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

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

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CONTENTS

INTRODUCTION

Water availability is a major constraint for production of grain in Australia and improving water use efficiency is a primary target for 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 sometimes imposed by excess water are not considered in 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 in guidelines to improve crop water use efficiency. However, understanding the principles is a powerful means to help determine appropriate solutions for the combinations of soil, climate, technology and finance found on a 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. This enables growers and advisers to improve their estimates of attainable water use efficiency. Chapter 3 also highlights the important trade-off between nitrogen use efficiency and water use efficiency that is critical in decision making – and the practical consequence that maximising water use efficiency may require nitrogen rates that are too costly, too risky or environmentally unsound. Thus, growers need to target water and nitrogen use efficiency collectively, rather than individually. This is particularly important when the price of nitrogen fertiliser is high relative to that of grain.

Chapter 4 presents information from diverse Australian environments on 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.

ACKNOWLEDGEMENTS

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CHAPTER 1
Crop growth and yield: physiological principles

This chapter discusses the two key principles that underlie the determination of yield in grain crops:

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

These principles will help us to:

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

Capture and efficiency in the use of resources drive crop growth

Figure 1 shows 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).

Thus, 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. Environmental factors, such as ambient temperature or soil salinity, modulate the rate of capture of resources and the efficiency in the transformation of resources into plant biomass and these are illustrated by the dashed lines in Figure 1.

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. Using a straight line to represent 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, when wheat crops established in compacted Mallee soil and crops where subsoil compaction was relieved

FIGURE 1 How crop biomass is driven

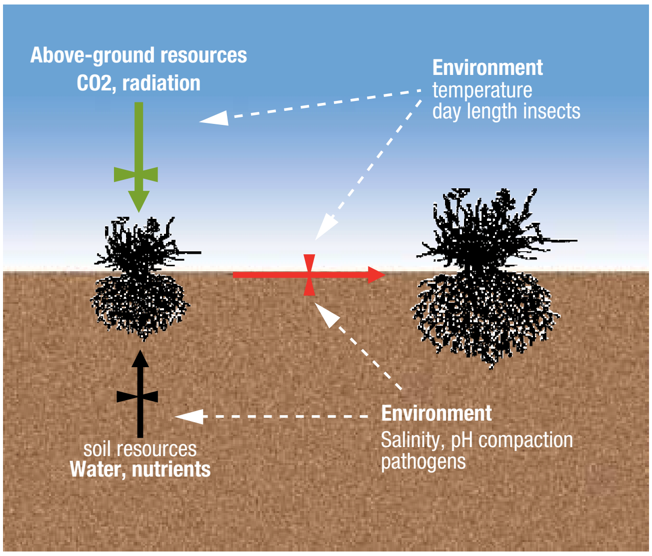
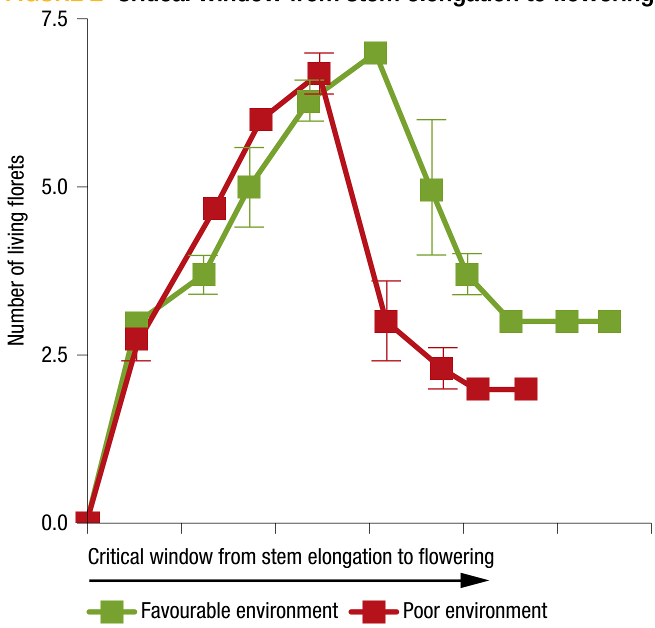


FIGURE 2 Critical window from stem elongation to flowering



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, leading to a 40 per cent reduction in intercepted radiation. Capture of water by the crop, measured as transpiration, was similarly reduced from 110 to 60 millimetres. Biomass per unit transpiration, however, was largely unaffected, at about 58 kilograms per hectare per millimetre for both crops. The next chapter will discuss further the stability or otherwise of water use efficiency.

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

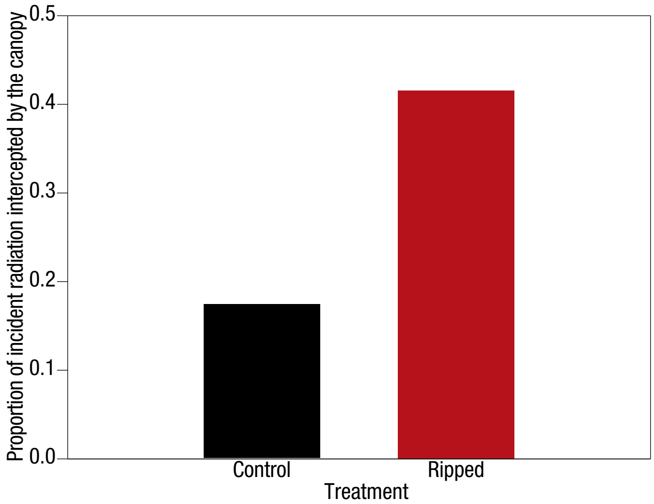
The production of biomass is proportional to the amount of water, radiation and nutrients captured by crops as modulated by the stresses discussed earlier (see Figures 1 and 2). However, the step from biomass to grain yield also depends on the occurrence of stresses during the critical windows when grain number and grain size are determined. For most annual crops, these windows have been identified, as illustrated in Figure 4. Grain number is reduced when stress occurs in critical developmental stages, usually around flowering. Compared to unstressed controls which produce 100 per cent of the (potential) number of grains (horizontal line in Figure 4), stressed crops exhibit depression of grain set and consequently lower grain number. Stress before or after this period has relatively less effect.

For wheat, the critical window for determining grain number is between stem elongation and shortly after flowering which for typical Australian crops spans the period from 20 to 30 days before to 10 days after flowering.

Figure 5 shows that final grain number in wheat is determined by two processes. First the wheat plant overproduces florets; each floret in a spikelet can produce one grain. Then, some of the later formed florets in each spikelet die; the extent of this floret mortality depends on

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.

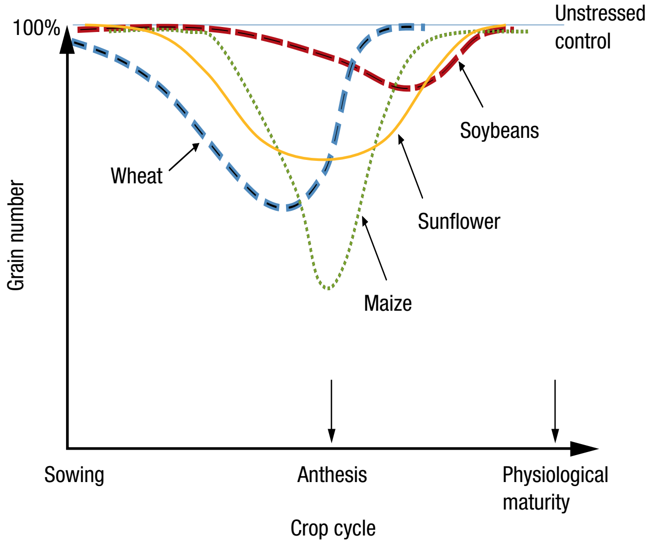
SOURCE: Sadras et al. (2005)

environmental conditions and determines final grain number. Each spikelet forms up to eight florets, but even under good conditions crops only set 'four wide' and under stress this may be reduced to only two or even one grain in each spikelet.

Over the same developmental window, the plant sets an upper limit for grain size which is also affected by environment. For example, elevation of temperature by 5°C over ambient between booting and anthesis can reduce maximum grain size of winter cereals by about 20 per cent.

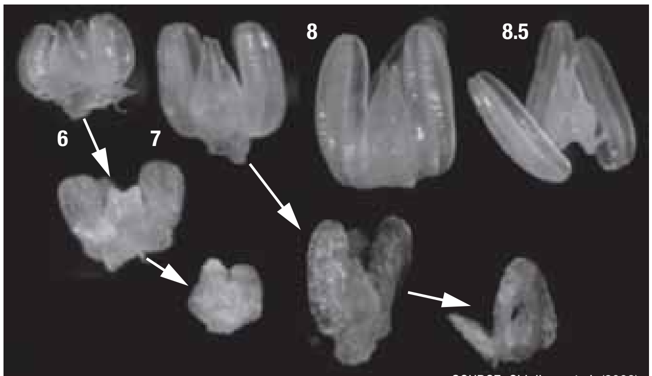
Thus by the end of this developmental window centred on flowering time, the maximum yield of the crop, defined in terms of number and size of grains, is pretty much defined. For this reason, stresses such as frost, high temperature, water deficit or low radiation occurring in this critical 'window' have a direct effect on yield. Appropriate choice of cultivar and sowing date allows growers to partially manage their risk by manipulating flowering time, and this is discussed in Chapter 4.

FIGURE 4 Impact of stress on grain number



SOURCE: Calviño and Monzon (2009)

FIGURE 5 Final grain number in wheat



SOURCE: Ghiglione et al. (2008)

CHAPTER 2
Water use efficiency: climate and crop drivers

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.

CO_2 uptake and water loss

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 thus a tight trade-off between uptake of CO_2 and water loss, and this explains the close link between crop production and water use.

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.**

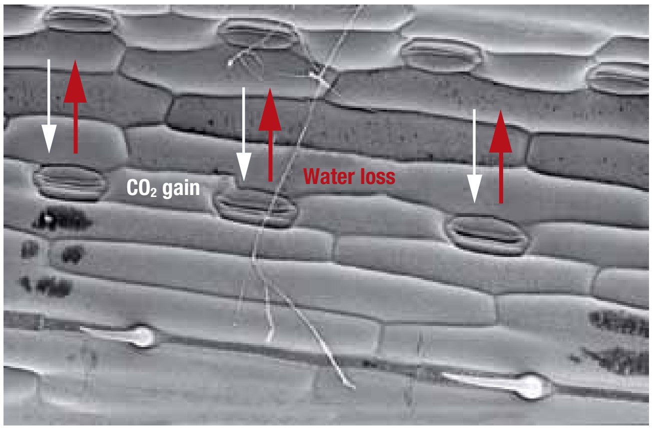


IMAGE: University of Bath, UK

Water use efficiency and vapour pressure deficit

Vapour pressure deficit (see Box 1), is one of the main drivers of water use efficiency, and understanding its influence helps understanding of the effects of management decisions such as crop choice, sowing date and fertiliser rate.

Liquid water moves from soil to root, and from root to shoot. In leaf cavities just below the stomata, water passes from liquid to 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 – the difference between the vapour pressure in the saturated leaf cavities and the less than saturated atmosphere. This difference in vapour pressure is therefore the driving force of crop transpiration.

Vapour pressure deficit has a large impact on water loss but little direct impact on CO_2 uptake. Thus with high vapour pressure deficit (a warm, dry atmosphere) 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 that biomass per unit transpiration for early sown barley was 47 kilograms per hectare per millimetre compared with late-sown barley that only produced 30kg/ha per mm. The early sown crop flowered earlier under cooler, moister conditions and, overall, experienced a lower vapour pressure deficit compared to that sown later. When 'normalised' for vapour pressure deficit (Figure 7b) the crops exhibit the same water use efficiency. In other words, the greater biomass per mm of

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, 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 effect of temperature and humidity, and is therefore a more robust measure of air dryness than relative humidity.

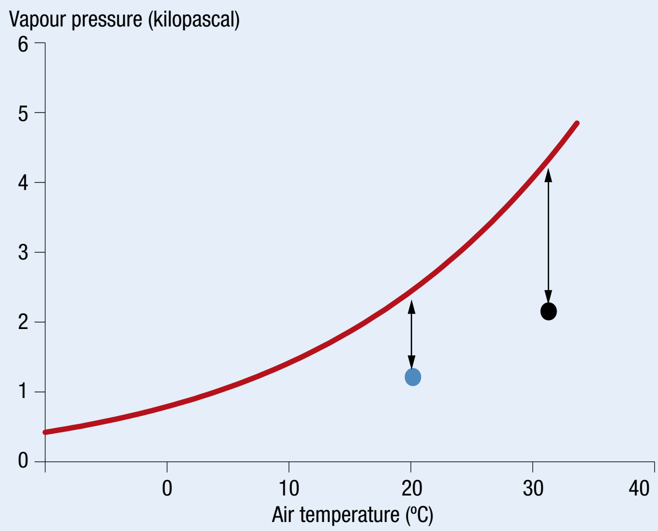
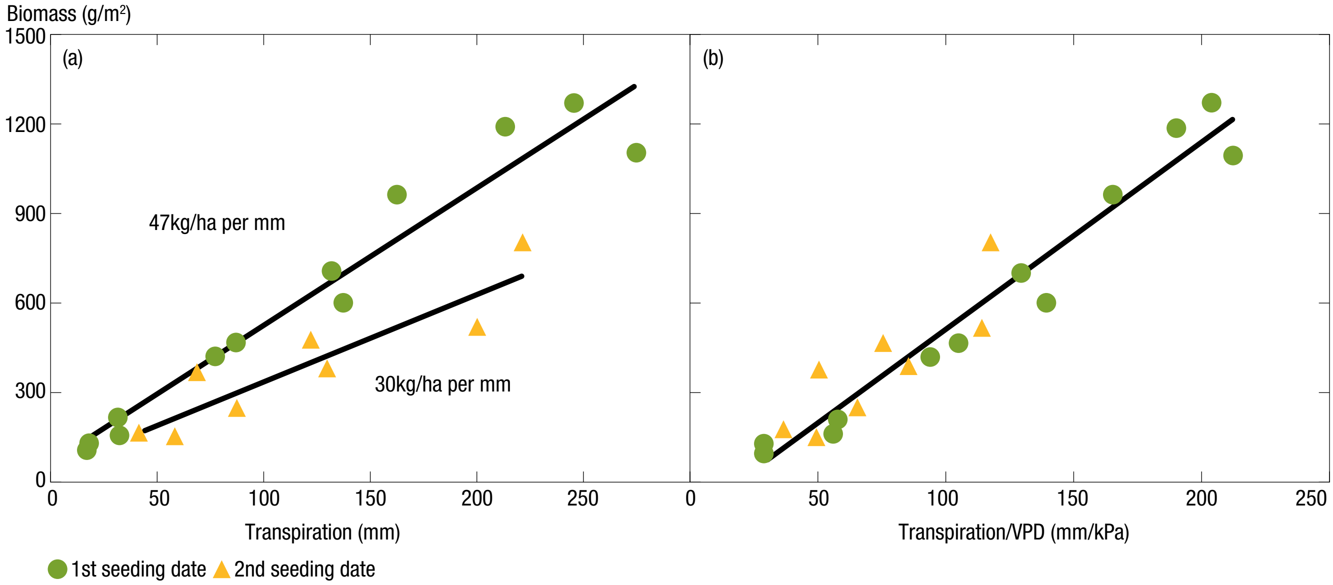


FIGURE 7 **Biomass and transpiration of early-sown barley**



(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 (VPD) the differences between 1st and 2nd seeding date disappeared.
SOURCE: Kemanian et al. (2005)

water use of the early sown crop was due to the lower ambient vapour pressure deficit.

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 mm – was originally derived under South Australian conditions. This parameter would therefore overestimate yield per millimetre in northern NSW and central Queensland, where the corresponding vapour pressure deficit is higher, and may 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.

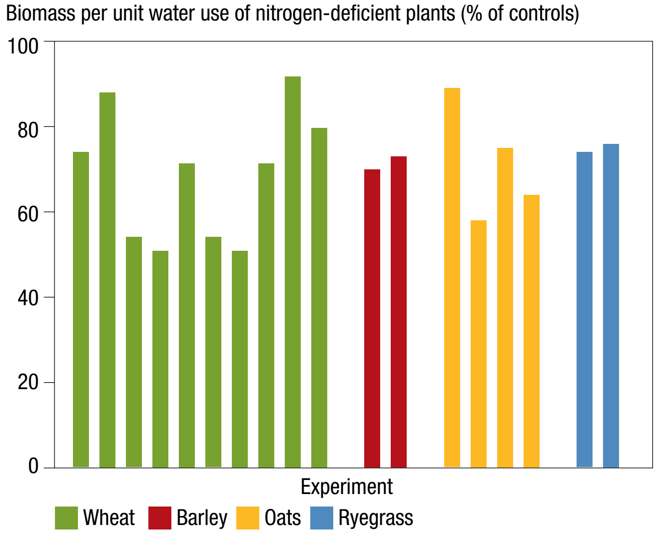
Water use efficiency and rainfall patterns

Seasonality and size of rainfall events also influence crop water use efficiency. In the southern and western grain-growing regions, rainfall is winter-dominant falling during the crop's growing season; whereas in the northern region it is summer-dominant with few (but heavier) rainfall events during the winter growing season. 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, but this is less so for the northern region. On the other hand, 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.

Water use efficiency and nitrogen availability

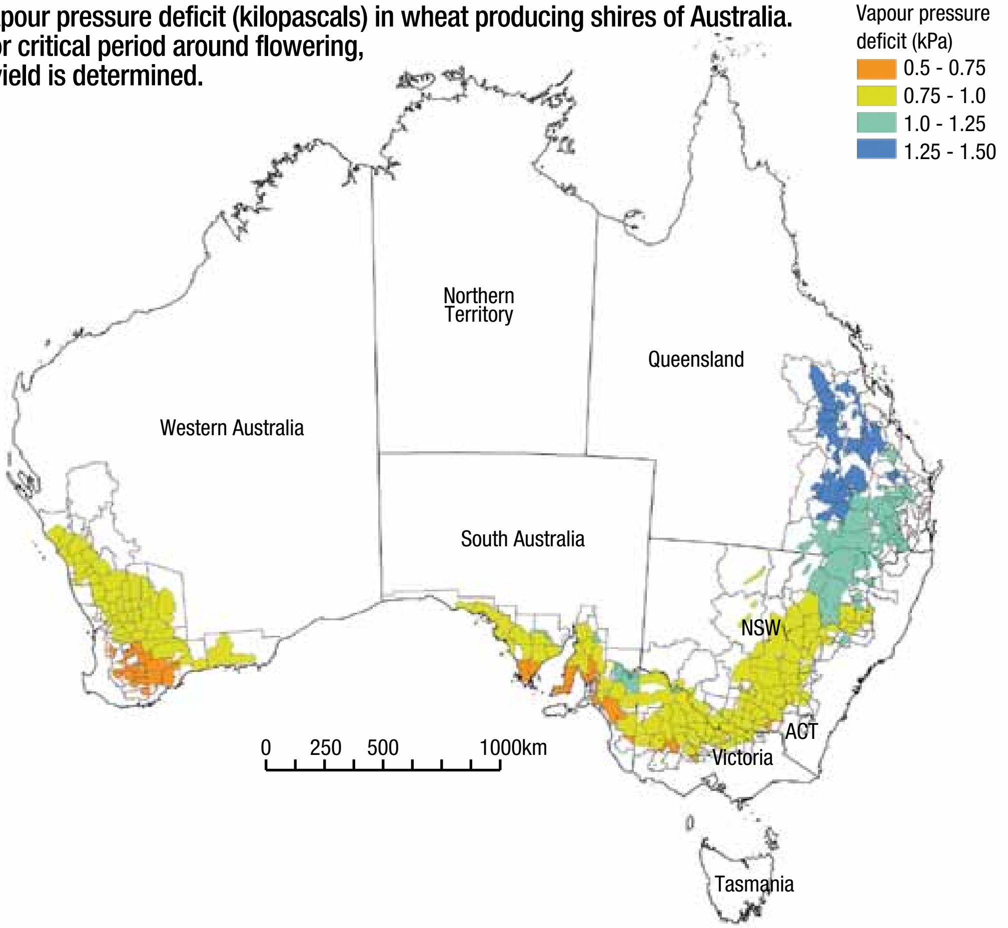
Nitrogen-deficient soils reduce water use efficiency. First, a nitrogen-deficient crop will have impaired photosynthesis; hence, above-ground dry matter per unit transpiration will drop. Figure 9 shows consistent reductions in above-ground

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)

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)

dry matter per unit transpiration of up to 50 per cent when nitrogen deficient crops were compared with well fertilised controls.

Second, the smaller root system and canopy associated with nitrogen deficiency reduces the ability of the crop to capture soil water and nutrients and increases soil evaporation as the smaller canopy provides less shade for the soil surface.

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 unsound.

Table 1 Effects of nitrogen (N) 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 of yield per unit N

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)

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

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)

Water use efficiency and seed composition

The relationship between leaf photosynthesis and water loss (adjusted for vapour pressure deficit) is rather robust and there is not much difference between crop species. The main exception is 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: 1 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 (Box 2). This approach relates grain yield and 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, we present location-specific parameters for benchmarking wheat water use efficiency for crops grown with a wide range of nitrogen supply.

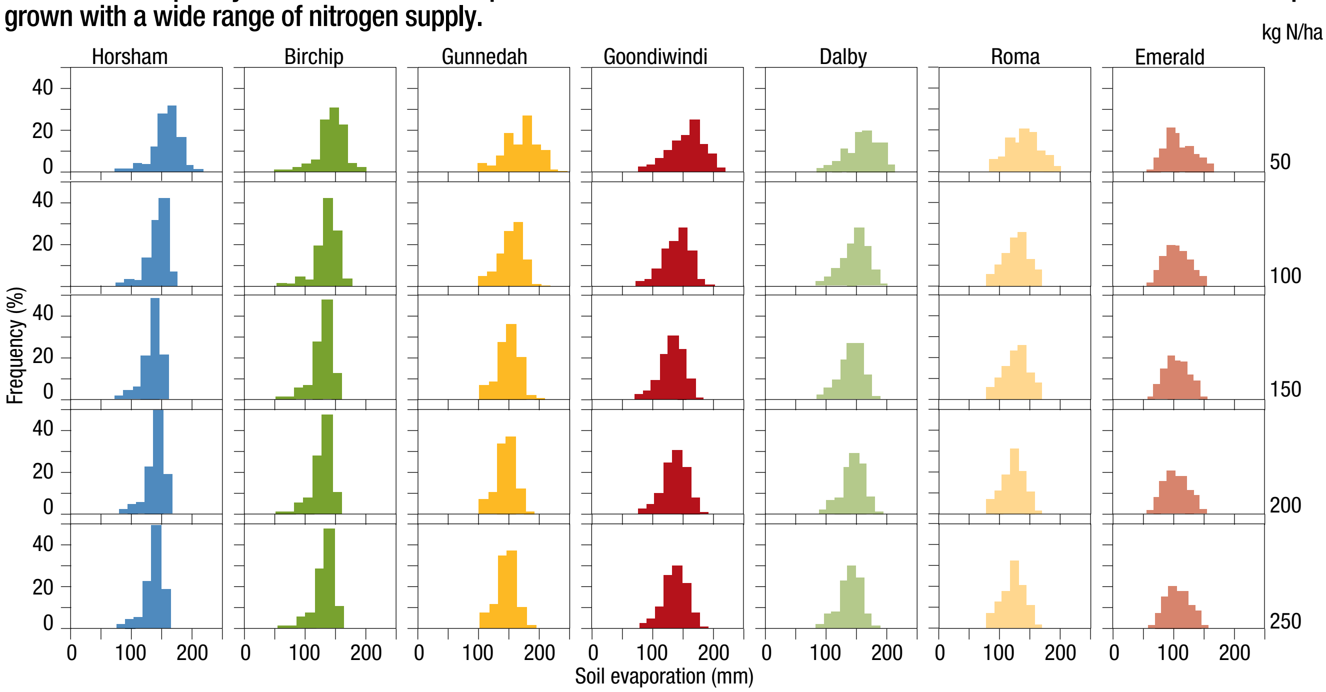
French and Schultz parameters: expected effects of climate and nitrogen

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 20 kg/ha per mm. This slope accounted for varieties and management practices typical of the 1960s and 1970s, and was limited to South Australian environments. Current varieties are closer to 25 kg/ha/mm. The second parameter is the water use for zero yield, which is interpreted as unproductive soil evaporation. This parameter is usually was set to 110 mm, 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 showed 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 reference in southern locations.

The approach of French and Schultz has known limitations; for example it does not account for timing of rainfall. As we have seen 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 we understand its limitations and, very importantly, we use the right parameters.

Using the principles outlined in Chapter 2, we can

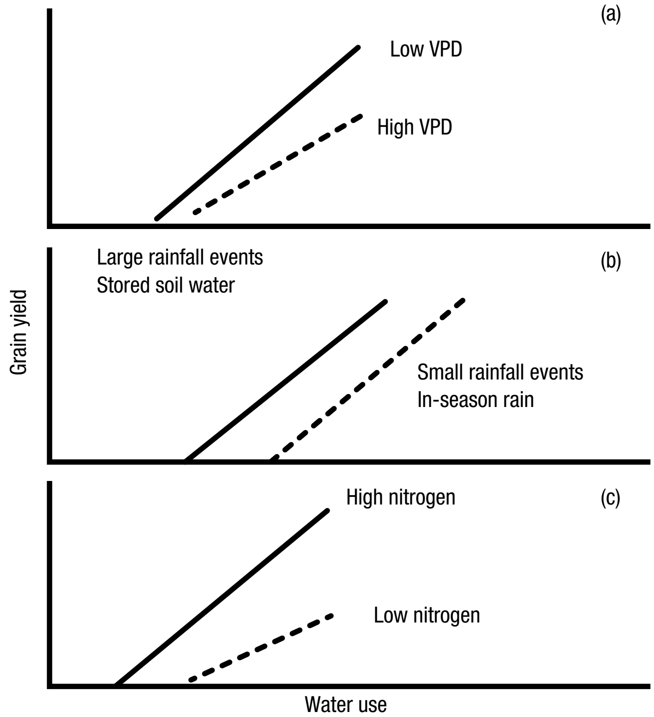
FIGURE 10 Frequency distribution of soil evaporation in a south-north transect from Horsham to Emerald for wheat crops grown with a wide range of nitrogen supply.



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. 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.

now discuss the effects of climate and nitrogen on the parameters of the French and Schulz model. First, the slope of the line decreases with increasing vapour pressure deficit (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, southern region), as opposed to locations with a dominance of stored soil water and large rainfall events (e.g. northern region) (Figure 11b). Third, nitrogen deficit reduces the slope and increases soil evaporation (Figure 11c). These predictions are based on the principles of crop physiology and agronomy outlined in Chapter 2, and have experimental support. Importantly, there is a nitrogen-driven trade-off between water use efficiency and nitrogen use efficiency (Table 2).

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

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

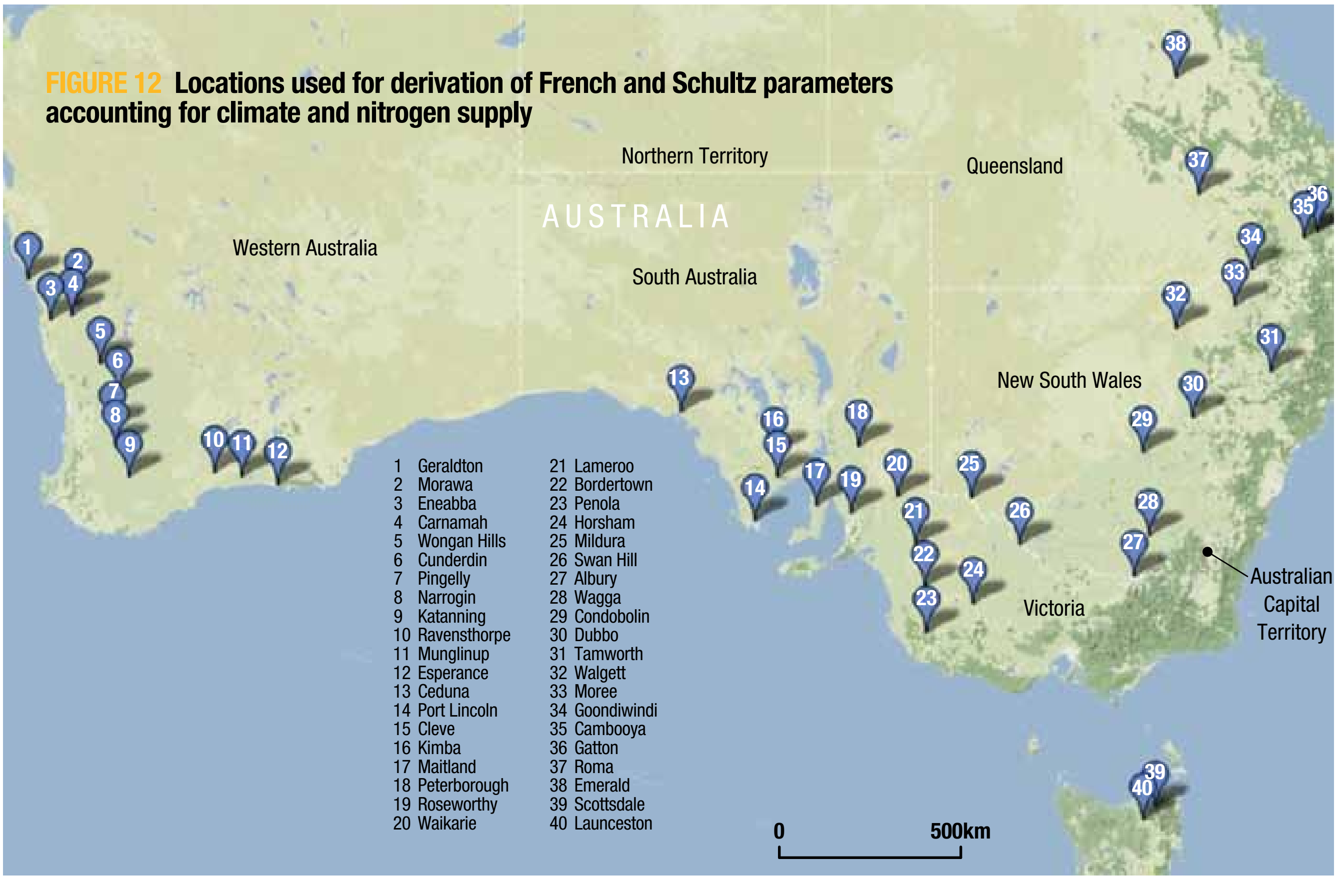
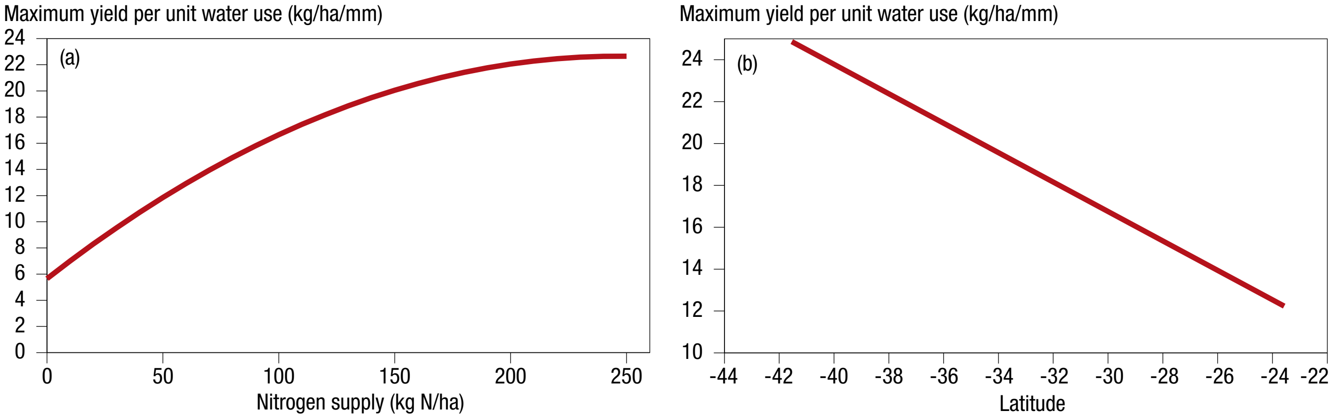


FIGURE 13 Maximum yield per unit water use as a function of (a) nitrogen and (b) location



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.

Estimating maximum yield per unit water use by location and nitrogen

We propose a three-step procedure to derive the 'slope' parameter representing maximum yield per unit water use accounting for nitrogen and location.

Step 1

Use the data in Figure 13a to account for the effect of nitrogen on maximum yield per unit water use. For severely limited crops (N supply < 50kg N/ha), 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 24kg grain/ha/mm. For intermediate N supply, maximum yield per unit water use 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 around 24 to 25kg grain/ha/mm. For a latitude of –23.5° (Emerald, the northernmost location) maximum yield per unit water use would be around 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

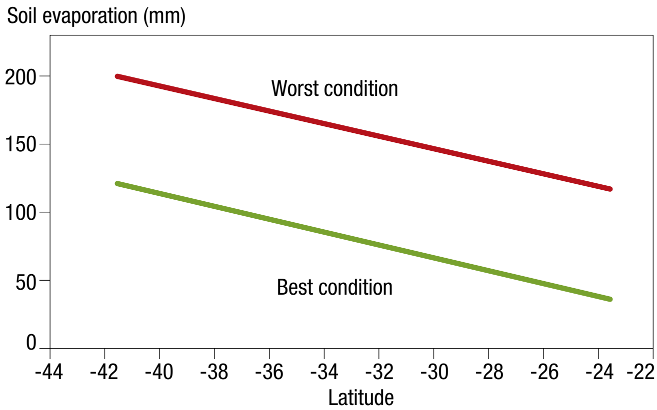
Select the lowest value from steps 1 and 2. For example, if we want to estimate the maximum yield per unit water use for Dalby (latitude = –27.1) with intermediate N supply (100kg N/ha), the location correction would return 14.7kg/ha/mm and the nitrogen correction would return 16.6kg/ha/mm. We therefore 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) also 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 we propose to use two boundary functions to 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

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 a large proportion of total crop water use accounted for through 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.

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 establishment and nutrient deficiency, 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. Approximate estimates of soil evaporation can be derived from Figure 14.

BOX 2 THE FRENCH & SCHULZ BENCHMARK

The paper published by R. J. French and J. E Schultz in the *Australian Journal of Agricultural Research* in 1984[1] has been central to the quest to increase Australian wheat yield and profitability over the past 25 years.

French and Schultz established a relationship between wheat yield and water use in Mediterranean environments of South Australia; they suggested that the relationship could be of value for developing crop growth models, predicting yields and providing guidelines for cropping strategies.

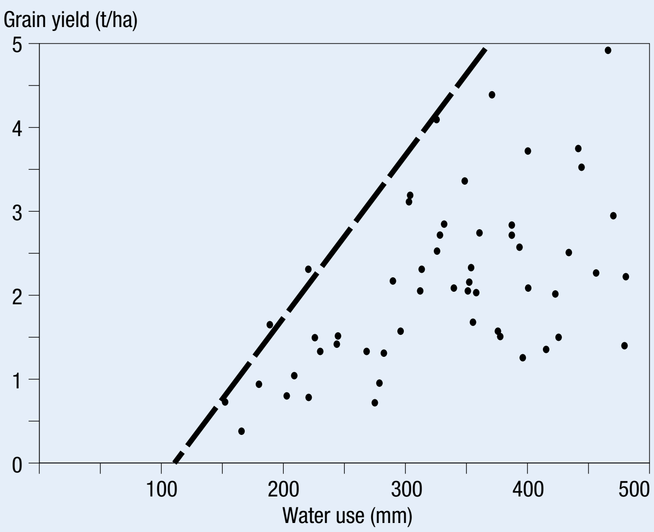
Their work was based on 61 field experiments conducted in South Australia between 1964 and 1975 using predominantly the variety Halberd. They measured rainfall and evaporation, soil water at sowing and harvest, and crop growth and yield.

Importantly, they selected sites with minimal risk of runoff or deep drainage allowing them to estimate the water used by the crops from the change in soil water content between sowing and maturity plus the rainfall over the same period. They also found that for sites that received low to moderate rainfall and had no accumulation of moisture from long fallow, growing season rainfall could be used to approximate water use. They noted that, when defined in this way, 'water use' is the sum of the water transpired (i.e. productively used by the crop), and the 'unproductive' direct evaporation from the surface of the soil and crop. The separation of these two components is the core of the French and Schultz approach.

Figure (i), from the publication, is a plot of grain yield and water use in the 61 experiments. Conventionally, a regression line would be fitted, but as French and Schultz commented, it would be of poor fit and do nothing to explain the complex effect of weather on growth and yield. Instead, they attempted to explain the results by separating the two components of water use. Conceptually, the water lost by evaporation can be obtained from the intercept on the water use axis of the linear relationship between yield and water use. For the most efficient crops this line has a slope of 20kg/ha/mm of water use, and intersects the axis at 110mm.

It is from this graph that the widely used French & Schultz benchmark is derived:

Attainable yield = (Water use - 110) x 20



French and Schultz showed that their interpretation of their data was in substantial agreement with many other Australian and international studies of water use carried out between 1960 and 1984.

French & Schultz speculated on whether the parameters 110 mm of evaporation and 20 kg/ha/mm applied beyond the South Australian environments used in their studies. They were able to demonstrate that for evaporation, the figure was highly variable, from 30 mm where crops used predominantly stored soil water (for example northern NSW and Queensland), to 170 mm - this figure they attributed to poor infiltration, surface ponding, and surface runoff on poorly structured soils.

For attainable yield per unit water use, French & Schultz recognised that as the drying power of the atmosphere rose, this benchmark would be lower - and that this would apply through the growing season at a given site, and also between geographic locations.

The main limitations to the practical application of the French & Schultz approach are how to accommodate the agronomic and climatic influences that influence both parameters, soil evaporation and attainable yield per unit water use. In this chapter, we present approaches that aim at these limitations while conserving the simplicity of the original method.

1 French, R. J. & Schultz, J. E. (1984). Water Use Efficiency of Wheat in a Mediterranean Environment. I The relation between Yield, Water Use and Climate. Aust. J. Agric. Res. 35, 743-64

CHAPTER 4
Crop management, water use and water use efficiency

The amount and distribution of rainfall are acknowledged as major factors influencing crop water use and yield. 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 of crops is generally not measured directly by farmers. However, 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 because in dry environments crops tend to use most of the water available to them regardless of management practice. While discussions on water use efficiency often focus on grain yield, is also important to remember that the objective of crop management is to maximise profit rather than water use efficiency (or even yield) *per se*. Management practices that improve profit will increase the economic water use efficiency (dollars per millimetre of crop water use).

Numerous studies have shown that on-farm water use efficiency is variable and while some of this is caused by environmental factors, such as soil type, vapour pressure deficit and the timing of rainfall events (as explained in Chapter 3), much of the variation is due to the management of the crop.

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 and water use to save water for use 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 and water use efficiency will be achieved by:

- maximising the capture and storage of rainfall and subsequent extraction of available soil water;
- increasing the efficiency with which available moisture is used; and
- minimising the severity of water deficits during key developmental stages of the crop (see Figure 4).

These goals can be achieved directly by altering the pattern of growth and water use through practices such as variety selection, time of sowing, sowing rate and canopy management; 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 access and effectively use available soil water. There may also be 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. However the proportion of rainfall retained by fallowing (also referred to as fallow efficiency) can be small, typically of the order of 20 per cent but frequently less. Nevertheless, despite the low efficiency of many fallows, storage of moisture can help with managing the risk associated with variable rainfall. Soil mineral nitrogen can also increase under fallows as cultivation stimulates the mineralisation of soil organic matter and yield improvements following fallow can be associated with increases in nitrogen more so than moisture.

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 less important because the accumulation of moisture by fallowing is often much less and yield gains are frequently small. The benefit of fallowing in regions with a winter-dominant rainfall pattern is influenced by the timing of rainfall. Very little of the summer (December to March) rainfall is stored and the value of fallowing depends more on rainfall captured and retained from the previous growing season. Soil texture is also important. In a study in the 1960s in South Australia using cultivated fallows, the mean increase in soil moisture after a 9 to 10-month fallow was only 9mm (maximum 38mm) on sandy soils and 38mm (maximum 125mm) on fine-textured soils. Each additional millimetre of moisture stored by the fallow increased grain yields by 8kg/ha. This yield benefit from fallowing was confirmed in a more recent survey of commercial wheat crops in the Mallee region of NSW, Victoria and South Australia. It was found that the initial moisture in the top metre of soil after fallowing was 39mm higher than after a cereal crop and 15mm higher than after pasture. However, in both cases yield after fallow was increased by 10kg/ha per mm of additional soil moisture.

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 appears to vary with 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 store summer rainfall may also depend on the size of the rainfall events, with the potential benefit of stubble retention being greatest where moderate rainfall is received during the fallow period. Small amounts of rain may evaporate quickly irrespective of the presence of stubble, whereas high rainfall may allow soil moisture to accumulate irrespective of the presence or absence of stubble.

Fallowing - implications for water use efficiency

While fallowing efficiency is often low, leading to only small increases in available soil moisture and crop water use, the benefits of this moisture can still be high because it is not subject to additional evaporative loss, and is stored at depth and likely to be used during the critical phase of growth immediately prior to flowering and during the grain filling period.

Work in southern NSW has indicated that the conversion efficiency of subsoil moisture used during grain filling can be up to 60kg 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.

Crop species

There are intrinsic differences in the water use efficiency of crops (Table 3) with wheat more water use efficient than grain legumes or canola whether considered in terms of total biomass production or grain yield. Differences in the composition of the grain – it is more energy efficient to produce starch rather than oil or protein (see Chapter 2) - partially explain the higher grain yield per unit water use of wheat compared to oilseed crops and pulses. Further, canola and the grain legumes are grown at lower plant densities and/or have less vigorous seedlings than wheat, contributing to greater early losses of moisture from soil evaporation and hence lower water use efficiency. The amount of winter growth made by the crop is therefore an important factor in determining 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, however, management in the preceding years is also important to water use efficiency because it influences 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.

Including legumes in the crop rotation is an effective way of improving water use efficiency through improvements in available nitrogen and reduced disease incidence.

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	WUEgy	Source
		(kg/ha.mm)		
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
Chickpeas	Western Australia	16.0 (11.1-18.3)	6.2 (2.6-7.7)	Siddique et al. 2001
Lentils		12.7 8.5-16.7)	6.7 (2.4-8.5)	
Lupins		17.3 (9.3-22.3)	5.1 (2.3-8.3)	
Faba beans		24.2 (18.7-29.6)	10.4 (7.7-12.5)	
Peas		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)	
Chickpeas	Tel Hadya, Syria	13.7 (9.4-18.1)	3.2 (2.1-5.2)	Zhang et al. 2000
Lentils		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)
	South-east Australia		9.9 (max =22.5)	Sadras and Angus 2006

* Based on simulated estimate of crop water use

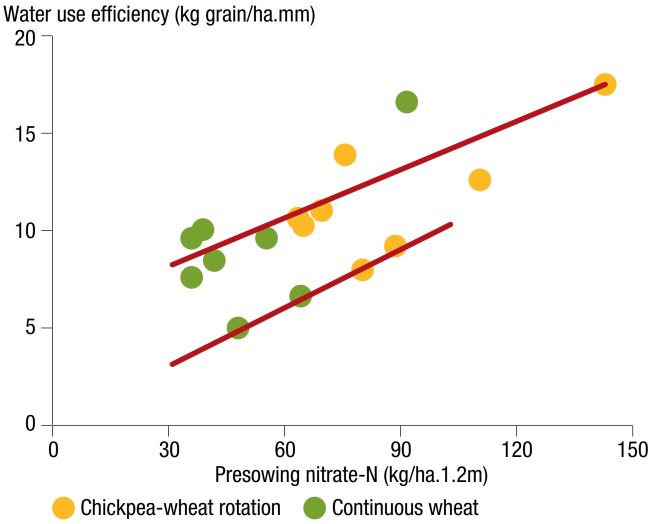
Table 4 The effect of previous crop on the initial soil moisture and mineral nitrogen levels, grain yield of wheat and rainfall use efficiency in the Mallee region of South Australia and Victoria.

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

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

Source: Sadras et al (2002)

FIGURE 15 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)

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 27 per cent compared to continuous wheat (11.7kg/ha/mm compared to 9.2kg/ha/mm). Improvements in water use efficiency were proportional to the amount of nitrate-N present in the soil (Figure 15). Similarly in the Mallee region of south-east Australia, 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).

Variety selection

Variety selection is a cost-effective way of maximizing water use efficiency. Using varieties that are tolerant to a range of environmental stresses allows effective use of growing season rainfall. Varieties can potentially improve water use efficiency in a number of ways.

Matching development to sowing date

Matching crop maturity type to sowing time is an effective means of improving water use efficiency and the interaction of variety and sowing date is described below. Early sowing will be most effective when matched with longer season varieties while later sowings require more rapidly maturing varieties to ensure that flowering occurs within the optimum flowering window.

Tolerance to subsoil limitations

Soil properties that restrict root growth, such as alkalinity, acidity, salinity or high concentrations of boron or aluminium limit the depth from which soil water can be extracted and limit yield per unit rainfall (see Figure 16). In the Mallee region of south-eastern Australia, for example, it has been estimated that there is an approximate 23 per cent reduction in yield per unit rainfall associated with the saline and alkaline subsoils of the region.

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. Understanding the major soil constraints and selecting varieties of crops that have a high level of tolerance to these stresses is an effective way of improving soil water use efficiency.

Tolerance to disease

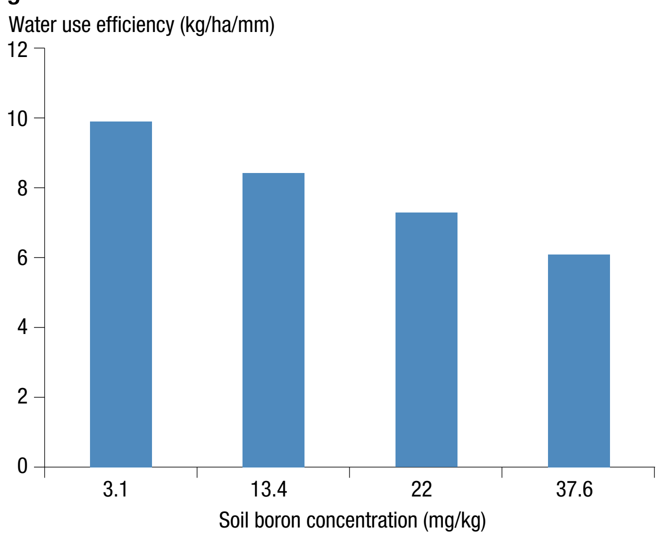
Both root and foliar diseases can reduce water use and water use efficiency. Root and crown diseases will reduce the ability of crops to take up water and nutrients from the soil, while foliar disease may reduce green leaf area and restrict biomass production. Using varieties that are tolerant or resistant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

Time of sowing

Responses to sowing time

Arguably, time of sowing is the most important management practice determining water use efficiency and yield. Many studies in a range of crops have shown that ‘late’ sowing will reduce yields, although for short-season varieties sowing very early may have little benefit or may reduce yields. Varieties of a given maturity have an optimum sowing period and in numerous studies (summarised in Table 5) delayed

FIGURE 16 Water use efficiency of wheat (cv Warigal) grown in soil with different concentrations of boron



SOURCE: Holloway and Alston (1992)

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

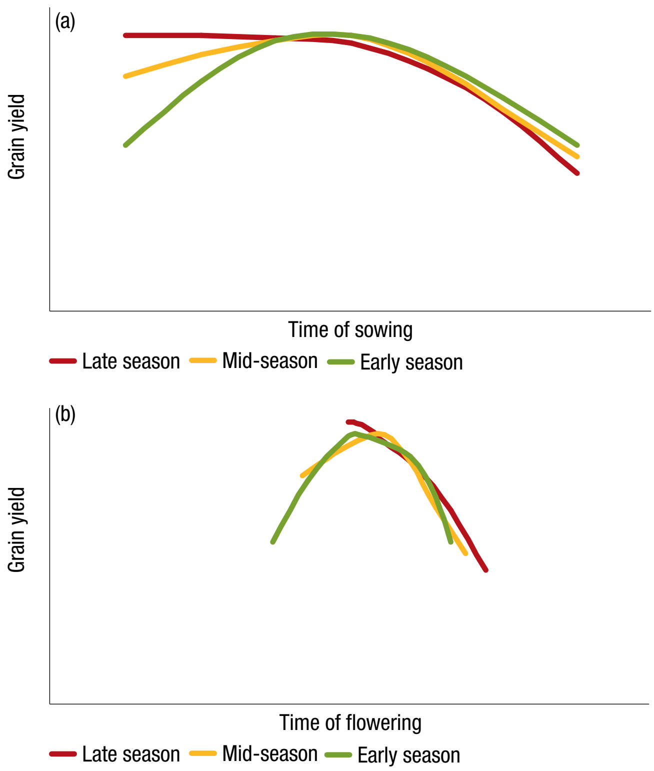
* Includes some irrigated trials
Data was derived from experiments conducted in NSW, Victoria, SA and WA, the majority of which were conducted between 1972 and 2008.

sowing beyond the optimum time reduced 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 which influences time of flowering. Rates of development vary among varieties and therefore the maturity group of a variety will affect how it responds to variation in sowing date and the optimum time of sowing.

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 appropriate. Early sowing increases the effective length of the growing season and using varieties with patterns of development that take advantage of this improves the efficiency of water use. Conversely, with late sowing and a shorter effective growing season, early flowering varieties with a more rapid pattern of development may be more suitable. Long season varieties that flower late in general will provide higher yields from early sowing, while short season, early-flowering varieties are better adapted to 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 17). For each variety the optimum sowing date will be that which causes the crop to flower within this optimum flowering window. The optimum flowering time is a compromise: flowering needs to be late enough to avoid damage from frost and disease, and to produce adequate amounts of biomass to establish a high yield potential, but on the other hand, early enough to minimise the effects of drought and heat stress. Sowing decisions, therefore, should 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.

FIGURE 17 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.

Time of sowing - implications for water use and water use efficiency

Time of sowing generally has only a small effect on total crop water use but can have a marked effect on water use efficiency and the highest water use efficiencies are consistently achieved when the crop is sown at the optimum time. An important aspect of sowing time in winter cereals is that it determines when the critical phase of crop development crop occurs and the environmental conditions under which the crop grows during this period. Late sowing reduces water use efficiency for a number of reasons: sowing into colder soil delays crop establishment and early vigour, which increases the proportion of crop evapotranspiration lost as soil evaporation; there is a higher likelihood of heat stress around flowering and during grain growth; and there are reductions in biomass per unit water

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	4194	292	14.3
	July	3280	260	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)

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)

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 than 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

The spatial arrangement of plants in crops, the result of the chosen row spacing and sowing rate, affects crop water use in two main ways: firstly it affects the rate of early growth and the degree and timing of canopy closure, and thus the proportion of crop water use lost as soil evaporation; and secondly it influences the partitioning of water use between the pre-anthesis and post anthesis periods.

Up to 50 per cent of total crop water use may occur as soil evaporation in areas with winter-dominant rainfall, with relatively lower losses for areas of summer-dominant rainfall (Table 7). Most soil evaporation occurs during the early stages of crop growth when ground cover is low and the soil surface is frequently wet. Practices that reduce soil evaporation improve overall water use efficiency by channeling more moisture through the plant as productive transpiration, and by shifting the balance of water use to later in the growing season. High rates of crop growth during winter without adequate spring rainfall can induce drought stress leading up to and during anthesis and grain filling, limiting yield and lowering overall water use efficiency. The best combination of sowing rate and row spacing will thus be influenced by the amount of growing season rainfall, the available soil moisture and the distribution of rainfall.

Decisions on row spacing and sowing rate will be made on many factors including local experience, stubble management practices, improved weed competition, disease management and machinery options. It is important, however, that decisions on changes in row spacing and sowing rate are made with an understanding of their impact on yield and water use efficiency. In theory, the level of competition between individual plants in a crop is minimised (and growth maximised) when plants are grown on a square, rather than a rectangular, arrangement. This means that as sowing rates are increased, the row spacing should be reduced to minimise 'rectangularity' and to reduce the intra-row competition. Conversely, as the row spacing is increased, without any adjustment to sowing rate, the degree of crowding within the row increases and the level of competition within the row intensifies.

Sowing rate

Most crops, especially the cereals, have great plasticity in their growth and can compensate for variation in plant density and row spacing. At low densities, tillers or branches are produced, and yields per plant are increased, compensating for the small number of plants per m^2. At very low plant densities the higher yield per plant may be insufficient to overcome the low plant populations and total yields are low. However, grain yields increase with plant populations to an optimum value, after which grain yield

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

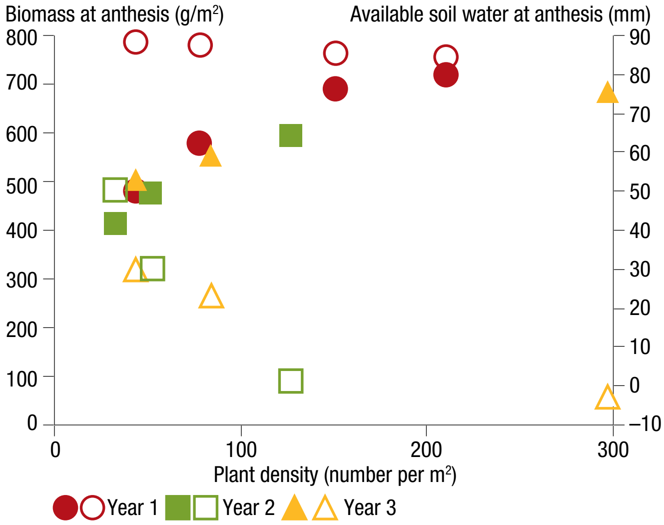
SOURCE: van den Boogaard et al. (1996).

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)

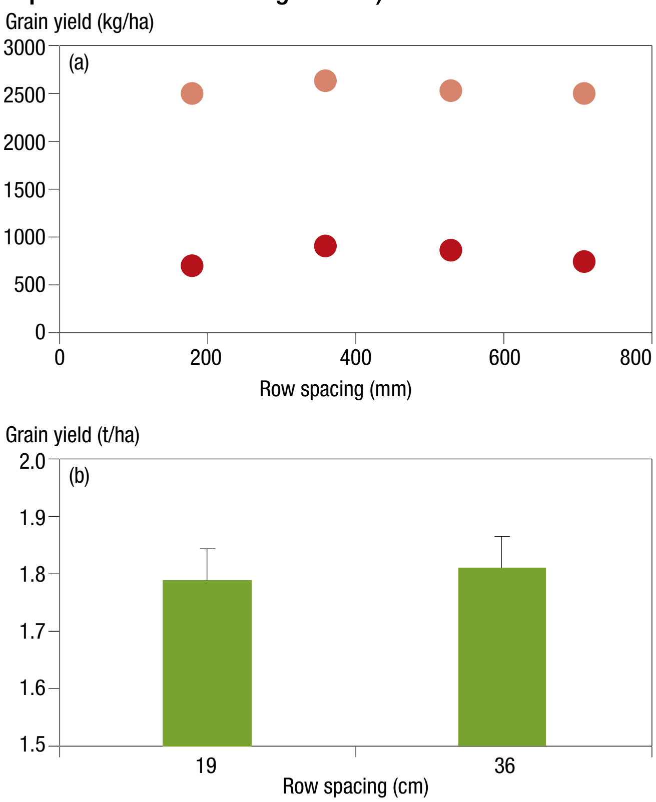
FIGURE 18 **The effects of plant density on biomass production (closed symbols) and available soil moisture (open symbols) at anthesis in three successive years**



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)

FIGURE 19 **The effect of row spacing on the grain yield of (a) chickpeas in south-east Queensland and (b) faba beans in Western Australia. (Effects of row spacing in both experiments were non-significant.)**



changes little over a wide range of sowing rates (Figure 18). There can be considerable site and season variation in the optimum plant density and in general, the drier the environment, the lower the optimum plant density will be.

Sowing rate - implications for water use efficiency

The amount and distribution of rainfall will largely influence the optimum sowing rate. Nevertheless grain yields (and water use efficiency) are quite stable over a wide range of sowing rates, which affords a degree of flexibility when deciding on the most appropriate sowing rate.

Increased sowing rates increase early crop growth rate and potentially reduce evaporation from the soil surface thus 'saving' water for use later in the season. On the other hand, high sowing rates will lead to vigorous early crop growth and water use which may cause early depletion of soil moisture if rainfall is low. This will be especially important if it leads to increased levels of stress during the critical period of growth (Figure 4). The effect of sowing rate on water use efficiency in winter cereals is therefore strongly influenced by the amount of soil moisture leading into spring.

In general, using low plant densities in low-rainfall regions, or in regions where crops depends on soil moisture reserves at sowing, helps to partition water use between the pre-flowering and post-flowering periods more effectively. This is illustrated in Figure 19 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, reducing yield and water use efficiency. Similar responses may also in low rainfall areas of the winter rainfall zone.

Row spacing

Studies in a range of environments with wheat show that increasing row spacing has relatively little effect on yield although yield is generally reduced at very wide row spacings (Table 9). These data also suggest that wide rows are more likely to be beneficial in very low yielding environments.

The small effect of row spacing on yield occurs because it alters the level of intra-plant competition. For a given sowing rate, increasing row spacing increases crowding in the row impacting on both root and shoot growth. These effects may be mitigated by increasing the width of the band over which seed is sown, thereby easing the severity of the intra-row competition and minimising the yield penalty of wide rows (Table 10).

Row spacing – implications for water use efficiency

Row spacing may have relatively little effect on water use efficiency. The potential gains in water use efficiency from altering row spacing will depend on how it affects the proportion of moisture lost from bare soil evaporation

Table 10 The effects of row spacing and the spread of seed within the row (row width) on the grain yield of wheat.

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		

Source: Anderson et al. (2005)

and how it influences the pattern of water use during the growing season. Increased row spacing can lead to increased exposure of the soil surface and raised soil evaporation, but where the maximum leaf area of the crop is small, or where the soil surface is not moist for long periods of time, altering row width has little effect on bare soil evaporation. For example, ground cover in crops with small leaf canopies is low and little affected by row width. In a study in Western Australia where the leaf area index at anthesis was 1.0 to 1.5 and crop yields ranged from 800 to 1500kg/ha, soil evaporative losses were 45 to 55 per cent of crop water use and unaffected by varying row width between 9cm and 36cm. In consequence, water use efficiency for grain yield was unaffected by row spacing. In wetter environments, wider row spacing will increase soil evaporation and may limit any potential gains in water use efficiency. The yield benefits from wide rows are most likely to be seen when crops rely on out of season rainfall or when the in-season rainfall is low and the wider rows allow a better match between the availability of soil moisture and the crop's moisture requirement during the critical stages of development late in the growing season.

Non-cereal crops

Grain yield responses to row width in pulses can vary depending on crop and seasonal conditions, but in most cases there are only small and non-significant effects. Table 11 shows that grain yield may be little affected by increasing row widths up to about 30cm after which yields are likely to decline. The lower plant populations at which pulses are grown, compared to cereals, may be a contributing factor to their yield stability to changes in row spacing. 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 30cm.

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 per cent (range = 8 to 27 per cent) for canola grown in 36cm row widths. Similar trends have been reported in South Australia, however, trial data from high rainfall sites in NSW showed no significant effect on yield from 36cm row spacing although there was some evidence that varieties may respond differently. Thus, the present evidence suggests that using wide rows in non-cereal crops may have limited benefit to the efficient use of seasonal rainfall or may cause reductions in efficiency. The selection of row spacing will therefore be a compromise between the potential reductions in water use efficiency, 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.

Crop nutrition

Crop nutrition influences 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, and the improvement in water use efficiency was achieved

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)

by a better partitioning of crop water use: 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 low rainfall, water use efficiency of crops can still be limited by low nitrogen supplies. A survey of commercial wheat crops demonstrated that many were largely below their water-limited potential yield, particularly in wetter years when the need for nitrogen was greater (see Figure 20). Modelling of yield at the surveyed sites using low inputs of nitrogen gave a similar result to the measured yields (Figure 20a) with the yield gap between potential and achieved yield tending to increase with rainfall. Using higher inputs of N in the model increases water use efficiency and closes the yield gap (Figure 20b). The work highlighted the important role of nitrogen to improve water use efficiency and the need to use nitrogen appropriately in response to growing season conductions.

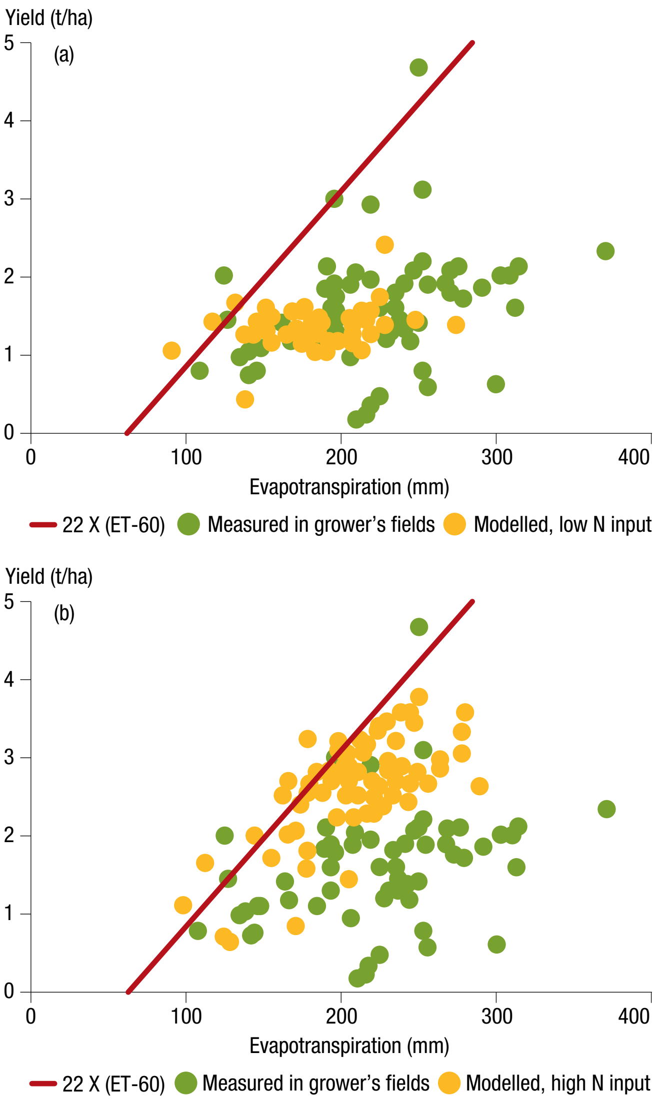
The potential value of adequate nitrogen supply was illustrated in another study using crop simulation of more than 300 crops from the Yield Prophet® database. Managing nitrogen so it was non-limiting to yield could

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
		45 (stubble removed)	2230	
		22.5 (standing stubble)	3420	
		45 (standing stubble)	2640	
South Australia	Field pea	22.5 (stubble removed)	2900	Hart Trial Cropping Results 2009
		45 (stubble removed)	2510	
		22.5 (standing stubble)	3060	
		45 (standing stubble)	2410	

FIGURE 20 **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)

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.

The strong interaction between moisture supply and nitrogen response (see Figure 20) 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 previous 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, 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.

Precision agriculture

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

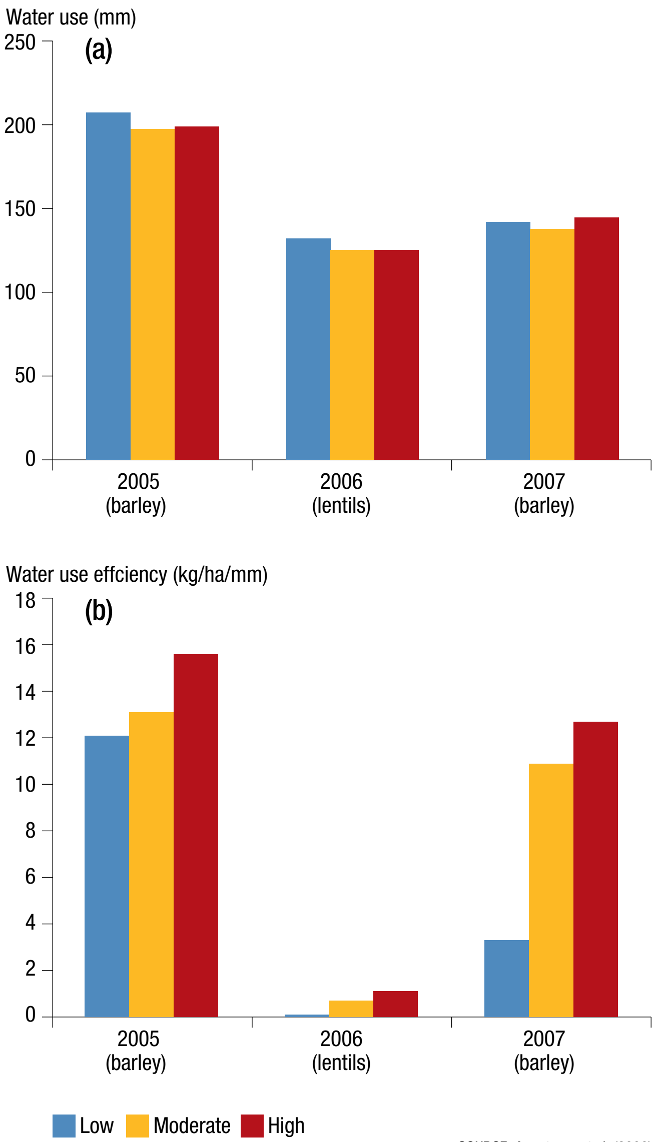
Table 13 **The grain yield response and water use efficiency in wheat to an application of 100kg N/ha applied at sowing or at different time after sowing at Mintaro, SA, in 2003. Water use efficiency is based on growing season rainfall (315mm)**

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)

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.

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)

DATA SOURCES

Anderson WK, Hamza MA, Sharma DL, D'Antuono MF, Hoyle FC, Hill N, Shackley BJ, Amjad M, Zaicou-Kunesch C (2005) The role of management in yield improvement of the wheat crop—a review with special emphasis on Western Australia. Australian Journal of Agricultural Research 56, 1137–1149.

Angus JF, Nix HA, Russell JS, Kruizinga JG (1980) Water use, growth and yield of wheat in a sub-tropical environment. Australian Journal of Agricultural Research 31, 873-86.

Armstrong RD, Fitzpatrick J, Rab MA, Abuzar M, Fisher PD, O'Leary GJ (2009) Advances in precision agriculture in south-eastern Australia. III. Interactions between soil properties and water use help explain spatial variability of crop production in the Victorian Mallee. Crop and Pasture Science 60, 870-884.

Beech D, Leach G (1988) Response of chickpea accession to row spacing and plant density on a vertisol on the Darling Downs, south-eastern Queensland. 1. Dry matter production and seed yield. Australian Journal of Experimental Agriculture 28, 367-376.

Bolland MDA, Riethmuller GP, Siddique KHM, Loss SP, D'Antuono MF (2001) Method of phosphorus fertiliser application and row spacing on grain yield of faba bean (Vicia faba L.). Australian Journal of Experimental Agriculture 41, 227-234.

Brand J, Lines M, Luke Gaynor, McMurray L, Matthews P (2010) The impact of row spacing on the growth and yield of lentil cultivars in southern Australia. In 'Food Security from Sustainable Agriculture, Proceedings of 15th Agronomy Conference. ' (Eds H Dove and RA Culvenor). (Australian Society of Agronomy: Lincoln, New Zealand)

Brueck H (2008) Effects of nitrogen supply on water-use efficiency of higher plants. Journal of Plant Nutrition and Soil Science 171, 210-219.

Calviño PA, Monzon JP (2009) Farming systems of Argentina: yield constraints and risk management. In: Crop physiology: applications for genetic improvement and agronomy. Eds V.O. Sadras, D.F. Calderini (Academic Press: San Diego).

Connor D, Theiveyanathan S, Rimmington G (1992) Development, growth, water-use and yield of a spring and a winter wheat in response to time of sowing. Australian Journal of Agricultural Research 43, 493-516.

Cooper PJM, Gregory PJ, Keatinge JDH, Brown SC (1987) Effects of Fertilizer, Variety and Location on Barley Production under Rainfed Conditions in Northern Syria 2. Soil Water Dynamics and Crop Water Use. Field Crops Research 16, 67-84.

Dalal RC, Strong WM, Weston EJ, Cooper JE, Wildermuth GB, Lehane KJ, King AJ, Holmes CJ (1998) Sustaining productivity of a Vertisol at Warra, Queensland, with fertilisers, no-tillage, or legumes 5. Wheat yields, nitrogen benefits and water-use efficiency of chickpea–wheat rotation. Australian Journal of Experimental Agriculture 38: 489-501.

Doherty D, Sadras VO, Rodriguez D, Potgieter A (2010) Quantification of wheat water-use efficiency at the shire-level in Australia Crop Pasture Science 61, 1-11.

Doyle AD, Fischer RA (1987) Dry matter accumulation and water use relationships in wheat crops. Australian Journal of Agricultural Research 30, 815-829.

Eberbach P, Pala M (2005) Crop row spacing and its influence on the partitioning of evapotranspiration by winter-grown wheat in Northern Syria. Plant and Soil 268, 195–208.
Field Crops Research 59, 175-179.

French RJ, Schultz JE (1984) Water use efficiency of wheat in a Mediterranean type environment. I. The relation between yield, water use and climate. Australian Journal of Agricultural Research 35, 743-764.

Ghiglione HO, Gonzalez FG, Serrago RA, Maldonado SB, Chilcott C, Cura JA, Miralles DJ, Zhu T, Casal JJ (2008) Autophagy regulated by day length determines the number of fertile florets in wheat. The Plant Journal 55, 1010-1024.

Holloway RE, Alston AM (1992) The effects of salt and boron on growth of wheat. Australian Journal of Agricultural Research 43, 987-1001.

Hooper P (2010) Strategic applciations of nitrogen fertilser to increase the yield and nitrogen use effciency of wheat. MSc Thesis. The Universityof Adelaide.

Jefferies SP, Wheeler R (1993) Chapter 12: Seedling rate experiments - cereals 1993. In 'South Australian Field Crop Evaluation Program Annual Report. SARDI, Adelaide.

Karrou M (1998) Observations on effect of seeding pattern on water-use efficiency of durum wheat in semi-arid areas of Morocco. Field Crops Research 59, 175-179.

Kemanian AR, Stöckle CO, Huggins DR (2005) Transpiration-use efficiency of barley. Agricultural and Forest Meteorology 130, 1-11.

Kleeman S, Gill GS (2008) Row spacing, water use, and yield of wheat (Triticum aestivum), barley (Hordeum vulgare) and faba bean (Vicia faba). In 'Global Issues. Paddock Action. Proceedings of 14th Agronomy Conference 2008 '. Ed. M Unkovich). (Australian Society of Agronomy: Adelaide, South Australia)

Kleeman S, Gill G (2010) Yield response of kabuli and desi chickpea (Cicer arietinum L.) genotypes to row spacing in southern Australia. In 'Food Security from Sustainable Agriculture. Proceedings of 15th Agronomy Conference. ' (Eds H Dove and RA Culvenor). (Australian Society of Agronomy: Lincoln, New Zealand)

Norton RM, Wachsmann NG (2006) Nitrogen use and crop type affect the water use of annual crops in south-eastern Australia. Australian Journal of Agricultural Research 57, 257-267.

Oweis T, Zhang H, Pala M (2000) Water use efficiency of rainfed and irrigated bread wheat in a Mediterranean environment. Agronomy Journal 92, 232-238.

Perry M (1987) Water-use efficiency of non-irrigated field crops. In 'Proceeding of the 4th Australian Agronomy Conference'. Ed. TG Reeves, pp. 83-99. (Australian Society of Agronomy: Melbourne, Vic).

Robertson M, Kierkegaard JA (2005) Water use efficiency of canola in an equi-seasonal rainfall environment. Australian Journal of Agricultural Research 56, 1373-1386.

Sadras VO, Roget D, O'Leary G (2002) On-farm assessment of environmental and management constraints to wheat yield and efficiency in the use of rainfall in the Mallee. Australian Journal of Agricultural Research 53(5), 587-598.

Sadras VO, Angus JF (2006) Benchmarking water use efficiency of rainfed wheat in dry environments. Australian Journal of Agricultural Research 57, 847-856.

Sadras VO, O'Leary GJ, Roget DK (2005) Crop responses to compacted soil: Capture and efficiency in the use of water and radiation. Field Crops Research 91, 131-148.

Sadras VO, Rodriguez D (2010) Modelling the nitrogen-driven trade-off between nitrogen utilisation efficiency and water use efficiency of wheat in eastern Australia. Field Crops Research 118, 297–305.

Sadras VO (2005) A quantitative top-down view of interactions between stresses: theory and analysis of nitrogen–water co-limitation in Mediterranean agro-ecosystems. Australian Journal of Agricultural Research 56, 1151-1157.

Siddique KHM, Regan KL, Tennant D, Thomson BD (2001) Water use and water use efficiency of cool season grain legumes in low rainfall Mediterranean-type environments. European Journal of Agronomy 15, 267-280.

Stapper M, Fischer R (1990) Genotype, sowing date and plant spacing influence on high-yielding irrigated wheat in southern New South Wales. II. Growth, yield and nitrogen use. Australian Journal of Agricultural Research 41(6), 1021-1041.

Tompkins DK, Fowler DB, Wright AT (1991) Water Use by No-Till Winter Wheat Influence of Seed Rate and Row Spacing. Agron. J. 83(4), 766-769.

van den Boogaard R, Veneklaas EJ, Peacock JM, Lambers H (1996) Yield and water use of wheat (Triticum aestivum) in a Mediterranean environment: Cultivar differences and sowing density effects. Plant and Soil 181, 251-262.

Yanusa IAM, Belford RK, Tennant D, Sedgley RH (1993) Row Spacing Fails to Modify Soil Evaporation and Grain Yield in Spring Wheat in a Dry Mediterranean Environment. Australian Journal of Agricultural Research 44 661-676.

Zhang H, Pala M, Oweis T, Harris H (2000) Water use and water-use efficiency of chickpea and lentil in a Mediterranean environment. Australian Journal of Agricultural Research 51, 295-304

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