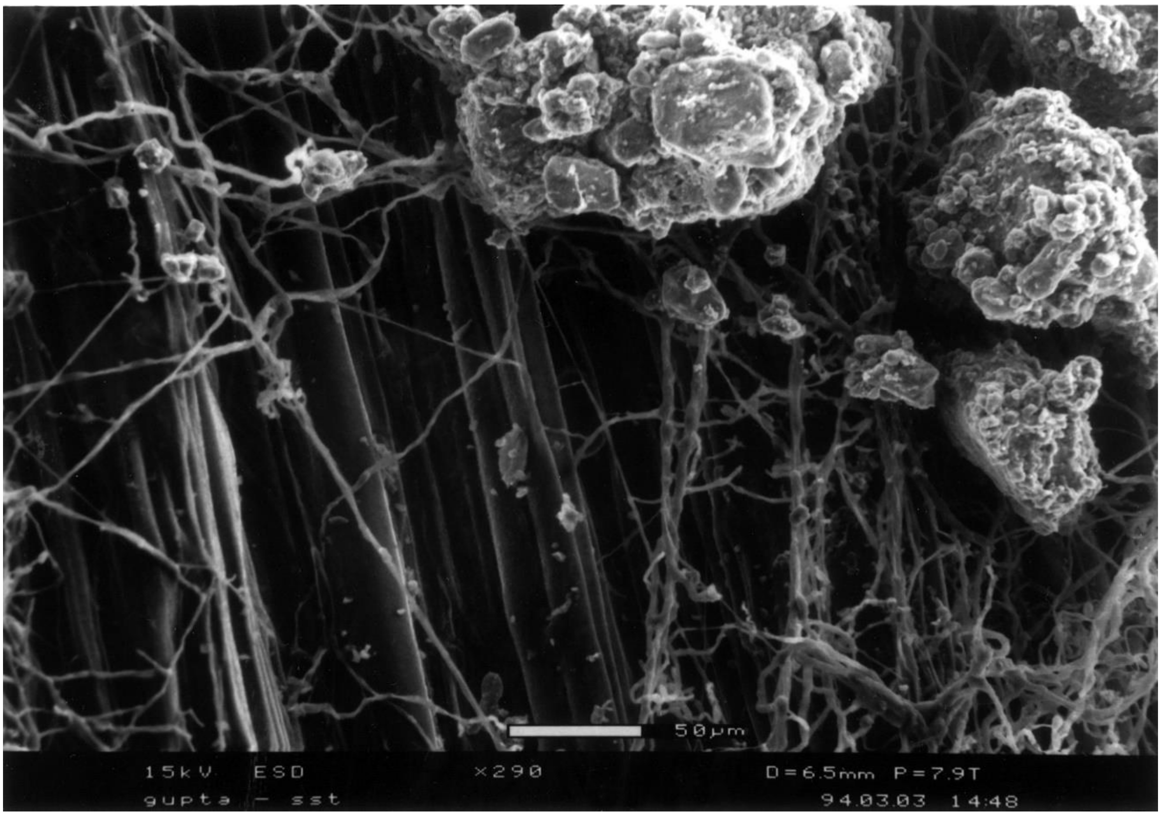
PART IV – MANAGING THE RESOURCES



Fungal hyphal network on cereal stubble in no-till systems
(Courtesy: Vadakattu Gupta)

Stabilizing flowering time in wheat for improved water use efficiency (Courtesy: Bonnie Flohr)

Compacted soil limits resource capture in wheat (water and N) while ripping (background) increases root access to resources
(Courtesy: Victor Sadras)

Chapter 13

Water use in rainfed systems: physiology of grain yield and its agronomic implications

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Introduction

Managing climate variability and its effects on water supply to dryland crops has always been a central theme for agriculture in the driest continent on earth. As we write in mid-2019, Australia has already dealt with catastrophic floods in north Queensland, unprecedented droughts and bushfires in Tasmania, and fish kills due to low rainfall and water levels in the Murray Darling river system. In 1987, when *Tillage* was published, there were many references to water conservation, infiltration and erosion, and an implicit understanding of the importance of efficient water use for agricultural production. Yet there was not one reference to the now classic work of French and Schultz (1984a, b) on water use efficiency, linking wheat yield to seasonal water use and growing season rainfall. French and Schultz' biophysically strong benchmark, intuitively relates yield and water, and became a hallmark of the next 30 years in Australian agriculture. Whereas more refined benchmarks have been advanced to account for some of the original simplifications (Sadras *et al.* 2015), the core principle remains: there is an upper limit of yield for a given availability of water, termed water-limited yield potential, and differences between actual and water-limited yield potential reveal yield gaps. The yield gap concept now drives diagnosis and agronomy to address the factors responsible for the failure of crops to achieve water-limited yield potential (Hochman *et al.* 2012, van Ittersum *et al.* 2013, van Rees *et al.* 2014, Hochman and Horan 2018).

Growers rely on two linked sets of principles to increase farm-level production and profit, and to manage risk in the face of variable rainfall and extreme events including frost and heat. One is the management of individual crops, primarily supported by crop science and agronomy. The other is the arrangement of crops (or more broadly, land use) in space and time, supported by farming system research. The core of this chapter outlines principles of crop science and agronomy linked to efficient water use at the paddock-scale with direct implications for management. We conclude with an example of scaling these principles to the farming system level.

First, we show the role of rainfall in shaping patterns of land use and cropping options, emphasising the importance of amount, seasonality and size of rainfall events. Next, we focus on the upper boundary of yield in relation to water use, and the main sources of variation of this boundary including variety, management and environment. Rather than focus on specific agronomy, we analyse growth in terms of capture and efficiency in the use of resources, the central role of grain number to accommodate environmental variation, and the link between grain number and growth rate in a species-specific critical window in the context of timing, intensity and duration of drought episodes. We briefly consider how the elements of CA can be considered through this lens, as can the opportunities provided by novel agronomy, including the management of legacies of water and N use across a cropping sequence.

We believe that better integration of (and in a sense rediscovering) these physiological principles into agronomy at both the crop and farm level will be central to improve water-limited yield potential, closing yield gaps and increasing farm productivity and profitability.

Rainfall patterns set the limits and opportunities for cropping

There are three features of rainfall relevant to agriculture: amount, seasonality and size of events (Figure 1). The amount of rainfall sets the boundary for major patterns of land use, with cropping feasible above a certain annual rainfall, and rangelands in the riskier, lower-rainfall environments (Figure 1A). Seasonality sets three cropping environments in Australia (Figure 1B): the summer-rainfall region of

Queensland and northern New South Wales, the winter-rainfall regions of south-eastern and south-western Australia, and a transition zone lacking seasonality between the northern and southern region. For the same amount of annual rainfall, the summer regime allows for a greater crop diversity and higher cropping intensity, whereas winter rainfall has favoured an autumn-sown spring cereal (wheat, barley) system in rotation with pastures, legumes, and more recently canola. Driven by the winter-rainfall regime, the cropping systems of south-eastern and south-western Australia have evolved in convergence with the ancient wheat-pulse system of the Mediterranean basin; in this regard, much of Australian agriculture is Levantine rather than European (Sadras and Dreccer 2015).

Seasonality also has a major impact on the proportion of water available from pre-season and in-season rainfall, with implications for management and risk. In the winter-rainfall regions, wheat relies primarily on in-season rainfall, compared with a larger contribution of stored soil moisture in summer-rainfall regimes (Figure 1C). The frequency of large rainfall events increases from south to north (Figure 1D). For the same amount of rainfall, large events favour deep drainage and runoff as sources of inefficiency, whereas small events favour soil evaporation losses (Sadras 2003, Sadras and Baldock 2003, Monzon *et al.* 2006, Verburg *et al.* 2012).

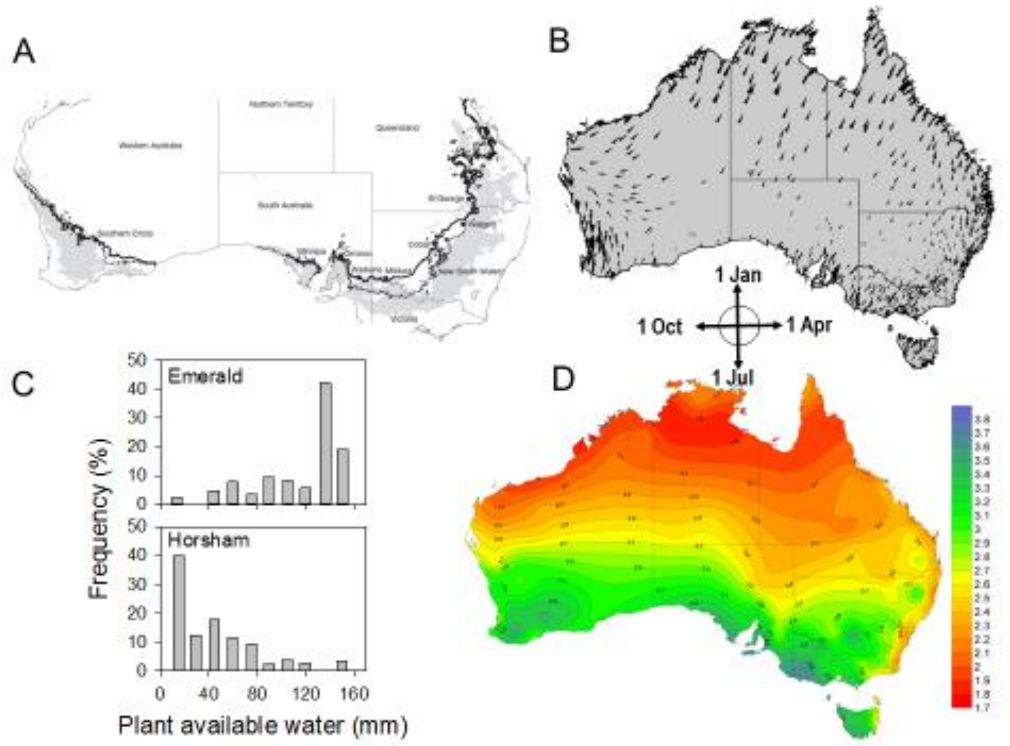

Figure 1. Amount, seasonality and size of rainfall events set boundaries and opportunities for cropping and influence the fate of water. (A) The amount of rainfall marks the transition from cropping into extensive grazing in Australia. The dotted line is the April-October 220 mm isohyet; the solid line is the 0.26 precipitation: evaporation ratio isopleth, and the grey area is the wheat growing region. (B) The seasonality of rainfall shapes cropping options. The length of Markham's vectors represents the intensity of seasonality and their direction in the 360^o dial indicates the time of the year with the greatest rainfall concentration. For example, the vector is large indicating strong seasonality and points towards early January in northern Queensland, is large and points towards mid-July in the southern and western region, and is small highlighting lack of seasonality in most of NSW (C) Seasonality of rainfall influences the contribution of stored water at sowing to total water availability – modelled soil plant available water at sowing for wheat at Emerald, a summer-rainfall location, and Horsham, a winter-rainfall location; (D) The size of rainfall events influences the fate of water, *e.g.* small events favour soil evaporation. The map shows power law coefficient of rainfall for the winter semester in Australia. Power law coefficients are the unitless slope of the relationship between frequency and size of non-zero rainfall events on a log-log scale; colour-coded coefficients indicate increasing dominance of larger events from blue to red. Sources and further details: (A) Nidumolu *et al*. (2012), (B, D) Williamson (2007), (C) Sadras and Rodriguez (2007)

Crop yield per unit evapotranspiration is agronomically and biophysically bounded

For wheat crops encompassing common sources of variation (namely soil, weather and management) yield-rainfall plots are scattered; seasonal rainfall typically accounts for about one-third of the variation in the yield of wheat in south-eastern Australia. In this context, French and Schultz (1984a, b) insightfully drew a boundary line capturing the upper limit of wheat yield for a given evapotranspiration; this boundary was later shown to hold for other rainfed systems (Figure 2).

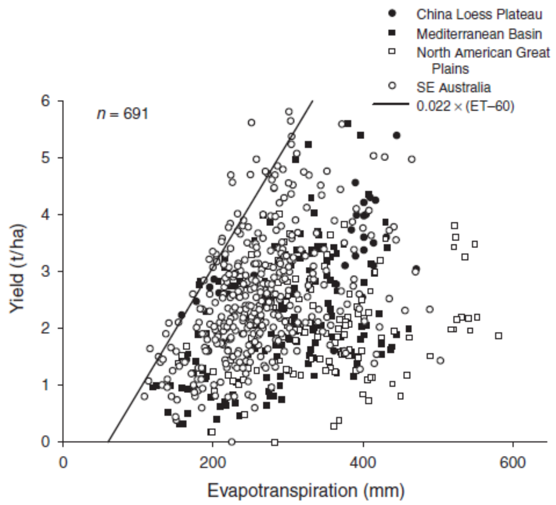

Figure 2. Relationship between yield and evapotranspiration for wheat crops in south-eastern Australia, Mediterranean basin, China Loess Plateau, and North American Great Plains. The boundary line has a slope of 22 kg/ha/mm and the x-intercept is 60 mm (source: Sadras and Angus 2006)

Two agronomic parameters define this boundary: the x-intercept, commonly interpreted as seasonal soil evaporation, and the slope of the line, representing the water-limited yield potential. It is important to make the distinction between the conceptual model, with robust theoretical and empirical support, and the parameters that need adjustment to account for variation with soil, climate and technology. Soil evaporation is not fixed, as noted by French and Schultz and others, but varies with soil, rainfall and management (Figure 3). Whilst French and Schultz inferred these parameters, they were shown to be in close agreement with subsequent empirical measurements (Unkovich *et al.* 2018).

In a north-south transect in eastern Australia, soil evaporation increases southwards in parallel to the greater proportion of in-season rainfall dominated by an increasing frequency of small events wetting the top soil more often (Figure 3). Management practices that increase the rate of canopy cover (*e.g.* high fertiliser rate, narrow rows, high sowing density, earlier sowing) would normally reduce soil evaporation, as illustrated in Figure 3B, D and Box 1 for nitrogen. The slope of the line increases southwards, in parallel to the reduction in vapour pressure deficit. Further, the slope initially set at 20 kg/ha/mm for south-eastern locations with technology of the early 1970s, including pre-Green Revolution cultivars, has increased to about 25 kg/ha/mm with newer, higher yielding varieties in these environments (Sadras and Lawson 2013). The concept of the boundary water use efficiency was first used in Australia, and more recently expanded to other crops worldwide as a practical benchmark for yield-gap analysis (Rattalino Edreira *et al.* 2018).

Crop growth depends on four resources and modulating abiotic and biotic factors

Crop biomass depends on the ability of the canopy to capture radiation and carbon dioxide, and on the ability of the root system to capture nutrients and water. Weather, soil, weeds, pathogens and herbivores modulate the rate of capture of these four resources, and the efficiency in the use of resources to produce biomass.

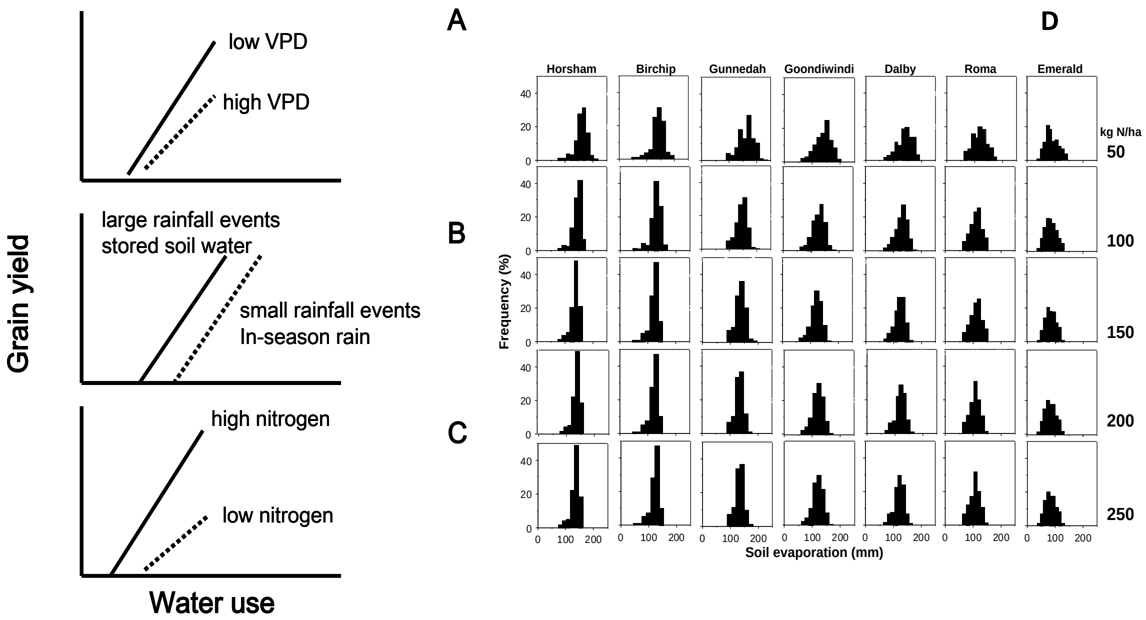

Figure 3. Influence of climate and nitrogen supply in the parameters of the French and Schultz benchmark. (A) Reduction in slope with increasing vapour pressure deficit. Vapour pressure deficit is a measure of air dryness; it increases inland and northwards, and it also increases with late sowings. (B) Increased soil evaporation with increasing frequency of small rainfall events and crop dependence on in-season rainfall as opposed to dominance of large rainfall events and crop reliance on stored soil water . (C) Nitrogen deficiency reduces the slope and increases soil evaporation. (D) Modelled soil evaporation highlighting: the declining evaporation from south (Horsham) to north (Emerald), the declining evaporation with increasing nitrogen supply, and the season-to-season variation in evaporation captured in the distribution of frequencies (source of histograms in D: Sadras and Rodriguez 2010)

Box 1 Effects of nitrogen on soil evaporation and water use efficiency

Norton and Wachsmann (2006) measured the response of canola to nitrogen rate from zero in controls up to 210 kg ha^{-1} in the Victorian Wimmera. In response to increasing nitrogen, shoot dry matter and yield increased (Table 1). High nitrogen increased the amount of water used by the crop by about 30 mm, and reduced wasteful soil evaporation by about 40 mm. In total, more nitrogen improved the water economy of the crop by 70 mm. High nitrogen, as a consequence, increased the water use efficiency of the crop from 17 to 28 kg dry matter ha^{-1} mm^{-1}, and from 5 to 8 kg grain ha^{-1} mm^{-1}. The fertiliser efficiency dropped from 35 kg grain ha^{-1} kg N^{-1} with 70 units of fertiliser to 13 kg grain ha^{-1} kg N^{-1} with 240 units of fertiliser. Comparison of yield per unit water use and yield per unit nitrogen fertiliser shows a universal trade-off: more nitrogen means higher water use efficiency and lower nitrogen use efficiency.

Table 1. Effect of nitrogen rate on canola yield, shoot dry matter, water use, soil evaporation, dry matter per unit water use, yield per unit water use, and yield per unit nitrogen fertiliser (source: Norton and Wachsmann 2006)

N rate (kg/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 N (kg/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

To illustrate crop growth analysis based on capture and efficiency in the use of resources, we consider the effect of soil compaction in a sandy Mallee soil as shown in Figure 4. Soil stress impairs root growth and function. This leads to:

- Reduced ability to capture water and nutrients;
- Reduced capture of water and nutrients closes a loop of reduced root growth;
- Reduced capture of water and nutrient compromises canopy growth and function (e.g. stomata close under water deficit);
- A smaller, less effective canopy captures less radiation and carbon dioxide (i.e. less photosynthesis);
- Reduced capture of radiation and carbon dioxide closes a loop of reduced canopy growth;
- Reduced capture of radiation and carbon dioxide closes a loop of reduced root growth.

Hence, all four resources limit crop growth in compacted soil. In a comparison of crops on compacted soil, and soil where deep-ripping (three-tyne ripper with 0.6-m-depth tynes spaced at 0.45 m) removed compaction, removal of soil stress improved root growth and canopy size with a 2-fold increase in capture of radiation from 18 to 40%. Increased transpiration and interception of radiation fully accounted for the increase in crop growth associated with alleviation of soil compaction. Control crops yielded between 1.2 and 2.9 t/ha and yield improvement from ripping ranged from nil to 43% depending on season and position in the landscape (Sadras *et al.* 2005).

In agriculture, the notion of a single limiting factor has dominated since von Liebig's law of the minimum. The inadequacy of the law of the minimum has been demonstrated, particularly in factorial experiments of fertilisation. For two resources A and B, the law of the minimum predicts yield isolines with two segments parallel to the A and B axis, and a break point when the crop shifts from A to B limited (Figure 5). For many reasons, actual responses do not conform to this pattern, *i.e.* actual yield

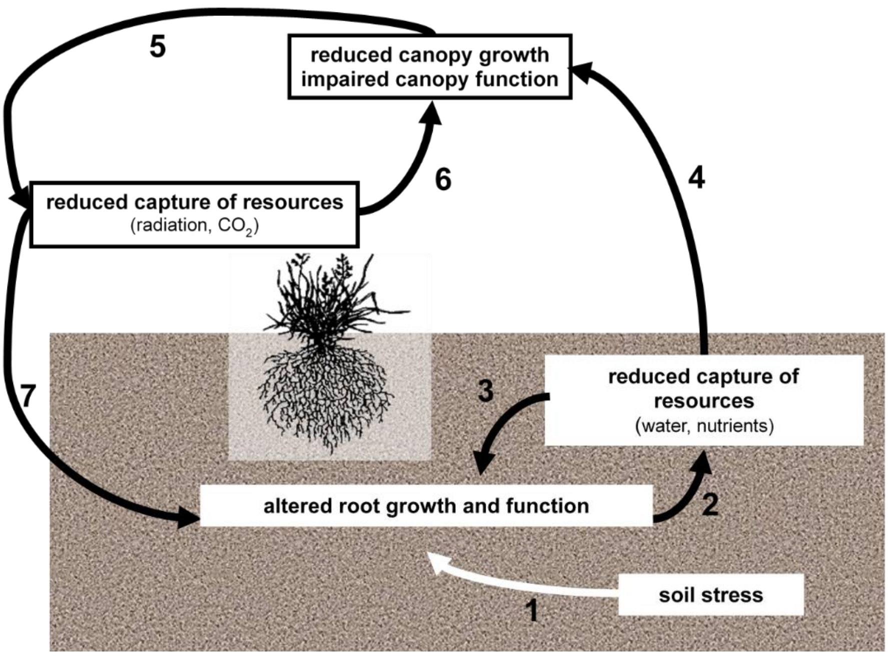

Figure 4. Effect of soil compaction on crop capture of soil and above-ground resources highlighting reinforcing loops. 1. Soil stress impairs root growth and function; this leads to 2) reduced ability to capture water and nutrients. 3) Reduced capture of water and nutrients closes a loop of reduced root growth. 4) Reduced capture of water and nutrient compromises canopy growth and function (e.g. stomata close under water deficit). 5) A smaller, less effective canopy captures less radiation and carbon dioxide (i.e. less photosynthesis). 6) Reduced capture of radiation and carbon dioxide closes a loop of reduced canopy growth. 7) Reduced capture of radiation and carbon dioxide closes a loop of reduced root growth (source: Sadras *et al.* 2005)

isolines are curvilinear (Figure 5). For example, a crop with very low N supply can still respond to P that stimulates root growth and enhances capture of N, and vice-versa. Duncan *et al*. (2018) showed higher yield per unit fertiliser N (relative to unfertilised control) in wheat crops with co-application of P, K and S.

Cossani and Sadras (2018) updated the theory of resource co-limitation, and outlined the underlying mechanisms with an emphasis on water and nitrogen. They define co-limitation as "the simultaneous limitation of yield per unit area by multiple resources over the agronomically relevant time scale (*e.g.* season, between cuts in forages) or developmentally relevant critical period." Theory predicts that for a given intensity of stress, growth is maximised under resource co-limitation; this prediction has been supported in field studies with wheat, barley, canola and maize where high yield associates with high water-N co-limitation. The improvement in wheat yield over the last five decades has been linked to increased nitrogen-water co-limitation (Cossani and Sadras 2019). Measures of crop water and nitrogen status with remote sensing could be integrated in a co-limitation framework for management applications (Cossani and Sadras 2018).

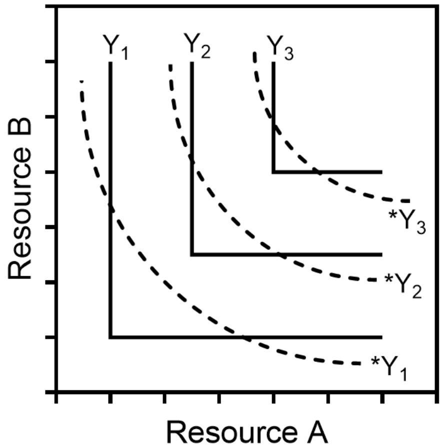

Figure 5. Response of crop yield to availability of two resources A, B. Solid lines are yield isolines (Y) expected from the law of the minimum, and dashed lines are yield isolines (Y*) resulting for interactions between resources, as supported by experiments. Subscripts 1 to 3 indicate increasing yield (source: Cossani and Sadras 2018)

Crops accommodate environmental variation through grain number

Across sources of variation, yield is primarily a function of grain number (Figure 6). Grain weight is important for quality and screenings are certainly undesirable, but large improvement in yield, say from 2 to 4 t/ha or from 3 to 6 t/ha, depends on grain number. Evolutionary and agronomic selection for conserved seed size explain the robust relationship between yield and grain number (Sadras 2007, Sadras and Denison 2009, Sadras and Slafer 2012, Slafer *et al.* 2014). Grain number can be seen as the 'coarse' regulator of yield and grain weight as the 'fine' regulator (Slafer *et al.* 2014).

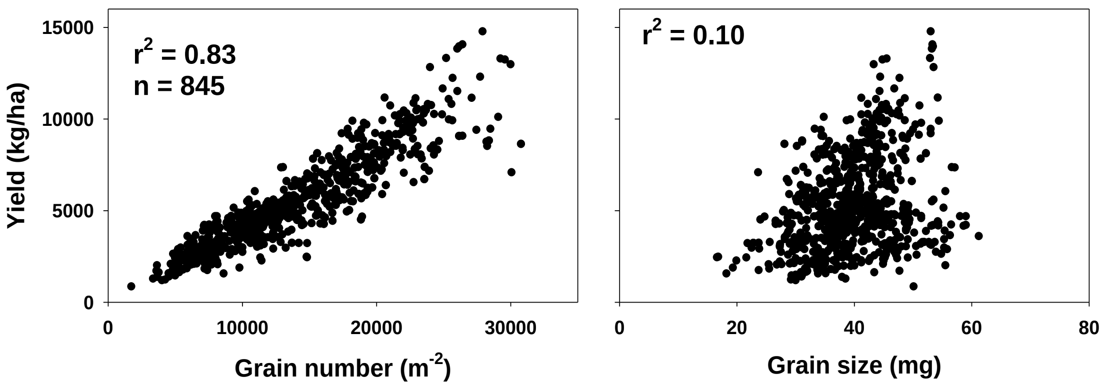

Figure 6. Crops accommodate environmental variation through grain number (left), whereas grain weight (right) is a secondary source of variation in yield (source: Slafer *et al*. 2014)

Despite the well-established relationship between yield and grain number, practices such as canopy management or nitrogen fertilisation often emphasise grain filling. Under some combinations of soil, water supply and phenology, over-fertilisation can lead to *haying-off* (van Herwaarden *et al.* 1998a, b, c). The asymmetric response to nitrogen of grain number and grain weight, however, reinforces the notion that management aimed at ensuring grain filling needs to account for the risk of nitrogen deficiency severely compromising grain number.

Figure 7 illustrates this asymmetry: excess nitrogen (nitrogen nutrition index, NNI > 1) can reduce grain weight at a rate of 26% per unit NNI, but nitrogen deficit (NNI < 1) can reduce grain number at 168% per unit NNI (Figure 7). Box 2 outlines the calculation and interpretation of the nitrogen nutrition index NNI. The asymmetric response to nitrogen of biomass and harvest index leads to the same conclusion: excess nitrogen can reduce harvest index at 16% per unit NNI whereas nitrogen deficit can reduce biomass at 157% per unit NNI (Figure 7).

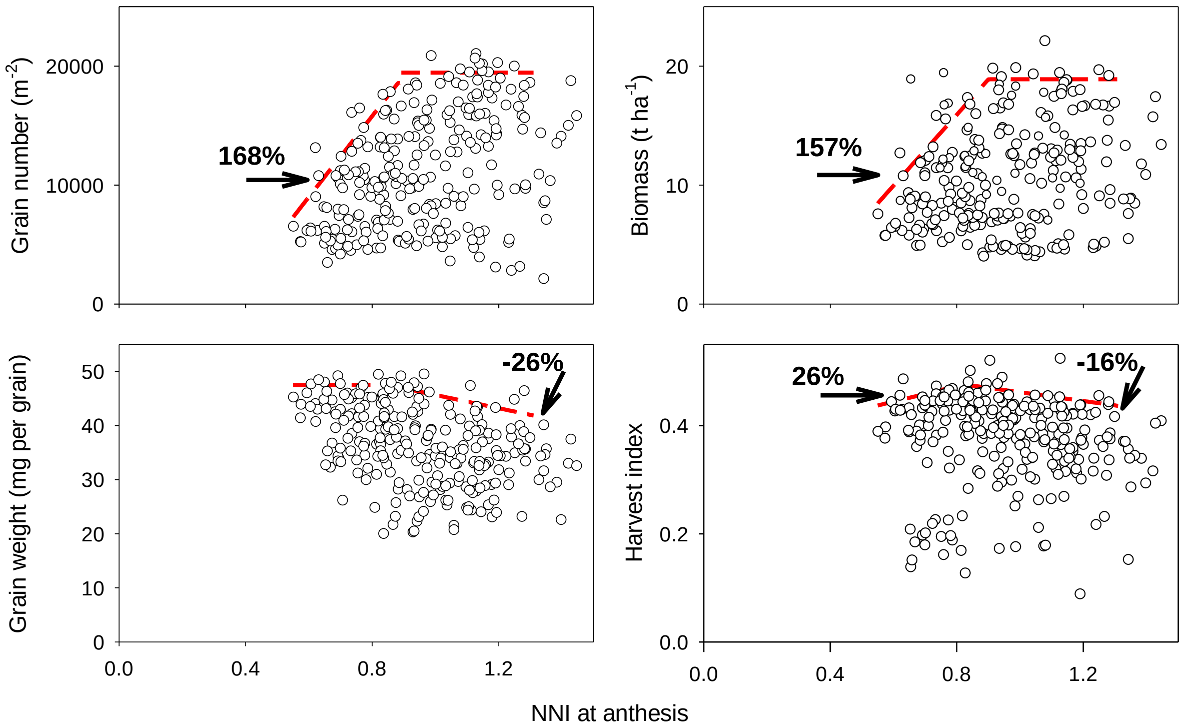

Figure 7. Relationships between wheat yield components and the nitrogen nutrition index NNI at anthesis. Red lines are boundary functions, and percentages are slopes on relative scales. Data from experiments, grower fields, and National Variety Trials in South Australia (source: Hoogmoed *et al*. 2018)

Grain number is defined in a species-specific developmental window

The general notion that grain number, and therefore grain yield, is most sensitive to stress at flowering is partially right. Detailed experiments to establish the most vulnerable stages show a wider window, from approximately stem elongation to about 10 days after flowering for wheat, barley and oat, with the most sensitive stage shortly before flowering (Figure 9A). For field pea, chickpea, lupin and canola, the most vulnerable stage is displaced towards pod set, or about 200 ºCd after flowering (Figure 9A). Critical periods have also been established for maize, sunflower and soybean

The importance of the critical period for crop management is three-fold. First, crop yield is proportional to the duration of the critical period, and the critical period shortens with lower photothermal quotient, defined as the radiation-to-temperature ratio (Fischer 1985). This partially explains the larger yield potential (*i.e*. with no extreme temperature or other stresses) in early-flowering crops.

Box 2 Nitrogen nutrition index

A nitrogen dilution curve describes the relationship between shoot nitrogen concentration and shoot biomass (Figure 8). Nitrogen in crop biomass dilutes for two reasons. First, the leaf-to-stem ratio of the crop declines with crop age; as leaves contain more nitrogen than stems, the concentration of nitrogen in shoot declines. Second, nitrogen moves from shaded leaves at the bottom of the canopy to well-lit leaves at the top with increasing ground cover. These dilution curves therefore assume two crop components, leaf and stem, and are therefore used only for the pre-flowering period, before significant spike growth.

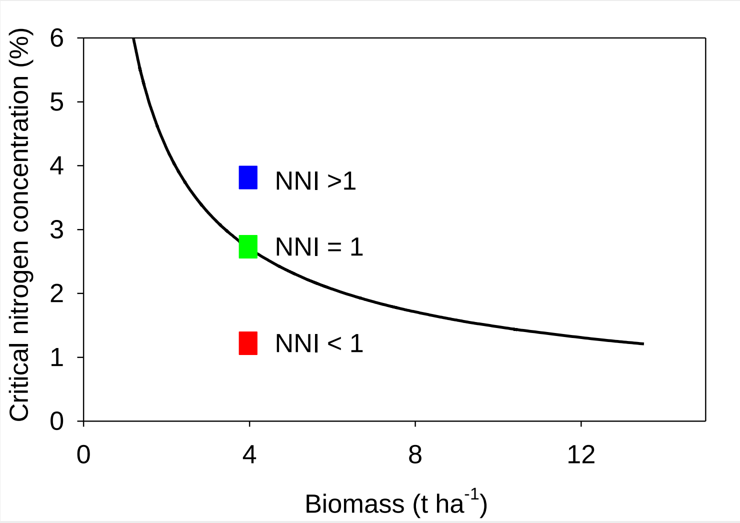

Figure 8. Critical nitrogen dilution curve for wheat under South Australian conditions. The curve, nitrogen concentration = 6.75 x biomass$^{-0.66}$, represents the minimum nitrogen concentration to achieve maximum biomass. The nitrogen nutrition index NNI is the ratio between actual and critical nitrogen concentration at a given biomass, where points below the curve (NNI < 1) indicate nitrogen deficit and points over the curve (NNI > 1) indicate excess nitrogen. The curve was derived in crops of Axe, Trojan, Mace, and Scout grown in six environments with fertiliser rate from nil to 240 kg N/ha (source: Hoogmoed and Sadras 2018)

An important implication of nitrogen-biomass dilution curves is that nitrogen concentration cannot be used as indicator of crop nitrogen status, unless it refers to a given biomass. Experiments with nitrogen rates are used to parametrise a 'critical' dilution curve, corresponding to the minimum nitrogen concentration required to achieve maximum biomass. At a given biomass, nitrogen can be insufficient (NNI<1), sufficient (NNI = 1) or excessive (NNI >1) for maximum growth. (Hoogmoed *et al.* 2018) illustrate the use of NNI to benchmark commercial crops and NVT in SA.

Second, grain number is proportional to crop growth rate in the critical window. This relationship is widespread and robust; it has been verified in wheat (Figure 10), field pea and chickpea (Figure 11), maize, sunflower and soybean (Andrade *et al.* 2005). In wheat, chickpea and soybean, the relationship between grain number and crop growth rate is linear. Linearity means that more grains are set per unit increase in growth rate with improving growing conditions; there is no morphological limit. Wheat accommodates better conditions with more tillers and more grains per head, whereas chickpea and soybean branch and set more pods with further growth. In maize and sunflower, the relationship is non-linear and grain number and yield level off at high growth rates; in these species, only one or two ears (maize) or a single head (sunflower) impose a morphological limit to yield under more favourable conditions.

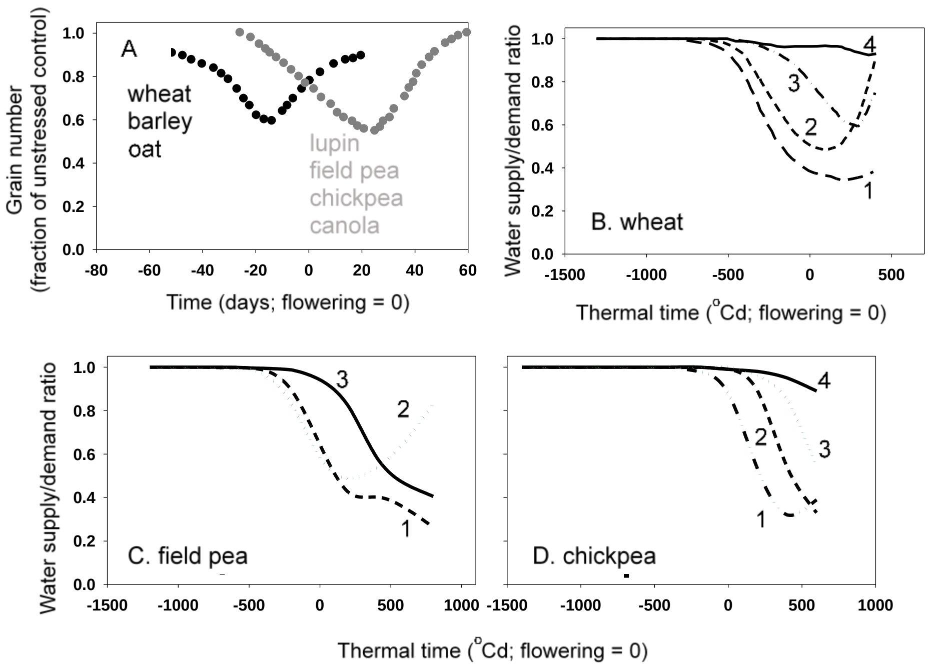

Figure 9. (A) The critical developmental window for the definition of grain number in cereals, pulses and canola. Patterns of water supply and demand in (B) wheat, (C) field pea, and (D) chickpea. Sources: (A) critical period of wheat, Fischer (1985); barley Arisnabarreta *et al*. (2008); oat, Mahadevan *et al.* (2016); lupin and fieldpea, Sandaña (2012); chickpea, Lake and Sadras (2014); canola, Kirkegaard *et al*. (2018). Drought patterns of (B) wheat, Chenu *et al*.(2013); (C) field pea, Sadras *et al*.(2012a), and (D) chickpea, Lake *et al*.(2016). Patterns of drought are numbered from 1 for early onset, progressively more severe water deficit during the season, to 3-4 for less severe or no water deficit.

Hence, two patterns – linear and non-linear – emerge for the relationship between grain number and crop growth rate. Field pea is interesting because we could have expected a chickpea-like linear pattern – more growth, more pods. Instead, field pea in South Australia shows a maize-like pattern where yield levels off at high growth rate (Figure 10). Growth and yield are decoupled in field pea under favourable growing conditions, setting a limit to yield potential. This can be tackled genetically, by selecting lines with a chickpea-type response. The reasons for the decoupling of growth and yield in field pea are unknown, but pod abortion in dense canopies might relate to the light microclimate (Heindl and Brun 1983, Myers *et al.* 1987). If so, agronomic solutions may be found by shifting from highly rectangular to a square crop configuration; precision seeding might help to 'straighten' the yield-growth relationship in field pea. The relationships between grain set and crop growth rate are unknown in lentil and fababean, but anecdotal evidence suggest it would be field pea-like, rather than linear as in chickpea. Third, crop management that seeks to avoid severe water stress during the critical period would improve yield. This requires a quantitative characterisation of the patterns of water stress in terms of timing, duration and intensity.

Yield peaks when crop critical windows are aligned with favourable conditions; hence the importance of managing flowering time with appropriate combinations of sowing date and selection of variety (Anderson *et al.* 1996, Flohr *et al.* 2017). Crop simulation has allowed optimal flowering periods to be identified for different environments across Australia for both wheat (Flohr *et al.* 2017) and canola (Lilley *et al.* 2019).

Many of the historic advances in Australian wheat yield have been due to better alignment of crop critical windows with favourable conditions. This includes the release of the faster developing Federation (Pugsley 1983), the development of no-till which allowed earlier sowing (Stephens and Lyons 1998, Flohr *et al.* 2018), and the century-long trend for breeders to produce faster developing cultivars (Eagles *et al.* 2009). Flohr *et al.* (2018) identified that wheat critical windows and optimal period for growth were well aligned at least in leading farmers' fields, and opportunities for further yield gains via this mechanism are limited.

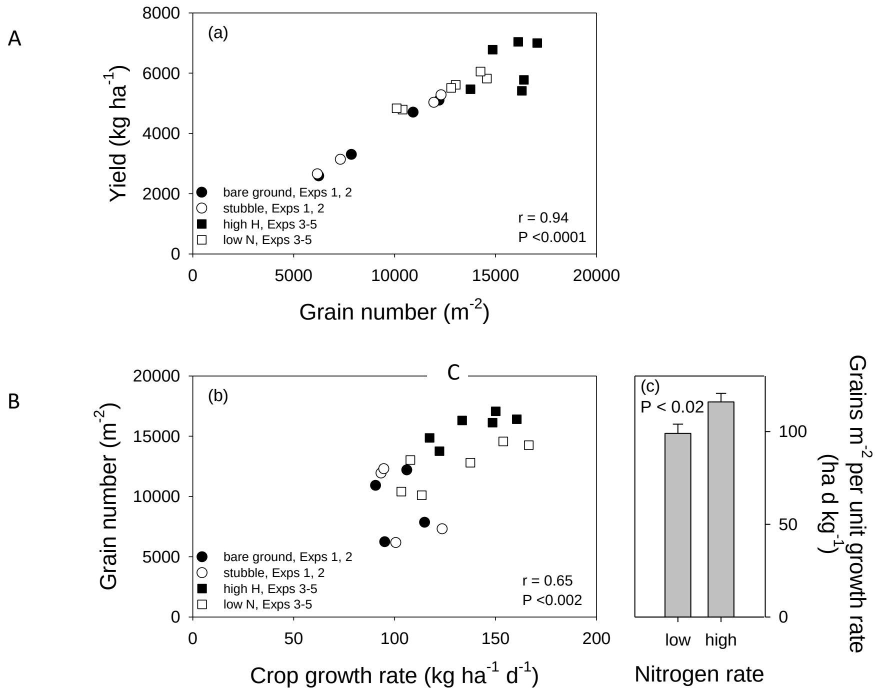

Figure 10. Relationship between (A) yield and grain number, and (B) grain number and crop growth rate in the critical window of wheat crops grown in South Australia with a combination of stubble and nitrogen rates. (C) Grain number per unit growth rate in crops with high and low nitrogen supply.Source: Sadras *et al*. (2012b)

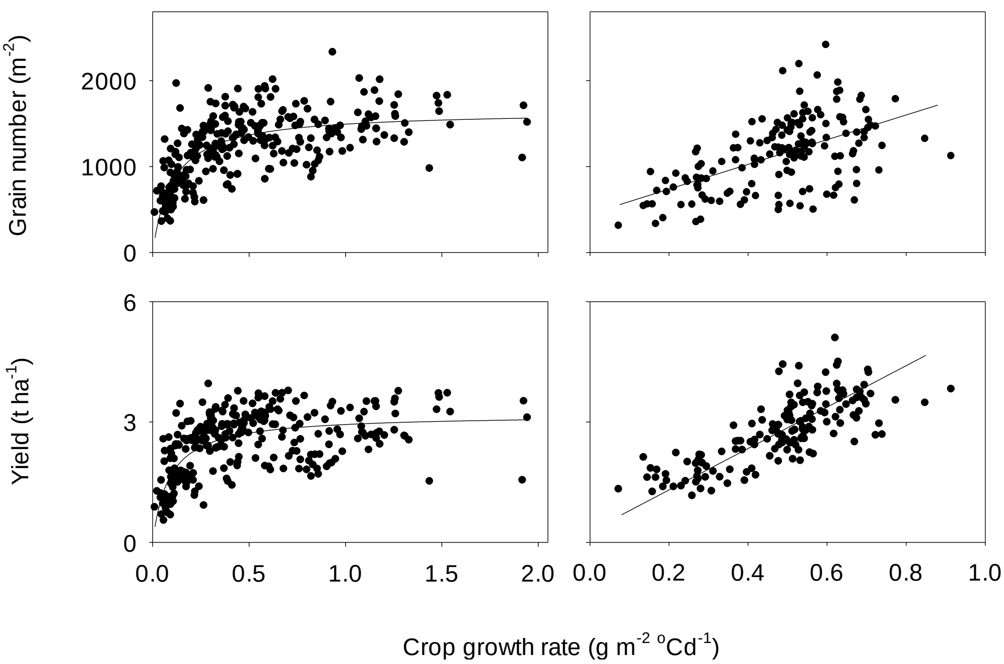

Figure 11. Relationship between crop growth rate in the critical window and grain number and yield of field pea (left) and chickpea (right) in South Australia (sources: field pea, Sadras *et al*. 2013; chickpea, Lake and Sadras 2016)

Effect of water deficit depends on the timing, duration and intensity of stress in relation to the critical window

'Terminal drought', 'dry finish', 'dry spring' are common descriptors of growing conditions in Australian regions. These descriptors are qualitative, vague and often do not reflect actual patterns. We suggest that this perception of 'terminal drought' has biased crop management towards the preservation of grain filling at the expense of grain number. Daily estimates of water supply and demand have been used to derive quantitative, probabilistic patterns of drought for major crops in Australia. Chapman and his colleagues pioneered this approach for sorghum in the northern region (Chapman *et al.* 2000), and drought patterns were later quantified and mapped for maize (Chauhan *et al.* 2013), wheat, field pea and chickpea (Figure 9BCD).

For wheat, drought pattern 1 in Figure 9B has an onset about 500 ^{o}Cd before flowering. Stress intensifies gradually, and the supply of water at flowering is only 40 % of the demand. This is the most severe drought, and many locations feature this pattern in about one third of seasons (Chenu *et al.* 2013). This pattern of stress largely overlaps with the critical period of grain set (Figure 9A). Thus, although stress is severe after flowering, most of the damage has occurred by the time the crop reaches grain filling, and it relates to grain number. The onset is slightly later and less intense for drought pattern 2, which recovers with rainfall late in the season. Drought pattern 3 is closer to 'terminal drought' as it develops after flowering and affects both grain set and filling.

The drought patterns 1, 2 and 3 for field pea are similar to those for wheat (Figure 9C vs 9B). Pattern 1 is the most severe, with an early onset and low supply/demand ratio at the critical period of pod set. Pattern 2 has an early onset, a gradual intensification of stress until pod set, and recovery following rainfall during grain fill. The similarity in the patterns of drought for wheat and field pea derive from soil-climate combinations that are common to both crops; for this reason, we expected similar patterns for chickpea in overlapping sites. However, the patterns for chickpea are different; pre-flowering stress is not evident, and drought of varying intensity develops with onset close to or shortly after flowering. It has been speculated that the lack of severe water stress before flowering relates to slow growth typical of chickpea at low winter temperature (Lake *et al.* 2016). Thus, similar soil-rainfall conditions where dry spells cause water deficit in vigorous wheat and pea crops, might be less likely to stress smaller chickpea canopies severely. Breeding efforts to improve growth under low temperature might shift the drought patterns of chickpea towards those of field pea and wheat.

Physiological principles support farming systems agronomy

An understanding of the ways in which agronomic management ultimately influences crop yield can be improved significantly by applying these crop physiological principles, at both the crop and system level. A good recent example is the work of Kitonyo *et al.* (2017) in South Australia who took a physiological approach to understand the impacts of no-till management (tillage, stubble and N supply and timing) on wheat through the lens of resource supply at critical growth periods. Tillage had little impact on resource supply at the critical period or, as a consequence, on yield. In contrast, fine-tuning stubble rates and the timing of N supply had significant impacts on N and water supply at the critical period; resultant effects on crop growth rate and radiation use efficiency between stem elongation and flowering explained impacts on grain yield.

The benefits of earlier sowing systems in wheat (Hunt *et al.* 2019) and canola (Kirkegaard *et al*. 2016) can also be explained in terms of the improved supply of water and efficiency of water use through deeper rooting, reduced evaporative loss and increased transpiration efficiency, combined with alignment of the critical window with seasonally favourable periods for growth (see Chapters 18 and 23). Critical to the success of these systems is the preceding agronomy of sound crop sequences to reduce weed seed banks and root disease and potentially to fix nitrogen and preserve water, along with strict weed control and maintenance of surface cover to maximise capture and storage of summer rainfall (Kirkegaard and Hunt 2010, Kirkegaard *et al.* 2014).

In dryland farming systems it makes sense to consider the water use efficiency across the crop sequence, rather than focusing on individual crops, because the legacies of water and N supply (along with weeds and disease) influence the performance of subsequent crops and consequently the profitability and efficiency of the sequence. In the northern grain region, Hochman *et al*. (2014) found that only 30% of the crop sequences surveyed in 94 paddocks were achieving >75% of predicted potential, much lower than for individual crops. Kirkegaard (2019) used a simulation study validated against a 30-yr field experiment in southern NSW to investigate the potential legacies of introducing both early-sown winter wheat and early-sown winter canola into the crop sequence in place of the later sown (May-June) spring crops that had been grown at the site. At the high rainfall site with relatively light textured soil, the simulation predicted significant yield increases for both crops, and small legacy effects on subsequent crops in the sequence, when firstly winter wheat, and then winter canola were introduced (Table 2). However, the higher yielding crop responded significantly to increased N supply (extra 50 kg/ha N as winter top-dressing), as the N rates applied to the spring crops were insufficient to support the higher yielding winter crops.

Table 2. The predicted impacts of sequential changes to management on the long-term mean yield of wheat and canola (t/ha) at the Harden long-term tillage site (source: Kirkegaard 2019)

Crop	Baseline (measured)	Weed Control	Weed control Early wheat	Weed control Early wheat Early canola	Weed control Early wheat Early canola +50 kg N/ha/yr^{-}
Wheat	4.5	4.7	5.6	5.5	6.0
Canola	2.9	3.1	2.9	3.3	5.0

This example demonstrates the potential to improve the water use efficiency (yield per mm annual rainfall) of the entire sequence; the early-sown winter crops were using water that was otherwise evaporated or leached in this high rainfall environment.

Conclusion

The physiological principles that underpin grain yield inform crop science and farming system agronomy, which in turn deliver increasing productivity of individual crops and crop sequences. Yield is a primary function of grain number, and grain number is defined in a crop-specific window. Extended critical windows associated with high radiation-to-temperature ratio are typical of early flowering and high latitudes and altitudes, which therefore favour yield potential. Management to increase growth rate in the critical window generally improves yield. For some combinations of crop and environment, growth and yield can be decoupled. This decoupling can be neutral (*e.g.* field pea) or negative (*e.g.* wheat haying off) for yield. The asymmetry between the responses of grain number and grain weight to management are important.

In a crop sequence, capturing the potential of higher-yielding, early sown crops requires pre-crop management that ensures increased supply of resources to the crop in the critical period. The legacies of reduced profile water and N following high yielding crops must be managed in environments where soil profiles may not refill. At both the crop and system level, novel agronomic management should be carefully considered in light of the underpinning physiology, rather than by agronomic recipes, especially in light of increasing climate variability.

References

Anderson WK, Heinrich A, Abbotts R (1996) Long-season wheats extend sowing opportunities in the central wheat belt of Western Australia. Australian Journal of Experimental Agriculture 36, 203-208

Andrade FH, Sadras VO, Vega CRC, Echarte L (2005) Physiological determinants of crop growth and yield in maize sunflower and soybean: their application to crop management modelling and breeding. *Journal of Crop Improvement* **14**, 51-101

Arisnabarreta S, Miralles DJ (2008) Critical period for grain number establishment of near isogenic lines of two- and six-rowed barley. *Field Crops Research* **107**, 196-202

Calviño PA, Monzon JP (2009) Farming systems of Argentina: yield constraints and risk management. In (Eds. VO Sadras DF Calderini) "Crop physiology: applications for genetic improvement and agronomy" pp 55-70 (Academic Press: San Diego)

Chapman SC, Hammer GL, Butler DG, Cooper M (2000) Genotype by environment interactions affecting grain sorghum. II. Frequencies of different seasonal patterns of drought stress are related to location effects on hybrid yields. *Australian Journal of Agricultural Research* **51**, 209-221

Chauhan YS, Solomon KF, Rodriguez D (2013) Characterization of north-eastern Australian environments using APSIM for increasing rainfed maize production. *Field Crops Research* **144**, 245-255

Chenu K, Deihimfard R, Chapman SC (2013) Large-scale characterization of drought pattern: a continent-wide modelling approach applied to the Australian wheatbelt – spatial and temporal trends. *New Phytologist* **198**, 801-820

Cossani CM, Sadras VO (2018) Water-nitrogen co-limitation in grain crops. *Advances in Agronomy* **150**, 231-274

Cossani CM, Sadras VO (2019) Increasing co-limitation of water and nitrogen drives genetic yield gain in Australian wheat. *European Journal of Agronomy* **106**, 23-29

Duncan EG, O'Sullivan CA, Roper MM *et al.* (2018) Influence of co-application of nitrogen with phosphorus potassium and sulphur on the apparent efficiency of nitrogen fertiliser use grain yield and protein content of wheat: Review. *Field Crops Research* **226**, 56-65

Eagles HA, Cane K, Vallance N (2009) The flow of alleles of important photoperiod and vernalisation genes through Australian wheat. *Crop and Pasture Science* **60**, 646-657

Fischer RA (1985) Number of kernels in wheat crops and the influence of solar radiation and temperature. *Journal of Agriculture Science* **105**, 447-461

Flohr BM, Hunt JR, Kirkegaard JA, Evans JR (2017) Water and temperature stress define the optimal flowering period for wheat in south-eastern Australia. *Field Crops Research* **209**, 108-119

Flohr BM, Hunt JR, Kirkegaard JA *et al*. (2018) Fast winter wheat phenology can stabilise flowering date and maximise grain yield in semi-arid Mediterranean and temperate environments. *Field Crops Research* **223**, 12-25

French RJ, Schultz JE (1984a) 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

French RJ, Schultz JE (1984b) Water use efficiency of wheat in a Mediterranean type environment. II. Some limitations to efficiency. *Australian Journal of Agricultural Research* **35**, 765-775

Heindl JC, Brun WA (1983) Light and shade effects on abscission and c-14 photoassimilate partitioning among reproductive structures in soybean. *Plant Physiology* **73**, 434-439

Hochman Z, Gobbett D, Holzworth D *et al*. (2012) Quantifying yield gaps in rainfed cropping systems: A case study of wheat in Australia. *Field Crops Research* **136**, 85-96

Hochman Z, Horan H (2018) Causes of wheat yield gaps and opportunities to advance the water-limited yield frontier in Australia. *Field Crops Research* **228**, 20-30

Hoogmoed M, Neuhaus A, Noack S, Sadras VO (2018) Benchmarking wheat yield against crop nitrogen status. *Field Crops Research* **222**, 153-163

Hoogmoed M, Sadras VO (2018) Water stress scatters nitrogen dilution curves in wheat. *Frontiers in Plant Science* **9,** 406

Hunt JR, Lilley JM, Trevaskis B *et al.* (2019) Early sowing systems can boost Australian wheat yields despite recent climate change. *Nature Climate Change* **9**, 244-247

Kirkegaard JA, Hunt JR (2010) Increasing productivity by matching farming system management and genotype in water-limited environments. *Journal of Experimental Botany* **61**, 4129-4143

Kirkegaard JA, Hunt JR, McBeath TM *et al.* (2014) Improving water productivity in the Australian grains industry – a nationally coordinated approach. *Crop and Pasture Science* **65**, 583-601

Kirkegaard JA, Lilley JM, Brill RD *et al*. (2018) The critical period for yield and quality determination in canola (*Brassica napus* L.). *Field Crops Research* **222**, 180-188

Kirkegaard JA (2019) Incremental transformation: success from farming systems synergy. *Outlook on Agriculture* **48**, 105-112.

Lake L, Chenu K, Sadras VO (2016) Patterns of water stress and temperature for Australian chickpea production. *Crop and Pasture Science* **67**, 204-215

Lake L, Sadras VO (2014) The critical period for yield determination in chickpea (*Cicer arietinum* L.) *Field Crops Research* **168**, 1-7

Lake L, Sadras VO (2016) Screening chickpea for adaptation to water stress: Associations between yield and crop growth rate. *European Journal of Agronomy* **81**, 86-91

Lilley JM, Flohr BM, Whish JPM *et al*. (2019) Defining optimal sowing and flowering periods for canola in Australia. *Field Crops Research* **235**, 118-128

Mahadevan M, Calderini D,F Zwer PK, Sadras VO (2016) The critical period for yield determination in oat (*Avena sativa* L.). *Field Crops Research* **199**, 109-116
Monzon JP, Sadras VO, Andrade FH (2006) Fallow soil evaporation and water storage as affected by stubble in sub-humid (Argentina) and semi-arid (Australia) environments *Field Crops Research* **98**, 83-90
Myers RL, Brun WA, Brenner ML (1987) Effect of raceme-localized supplemental light on soybean reproductive abscission. *Crop Science* **27**, 273-277
Nidumolu UB, Hayman PT, Howden SM, Alexander BM (2012) Re-evaluating the margin of the South Australian grain belt in a changing climate. *Climate Research* **51**, 249-260
Norton R, Wachsmann N (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
Pugsley AT (1983) The impact of plant physiology on Australian wheat breeding. *Euphytica* **32** 743-748
Rattalino Edreira JI, Guilpart N, Sadras V *et al*. (2018) Water productivity of rainfed maize and wheat: A local to global perspective. *Agricultural and Forest Meteorology* **259**, 364-373
Sadras VO (2003) Influence of size of rainfall events on water-driven processes I. Water budget of wheat crops in south-eastern Australia. *Australian Journal of Agricultural Research* **54**, 341-351
Sadras VO (2007) Evolutionary aspects of the trade-off between seed size and number in crops. *Field Crops Research* **100**, 125-138
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, Baldock JA (2003) Influence of size of rainfall events on water-driven processes. II. Soil nitrogen mineralisation in a semi-arid environment. *Australian Journal of Agricultural Research* **54**, 353-361
Sadras VO, Cassman KG, Grassini P *et al*. (2015) “Yield gap analysis of rainfed and irrigated crops: Methods and Case Studies” (FAO: Rome)
Sadras VO, Denison RF (2009) Do plant parts compete for resources? An evolutionary perspective. *New Phytologist* **183**, 565-574
Sadras VO, Dreccer MF (2015) Adaptation of wheat barley canola field pea and chickpea to the thermal environments of Australia. *Crop and Pasture Science* **66**, 1137-1150
Sadras VO, Lake L, Chenu K *et al*. (2012a) Water and thermal regimes for field pea in Australia and their implications for breeding. *Crop and Pasture Science* **63**, 33-44
Sadras VO, Lake L, Leonforte A *et al*. (2013) Screening field pea for adaptation to water and heat stress: Associations between yield crop growth rate and seed abortion. *Field Crops Research* **150**, 63-73
Sadras VO, Lawson C (2013) Nitrogen and water-use efficiency of Australian wheat varieties released between 1958 and 2007. *European Journal of Agronomy* **46**, 34-41
Sadras VO, Lawson C, Hooper P, McDonald GK (2012b) Contribution of summer rainfall and nitrogen to the yield and water use efficiency of wheat in Mediterranean-type environments of South Australia. *European Journal of Agronomy* **36**, 41-54
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 (2007) The limit to wheat water use efficiency in eastern Australia. II. Influence of rainfall patterns. *Australian Journal of Agricultural Research* **58**, 657-669
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, Slafer GA (2012) Environmental modulation of yield components in cereals: Heritabilities reveal a hierarchy of phenotypic plasticities. *Field Crops Research* **127**, 215-224
Sandaña P, Calderini DF (2012) Comparative assessment of the critical period for grain yield determination of narrow-leafed lupin and pea. *European Journal of Agronomy* **40**, 94-101
Slafer G, Savin R, Sadras VO (2014) Coarse and fine regulation of wheat yield components in response to genotype and environment. *Field Crops Research* **157**, 71-83
Stephens DJ, Lyons TJ (1998) Variability and trends in sowing dates across the Australian wheatbelt. *Australian Journal of Agricultural Research* **49**, 1111-1118
Unkovich M, Baldock J, Farquharson R (2018) Field measurements of bare soil evaporation and crop transpiration and transpiration efficiency for rainfed grain crops in Australia – A review. *Agricultural Water Management* **205**, 72-80
van Herwaarden AF, Farquhar GD, Angus JF *et al*. (1998a) ‘Haying-off’ the negative grain yield response of dryland wheat to nitrogen fertiliser I. Biomass grain yield and water use. *Australian Journal of Agricultural Research* **49**, 1067-1082
van Herwaarden AF, Angus JF, Richards RA, Farquhar GD (1998b) ‘Haying-off’ the negative grain yield response of dryland wheat to nitrogen fertiliser II. Carbohydrate and protein dynamics. *Australian Journal of Agricultural Research* **49**, 1083-1094

van Herwaarden AF, Richards RA, Farquhar GD, Angus JF (1998c) 'Haying-off' the negative grain yield response of dryland wheat to nitrogen fertiliser. III The influence of water deficit and heat shock. *Australian Journal of Agricultural Research* **49**, 1095-1110

van Ittersum MK, Cassman KG, Grassini P *et al*. (2013) Yield gap analysis with local to global relevance—A review. *Field Crops Research* **143**, 4-17

van Rees H, McClelland T, Hochman Z *et al*. (2014) Leading farmers in South East Australia have closed the exploitable wheat yield gap: Prospects for further improvement. *Field Crops Research* **164**, 1-11

Verburg K, Bond WJ, Hunt JR (2012) Fallow management in dryland agriculture: Explaining soil water accumulation using a pulse paradigm. *Field Crops Research* **130**, 68-79

Williamson G (2007) "Climate and root distribution in Australian perennial grasses; implications for salinity mitigation" PhD Thesis, The University of Adelaide.