby easing the severity of the intra-row competition and minimising the yield penalty of wide rows (Table 10).

FIGURE 18 Measured (green symbols) and modelled (yellow 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. Modelling of yield at the surveyed sites using low inputs of nitrogen gives a similar result to the measured yields, with substantial yield gaps evident. Increasing the nitrogen inputs predicts a closing of the yield gap.



SOURCE: Sadras (2005)

Table 10 **The effects of row spacing and the spread of seed within the row (row width) on the grain yield of wheat. Source: Anderson et al. (2005)**

Row width (cm)	Row spacing (cm)		
	18	24	36
2.5	1.19	0.88	0.92
5.0	1.03	0.93	1.01
7.5	0.96	0.99	1.06
LSD (P=0.05)	0.09		

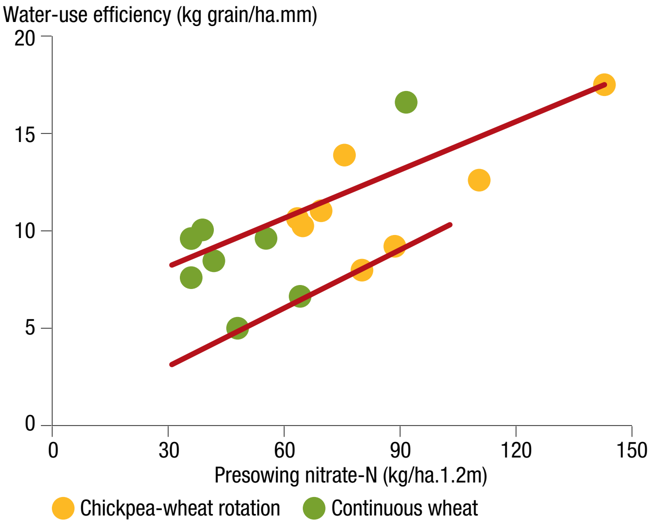
While increased row spacing can lead to increased bare soil evaporation and reduce water use efficiency, the effect may not be important in crops with small canopies and the yield reductions in this case may be most strongly related to increased competition within the row. Where the maximum leaf area of the crop is small, altering row width has little effect on bare soil evaporation because the level of ground cover is low and little affected by row width. In a study in Western Australia where the leaf area index at anthesis was 1.0-1.5 and crop yields ranged from 800 to 1500 kg/ha, soil evaporative losses were unaffected when the row width was increased from 9 cm to 36 cm. In all cases bare soil evaporation was 45-55% of crop water use. Consequently, water use efficiency for grain yield was unaffected by row spacing. As with responses to sowing rate, the yield benefits from wide rows may be seen when crops rely on out of season rainfall or when the in-season rainfall is low with dry springs: this may allow a better match between the availability of soil moisture and the crop's moisture requirement during critical stages of development.

Grain yield responses to row width in pulses can vary depending on crop and seasonal conditions, but in most cases there are small and non-significant effects of row spacing or a reduction in yield with wide row spacing (Table 11). Yield increases with wider row spacing occur occasionally under low yielding conditions, but under high yielding conditions yields more often decline or show little response. Table 11 shows that grain yield may be little affected by increasing row widths up to about 30 cm but yields are likely to decline at greater widths. The lower plant populations at which pulses are grown, compared to cereals, may be a contributing factor to their greater yield stability to changes in row spacing. In faba bean, shading can reduce pod set on the lower nodes and using wide rows may improve light penetration in the canopy. It is often observed that plant height and the height to podding are greater in legumes grown in wide rows, which may reduce harvest loss, especially when height is restricted by low rainfall. The improvement in plant height and in pod height may be associated with greater crowding within the rows at wide row widths if sowing rate is not adjusted as row width is increased. While water use efficiency was not measured in these experiments, the differences in the efficient use of seasonal rainfall will reflect the yield responses: thus there may be reductions in rainfall use efficiency as row spacing increases beyond 30 cm.

Canola yields generally are lower when grown under wide rows although there is evidence that varieties differ in their response. Trials over eight sites in Western Australia showed an average yield loss of 14% (range = 8-27%) for canola grown in 36 cm row widths. Similar trends have been reported in South Australia. A trial at Roseworthy measured average yield losses of 8% at 36 cm and 17% at 54 cm row widths compared to the standard 18cm row width, but there were differences among varieties in the response. Trail data from high rainfall sites in NSW tend to show no significant effect on yield from 36 cm row spacings and in a trial at Wagga Wagga, yields among six varieties of canola grown at 36 cm spacing ranged from a 14% yield loss to a 15% improvement.

The present evidence suggests that using wide rows may have limited benefit to the efficient use of seasonal rainfall or may cause significant reductions in efficiency. Using 30 cm spacings may have small impacts on yield but going to wider spacings runs the risk of reductions in yield (and hence efficient use of growing season rainfall). Exceptions to this may occur in some low yielding environments when total season rainfall or its distribution during the growing season results in significant levels of moisture stress during key stages of development. The selection or row spacing will therefore be a compromise between the potential reductions in water use efficiency and the benefits of using wider rows

FIGURE 19 **The relationship between the amount of soil nitrate-N in May and grain yield of wheat in a chickpea-wheat rotation ● compared to continuous wheat ● in two years.**



SOURCE: Dalal et al (1998)

in other aspects of crop management, such as weed and disease management, residue management and the ability to inter-row sow.

Crop nutrition

Having an adequate and balanced supply of nutrients is essential to improve yield and water use efficiency. For example, grain yield among commercial crops in the Mallee region of south-eastern Australia was found to be related in part to the rate of nitrogen, phosphorus and sulfur applied.

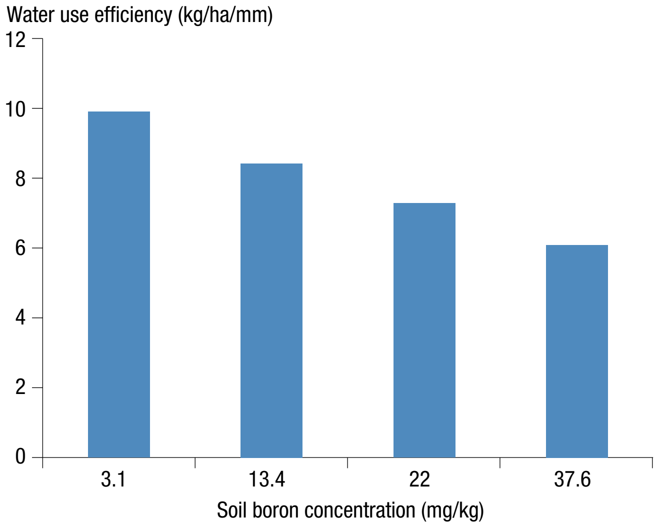
Crop nutrition can affect a number of aspects of crop growth related to water use and water use efficiency, such as root growth, the rate of canopy development, biomass production and harvest index. An example from two sites that showed large responses to improved nutrition from a region with winter-dominant rainfall is shown in Table 12. Fertiliser increased yield with no change in total water use. The improvement in water use efficiency was achieved by a better partitioning of crop water use, with a reduction in unproductive soil evaporation and significant increase in transpiration.

Nitrogen is the nutrient required in largest amounts by crops and its supply can greatly affect growth, yield and water use efficiency. Surveys and crop simulation studies in southern and western Australia have highlighted the importance of adequate nitrogen nutrition to yield and to water use efficiency. Work in the Mallee region of south-eastern Australia indicates that even in environments with

Table 11 The effects of row spacing on the grain yield of different pulse crops.

Location	Crop	Row spacing (cm)	Grain yield (kg/ha)	Source
Queensland	Chickpea	18	2480	Beech and Leach 1988
		36	2620	
		53	2520	
		71	2490	
		18	690	
		36	890	
		53	850	
		71	740	
South Australia	Kabuli chickpea	18	933	Kleeman and Gill 2010
		36	900	
		54	883	
	Desi chickpea	18	1601	
		36	1383	
		54	1117	
South Australia	Kabuli chickpea	22.5 (stubble removed)	1300	Hart Trial Cropping Results 2009
		45 (stubble removed)	1270	
		22.5 (standing stubble)	1350	
		45 (standing stubble)	1270	
Victoria	Lentil	19 (stubble slashed)	470	Brand, Lines et al. 2010
		30 (stubble slashed)	500	
		30 (standing stubble)	520	
Western Australia	Faba bean	19	1830	Bolland, Reithmuller et al. 2001
		38	1870	
South Australia	Faba bean	18	780	Kleeman and Gill 2008
		36	980	
		54	950	
South Australia	Faba bean	22.5 (stubble removed)	3310	Hart Trial Cropping Results 2009
		454 (stubble removed)	2230	
		22.5 (standing stubble)	3420	
		454 (standing stubble)	2640	
South Australia	Field pea	22.5 (stubble removed)	2900	Hart Trial Cropping Results 2009
		454 (stubble removed)	2510	
		22.5 (standing stubble)	3060	
		454 (standing stubble)	2410	

FIGURE 20 **Water use efficiency of wheat (cv Warigal) grown in soil with different concentrations of boron**



SOURCE: Holloway and Alston (1992)

low rainfall, crops are still limited by low nitrogen supplies, but particularly in wetter years (see Figure 18). The potential value of optimum nitrogen supply was illustrated in another studies using crop simulation of over 300 crops from the Yield Prophet® database. Managing nitrogen so it was non-limiting to yield could potentially increase water use efficiency from 16.9kg/ha/mm with current farmer practice to 19.6kg/ha/mm. Combining improved nitrogen nutrition with early sowing and high plant density lifted water use efficiency further to 21.4kg/ha/mm.

Improving the supply of nitrogen from fallowing or from growing wheat after a legume increases the water use and water use efficiency of a following wheat crop. In Queensland for example, the water use efficiency of wheat grown in a chickpea-wheat rotation was directly related to the amount residual nitrate at the start of the growing season (Figure 19). In recent times nitrogen fertiliser has been increasingly used to supply nitrogen to the crop, especially in the medium and high-rainfall areas. The strong interaction between moisture supply and nitrogen response (see Figure 18) and the desire to improve the economic and biological efficiency of nitrogen use has seen a shift in nitrogen management to delayed or split applications of fertiliser from the conventional approach of applying the nitrogen at sowing.

Unless available soil nitrogen is very low, applications of nitrogen fertiliser can be deferred to later in the growing season without penalising grain yield. Table 13 shows that not only can adding nitrogen improve yield and the efficiency of water use but that strategic post-sowing applications can enhance this effect. The supply of nitrogen can be used to manipulate canopy development and biomass production and water use. It also can be matched to the conditions of the growing season and provide greater flexibility in nitrogen management. The principles of nitrogen management for high water use efficiency can be summarised as:

- estimating the demand for nitrogen based on target yields and protein concentrations;
- estimating the soil available nitrogen at the start of the season;
- monitoring growth conditions, but especially water availability; and
- adjusting the timing of nitrogen applications to match supply of nitrogen to crop growth, but targeting the critical yield-forming period leading up to flowering.

Variety selection

The choice of variety can be an important aspect of managing crops for maximum water use efficiency. Choosing the most appropriate variety to suit the environmental conditions or which has tolerance to pests and disease is an effective way of improving water productivity. Variety selection can potentially improve water use efficiency in a number of ways.

Matching development to sowing date

Table 12 **The effect of nutrition on yield, water use and water use efficiency of barley grown at two sites in winter-rainfall locations of Syria, Jindiress (478mm average annual rainfall) and Breda (278mm average annual rainfall)**

	Site and fertiliser treatment			
	Jindiress		Breda	
	Nil	Fertiliser	Nil	Fertiliser
Grain yield (kg/ha)	3260	4610	1510	2010
Crop water use (ET; mm)	331	356	235	239
WUE (kg/ha/mm)	9.8	12.9	6.4	8.4
Transpiration (T; mm)	188	232	76	96
Soil evaporation (Es; mm)	143	124	159	143
Es/ET (%)	43	35	68	60

SOURCE: Cooper et al. (1987)

Matching crop maturity type to sowing time is an effective means of improving water use efficiency. Early sowing will be most effective when varieties are able to flower at the appropriate time and can take full advantage of the extended growing season. The response to time of sowing is affected by the maturity type of the variety and to improve yield and water use efficiency, variety needs to be matched to sowing date.

Tolerance to subsoil limitations

Soil properties that restrict plant growth, such as alkalinity, acidity, salinity or high concentrations of boron or aluminium lead to incomplete use of available soil water and limit yield per unit rainfall (see Figure 20). In the Mallee region of south-eastern Australia for example, it was estimated that there was approximately a 23 per cent reduction in yield per unit rainfall associated with saline and alkaline subsoils. Selecting varieties with enhanced tolerance to these soil stresses may help to improve water use and water use efficiency.

However, tolerance to a particular subsoil constraint may not necessarily improve root growth and water use if there are other major limitations. This may occur, for instance, in soils with high levels of boron and salt, where the value of improved boron tolerance may be negated by the effects of salinity.

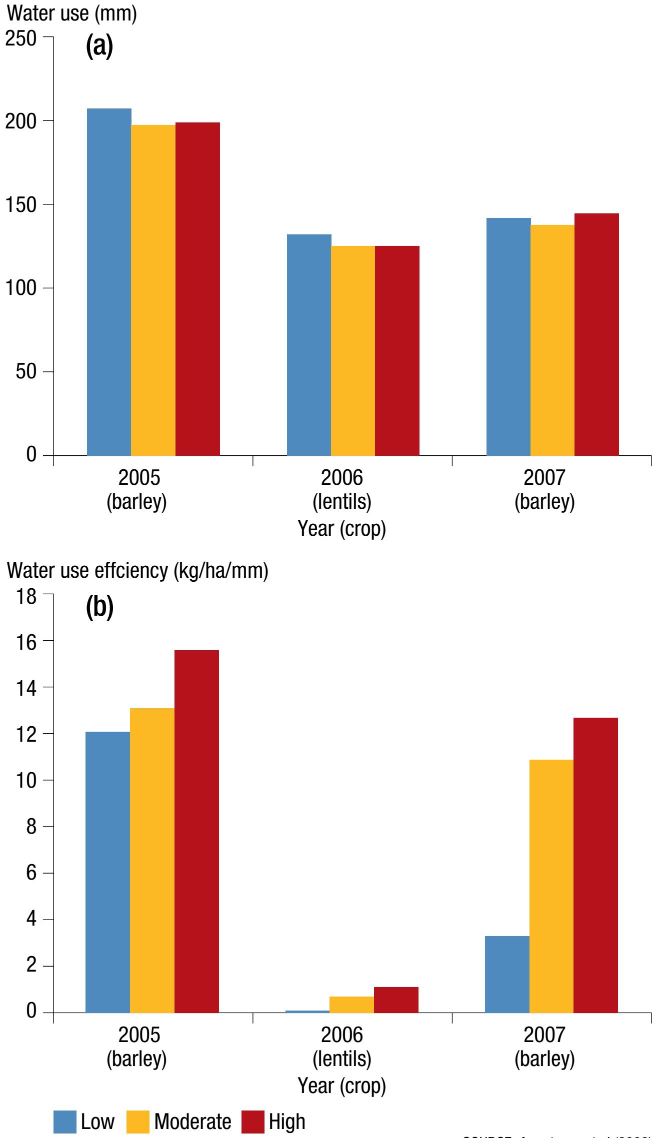
Tolerance to disease

Both root and foliar diseases can reduce water use and water use efficiency. Root and crown diseases will reduce the ability of crops to take up water and nutrients from the soil, while foliar disease may reduce green leaf area and restrict biomass production. Using varieties that are tolerant or resistant to the expected suite of diseases in the region helps to underpin water use efficiency.

Precision agriculture

Variation in soil properties and landform can lead to high spatial variation in growth and grain yield and this is reflected

FIGURE 21 Variation in (a) total crop water use and (b) water use efficiency among different production zones over three years in a paddock at Birchip, Victoria



SOURCE: Armstrong et al (2009)

Table 13 The grain yield response and water use efficiency in wheat to an application of 100kg N/ha applied at sowing or at different time after sowing at Mintaro, SA, in 2003. Water use efficiency is based on growing season rainfall (315mm)

N treatment	Grain yield (t/ha)	Water use efficiency (kg/ha/mm)
Nil	2.25	7.14
Sowing	2.86	9.08
3.5 leaf	3.00	9.52
1st node	3.02	9.59
3.5 leaf + 1st node	3.17	10.05
3.5 leaf + awn appearance	3.05	9.68
1st node + awn appearance	2.96	9.39
Sowing + 3.5 leaf + awn appearance	2.95	9.37
LSD (P = 0.05)	0.14	

SOURCE: Hooper (2010)

in spatial variation in water use efficiency (see Figure 21). Interestingly, the variation in total water use in this example is much less and not strongly related to water use efficiency, suggesting the variation in water use efficiency is caused by differences in the partitioning of water use between transpiration and soil evaporation.This may, for example be associated with differences in early vigour and canopy development as well as the ability of the crop to exploit soil moisture reserves though the degree of root growth.

There is little data at present to indicate what potential gains can be made in water use efficiency by site-specific management but, in principle, developing management programs that enhance yield in different production zones may contribute to an overall improvement in water use efficiency. Alternatively, altering inputs according to soil type to increase profits may improve the economic water use efficiency ($ per ha/mm) without major shifts in biological water use efficiency.

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