

Interactions between the water and nitrogen economies of crops:

Physiological, agronomic, economic, breeding and modelling perspectives

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Contents

Acknowledgements.....	4
Executive Summary.....	5
Chapter 1.....	5
Chapter 2.....	8
Research gaps.....	9
Interactions between the water and nitrogen economies of crops:	12
Summary	13
Introduction.....	14
Background: crop yield, soil and climate	16
<i>Crop yield and environmental constraints</i>	16
<i>Climate</i>	17
The photothermal environment	17
Rainfall patterns.....	18
Supply and demand of water and nitrogen in relation to critical periods of yield determination	21
Extreme temperatures	22
<i>Soil</i>	24
Soil texture, soil water and soil nitrogen	24
Soil water and nitrogen mineralisation	26
Soil nitrogen and crop water use	27
Regional differences in soils.....	28
A physiological perspective: co-limitation.....	30
<i>The effect of nitrogen deficit on the water economy of crops</i>	30
<i>The effect of water deficit on the nitrogen economy of crops</i>	32
<i>Combined effect of water and nitrogen deficit on crop growth and yield: co-limitation</i> ...	34
An agronomic perspective: yield gap and management practices	35
Overview.....	35
Yield gap.....	37
Wheat in winter-rainfall environments	38
Varieties, fertilisers and logistics.....	43
Wheat and sorghum in summer-rainfall environments.....	44
An economic perspective: dealing with risk	46
Production economics	48

<i>Risk and uncertainty</i>	49
<i>Seasonal climate forecasts</i>	51
A breeding perspective: the water and nitrogen economies of high-yielding varieties.....	53
<i>Water and nitrogen related traits of wheat</i>	54
<i>Water and nitrogen related traits of other crops</i>	62
A modelling perspective	65
Conclusions: further research	67
References	71
The value of soil and climate information to support nitrogen management.....	88
Introduction.....	89
Method	90
<i>Sites</i>	90
<i>Climate</i>	91
<i>Simulated scenarios</i>	92
<i>Economic analysis</i>	93
<i>Data analysis</i>	94
Results	94
<i>Yield</i>	94
<i>Total Factor Productivity</i>	96
<i>Nitrogen Stress Index</i>	98
<i>Water Stress Index</i>	99
<i>Water Use Efficiency</i>	101
Discussion	105
References	108

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Genesis T. Yengoh first proposed the insightful distinction between proximal and ultimate causes of yield gaps in the FAO workshop “Crop yield and water-productivity gaps” Rome, 3-4 October 2013.

Executive Summary

Shortage of both water and nitrogen are widespread in the Australian cropping regions. The effects of water and nitrogen on biological processes relevant to agriculture (e.g. soil nitrogen mineralisation, photosynthesis) can be additive, synergistic or antagonistic.

Research with an exclusive focus on water or nitrogen risks overlooking synergies and trade-offs, hence the need for explicit consideration of the links between the economies of water and nitrogen in crops and cropping systems.

This report has two chapters. In Chapter 1, we review the literature on water and nitrogen interactions from physiological, agronomic, economic, breeding and modelling perspectives. In Chapter 2, we present new information from modelling studies assessing the economic value of three sources of information for decision making: initial soil nitrogen, initial soil water, and seasonal rainfall forecast.

We conclude with a list of research gaps.

Chapter 1

We review the interactions between the water and nitrogen economies of crops from complementary physiological, agronomic, economic, breeding and modelling perspectives. Our primary focus is wheat, the main crop in Australia. We also discuss other species for comparison, including forage crops where advanced notions on the physiology of water and nitrogen have been proposed, sorghum where current understanding of stay-green illuminates some of the connections between nitrogen and water, and legumes, where intra-specific variation in nitrogen fixation under drought seems relevant for crop yield.

The review opens with a background section where we define yield gaps and outline aspects of soil and climate relevant to the economies of water and nitrogen. Climate factors include the photothermal environment setting the yield potential, rainfall patterns (amount, seasonality, size structure of rainfall events), synoptic aspects of rainfall relevant to forecasting, supply and demand of water and nitrogen in relation to critical periods of yield determination and extreme temperatures as major factors that disrupt crop reproduction and yield. We discuss the role of soil texture in determining

the upper and lower limits for soil water and nitrogen storage and their implications for crop growth, water as the primary driver of soil nitrogen mineralisation, the influence of nitrogen availability on crop water uptake, and coarse regional differences in soils with implications for the water and nitrogen economies of crops.

Physiologically, we emphasise synergies that are mediated by genotypic variation and environmental sources of variation other than water and nitrogen, and the nitrogen-driven trade-off between the efficiency in the use of water and the efficiency in the use of nitrogen. The concept of nitrogen-water co-limitation is discussed briefly. Plants in the field are often exposed to multiple stresses. As a single limiting factor is unlikely, the Liebig paradigm is generally inappropriate to understand and manage crops. Theory indicates that plant growth is maximised when it is equally limited by all resources, and modelling and experimental evidence supports this proposition: water and nitrogen co-limitation favours wheat grain yield.

Agronomically, there is a widespread recognition that supply of nitrogen should match the supply of water, but this remains a challenge in dryland systems with uncertain rainfall. The consequences of the mismatch between supply of water and nitrogen is a common and often large gap between actual yield and water-limited yield potential. The causes are analysed from an economic perspective, where the inherent risk of dryland farming is highlighted as the dominant driver of nitrogen fertilisation decisions; we discuss aspects of risk aversion and the role of seasonal rainfall forecasts as a risk management tool. Current agronomic approaches to deal with the matching of nitrogen and water are compiled, mostly from unpublished, local sources for the winter-rainfall environments of south-eastern and western Australia and for the summer-rainfall, northern region.

A data set of 274 wheat crops was compiled that spans the range of soil, climates and management in Australia. Frequency distributions and quantile regressions were used in the analysis. Median wheat yield was 2.7 t ha⁻¹ and median grain nitrogen concentration 1.7% where fertilisation was below 25 kg N ha⁻¹ in comparison to median yield of 5.3 t ha⁻¹ and median grain nitrogen concentration 2.1% for their counterparts with more than 151 kg N ha⁻¹. Yield and biomass responses to fertiliser were 2-3 larger under favourable conditions (90th percentile) than under stress (10th percentile). Grain nitrogen concentration correlated with nitrogen fertiliser rate under favourable conditions but not under conditions conducive to low grain protein. Variation in yield was mostly related to variation in biomass, whereas median harvest index was relatively stable, ranging from 0.38 with less than 25 kg N ha⁻¹ to 0.41 at

151 kg N ha⁻¹ or more. The relationship between harvest index and fertiliser had slopes undistinguishable from zero for both 90th and 10th percentiles.

Comparison of nitrogen export in grain, and the input of nitrogen fertiliser across these environments indicate a cutting point for fertiliser around 50 kg N ha⁻¹; below this rate, export exceeds input suggesting likely soil mining. This coarse estimate of partial nutrient balance is consistent with a detailed, long-term experiment at a single site in Victoria where the ratio between nitrogen removed and applied was 1 for rates of fertilisation between 40 and 80 kg N ha⁻¹.

The breeding perspective is based on re-analyses of studies comparing historic series of cultivars; the question is how selection for yield has changed water and nitrogen related crop traits. Changes in nitrogen related traits seem more common and profound than changes in water related traits. Comparisons of shifts in the wheat phenotype in Australia, UK, Argentina and Italy suggest that improving nitrogen use efficiency is easy – it requires selection for yield and letting grain protein concentration to drift unchecked. The result is higher yield per unit nitrogen uptake, at the expense of reduced protein. A more interesting proposition, we propose, is to increase nitrogen uptake to match yield gains and conserve protein in grain. Increased stomatal conductance is the most conspicuous change in crop phenotype in response to selection for yield in diverse crops and environments. The impact of increased stomatal conductance on the water economy of the crop is unclear, and partially conflicts with the perception that reduced conductance at high vapour pressure deficit is required to increase water use efficiency. High stomatal conductance at high vapour pressure deficit, however, favours evaporative cooling and might be relevant to adaptation to thermal stress.

From a modelling perspective, water and nitrogen primarily linked by scaling physiological rates (leaf expansion, photosynthesis) by either water or nitrogen. Further, in crops where water limits growth, reduced biomass would reduce nitrogen demand. Reciprocally, nitrogen limitation during crop expansion would reduce leaf area index and evaporative demand. The modulation of canopy size by nitrogen also impacts on the partitioning of water use between transpiration and soil evaporation. Water and nitrogen interactions are also captured in the water-driven uptake of nitrogen by mass flow and diffusion and in the water-driven fate of nitrogen in soil (e.g. leaching mineralisation).

Chapter 2

Where crop nitrogen is in short supply relative to the availability of water, a yield gap emerges often associated to a reduction in profits. Conversely, where nitrogen supply exceeds the requirement to achieve the water-limited yield, the return in nitrogen investment will be small or even negative. Therefore, matching nitrogen availability to water supply is critical in rainfed cropping.

We used regional knowledge of crops and soils to parameterise the APSIM model and compare six strategies to inform nitrogen fertilisation practices in wheat. Rates of fertiliser were informed by (i) initial soil water (ISW); (ii) initial soil nitrogen (ISN); (iii) both ISW and ISN or (iv) seasonal rainfall forecast (POAMA). These were compared with two controls: (v) a control where fertiliser decisions were the same every year, i.e. ignoring soil or climate information; and (vi) a control we called perfect knowledge, when the decision of N fertilisation was based on actual rainfall.

Eleven sites across Northern, Southern and Western Australia were selected to capture different climates and soils: Dalby, Emerald, Goondiwindi, Minnipa, Yorketown, Merredin, Moora, Wongan Hills, Condobolin, Wagga Wagga and Birchip. The modelling included the six management strategies and rates of nitrogen from zero to 250 kg N/ha, in 10 kg N/ha increments. APSIM was then used to simulate yields, water and N use, water stress index and nitrogen stress index. Efficiency measures were also calculated, including water use efficiency (WUE, yield per unit evapotranspiration), total factor productivity (TFP, yield per unit N fertiliser), gross margin (GM) and financial risk. Two measures of risk were used: the chance of achieving a negative gross margin; and a return on investment lower than 1.1.

As expected from theory, simulated TFP decreased and WUE increased with increasing N rate. The median WUE under the different strategies and sites was lower than $14.8 \text{ kg ha}^{-1} \text{ mm}^{-1}$, though ten out of twelve simulated sites had WUE less than $10 \text{ kg ha}^{-1} \text{ mm}^{-1}$.

The profit-risk curves varied with location and fertilisation strategy. The highest percentage increase of GM was simulated when information about ISN and the combined ISW and ISN were used to decide on the amount of N to apply. Soil type and climate were the main sources of variation among sites, and for a given site, differences in initial soil water and nitrogen were major sources of differences in yield, TPF, stress indices, WUE, GM and risk of crop failure between strategies. For

example, for Dalby (Qld), the most profitable strategy was using both ISW and ISN information to decide on the application of 100kg N ha⁻¹, returning a GM of \$344 ha⁻¹. The associated risk i.e. achieving a negative GM was 47%. Using only information about ISN would allow for a GM of \$261 ha⁻¹ associated to a 26% chance of a negative gross margin. These results illustrate the importance of using information on water and nitrogen availability at sowing to inform nitrogen management.

The value of POAMA to support N management decisions differed across Australia's grains regions, and across levels of investment in N fertilisers. The clearest results were observed at Dalby, Wongan Hills and Condobolin where using POAMA forecasts to decide on N rate reduced risk and increased profit. The results from POAMA in Victoria and South Australia might be affected by soil parameters and merit more detailed studies.

Yield and consequently farmers' profit, depend not only on nitrogen management, but also on farmers capacity to match genotype and management to the growing environment and expected seasonal conditions. Thus, the full potential from soil information and forecasts can only be captured by integrating this information with crop variety (e.g. maturity group, tillering pattern, lodging, disease tolerance), soil (depth, available water, physical and chemical constraints), management and climate (sowing window against frost and heat risk).

Research gaps

1. Yield-soil nitrogen relations are highly scattered because other factors such as water constrain crop responses to nutrients. Plant-based diagnostic tools remove some of this noise. Thus, we propose to develop nitrogen dilution curves for major crops accounting for by the effects of water deficit, and explicitly including a compartment of water soluble carbohydrates. These dilution curves will allow for unequivocal assessment of the nitrogen status of crops, which are in turn necessary for calibration of tools for both diagnostic purposes in crop management, and high-throughput methods in breeding.
2. Fertiliser recommendations are generic, but there is an increasing interest in variety-specific differences in response to nitrogen. Thus, we propose to (a) assess the nitrogen demand and responsiveness to fertiliser, in terms of yield

and protein, of new wheat and barley varieties and (b) explore the benefits of tailoring fertiliser management to specific varieties.

3. The French & Schultz model has been instrumental in crop management for rainfed systems in Australia. By analogy to the yield-evapotranspiration relationship, we propose to investigate the nitrogen uptake vs evapotranspiration relationship, particularly its association with grain protein, the nitrogen:water ratio required to close the yield gap and its potential applications in crop management.
4. Growers are familiar with the concept of bucket size for water, but there is no equivalent for nitrogen. We thus propose to expand the concept of plant available nitrogen and field methods to measure it. Practical aspects of soil sampling need some attention, e.g. spatial variation, transport from the farm to the lab, and timeliness of lab results to support decisions.
5. There is large variation in the impact of nitrogen supply on water uptake, thus the need to establish the combination of crops, soils and growing conditions where additional nitrogen can contribute further soil water uptake. This is more likely to be relevant in the northern region, where stored soil water is important.
6. Some components of cropping systems (pasture, green manure) contribute nitrogen but may reduce water available to subsequent crops. We therefore need to quantify the trade-offs between nitrogen supply and water consumption by pastures and green manures in different combinations of soil, climate and rotations in both winter- and summer-rainfall regions.
7. Risk analysis of fertiliser decisions generally assumes that all the benefit of nitrogen application is constrained to a single season. Given emerging experimental evidence, we need to (a) determine the size of the carry over effect for different combinations of crop, soil, climate and management and (b) update risk analysis to account for carry-over of nitrogen beyond the application season.
8. Comparison of old and new varieties has been useful in identifying the increasing demand of nitrogen in new wheat varieties. Following on this work, it is of interest to: (a) determine the physiological and genetic basis of nitrogen uptake in old and new wheat varieties with proven difference in nitrogen uptake in winter-rainfall field conditions and (b) compare water and nitrogen related traits in historic sets of wheat varieties agronomically adapted to grow on stored soil water, e.g. the summer-rainfall environments of northern Australia. The environments where rainfall transitions from summer- to winter-dominant can also be of interest.
9. Superior soybean lines have been selected for maintenance of nitrogen fixation under drought. Research in temperate legumes lags behind soybean and other subtropical species. Hence, there is a need to screen temperate pulses for

nitrogen fixation in soil dry-down experiments, and establish the adaptive value (in terms of yield) of this trait.

10. Sorghum is the more important summer cereal in Australia and is supported by local breeding whereas growers rely on putatively less adapted maize hybrids developed overseas. We propose (a) to compare sorghum and maize to understand the differences in phenotypes (e.g. tillering, stomatal sensitivity, response to sowing density) between breeding programs in USA (maize) and Australia (sorghum) and (b) to determine the profitability and risk of different G x E x M combinations for sorghum and maize (hybrids, plant density, row configuration, sowing time, soil type and nitrogen fertilisation).
11. Modelling studies are a cost-effective approach to generate agronomically interesting information across regions and climates. We propose to model and map the nation-wide, probabilistic patterns of supply and demand of water and nitrogen for major crops as background for agronomic, e.g. timing of fertilisation, and breeding studies, e.g. root patterns. Associated with this proposition, there are species-specific gaps as well as gaps related to basic physiology and modelling. Nation-wide patterns of water stress have been produced for wheat, maize, sorghum, field pea and chickpea; remaining crops to be modelled are canola, lentil, lupin and faba bean. Associated with these, the quantification of the critical period of canola, lentil and faba bean need attention. The patterns of demand and supply for nitrogen need to be developed for all crops. To support this, we need improved models of nitrogen mineralisation accounting from variation in soil and crop residues, and better understanding of genotype-dependent root nitrogen uptake.
12. To test and capture the value of soil information (initial water and nitrogen) and POAMA forecasts, we would need to (i) establish a network of real farm case studies representing the North, South and West regions, (ii) compile and integrate soil, genotype, climate and management information, (iii) engage with growers to discuss these strategies in relation to relevant and actionable decisions, (iv) use APSIM to test the value of initial soil conditions and POAMA, (v) compare APSIM results with long-term (> 5 years) real-farm outcomes, (vi) formalise location-specific recommendations on the relative value of different sources of information.

Chapter 1

**Interactions between the water and nitrogen economies of crops:
Physiological, agronomic, economic, breeding and modelling perspectives**

Summary

This Chapter reviews the interactions between water and nitrogen from complementary physiological, agronomic, economic, breeding and modelling perspectives. Our primary focus is wheat, the main crop in Australia. We also consider forage crops, sorghum and legumes where advanced notions of water-nitrogen interactions have been proposed.

From a physiological perspective, we ask three questions: How does nitrogen deficit influence the water economy of the crop? How does water deficit influence the nitrogen economy of the crop? How do combined water and nitrogen deficit affect crop growth and yield? We emphasise synergies that are mediated by genotypic variation and environmental sources of variation other than water and nitrogen, and the nitrogen-driven trade-off between the efficiency in the use of water and nitrogen. The concept of nitrogen-water co-limitation is discussed briefly.

From agronomic and economic perspectives, there is a widespread recognition that supply of nitrogen should match the supply of water, but this remains a challenge in dryland systems with uncertain rainfall. Under-fertilisation is a common cause of gaps between actual yield and water-limited potential yield. The inherent risk of dryland farming is highlighted as the dominant driver of nitrogen fertilisation decisions; we discuss aspects of risk aversion and the role of seasonal rainfall forecasts as a risk management tool.

From a breeding perspective we ask how selection for yield has changed water and nitrogen crop traits. Changes in nitrogen traits seem more common and profound than changes in water related traits. Comparison of shifts in the wheat phenotype in Australia, UK, Argentina and Italy suggests that improving yield per unit nitrogen uptake is easy – it requires selection for yield and letting grain protein concentration to drift unchecked. The result is higher yield per unit nitrogen uptake, at the expense of protein. A more interesting proposition is to increase nitrogen uptake to match yield gains and conserve protein in grain. Increased stomatal conductance is a conspicuous response to selection for yield. The impact of increased stomatal conductance on the carbon and water economies of the crop is unclear, and partially conflicts with the perception that reduced conductance at high vapour pressure deficit is required to increase water use efficiency. High stomatal conductance at high vapour pressure deficit, however, favours evaporative cooling and may be relevant to adaptation to thermal stress.

From a modelling perspective (with a focus on APSIM), water and nitrogen are primarily linked by applying the minimum of the water and nitrogen stress to scale the rate of plant

processes. In crops where water limits growth, reduced biomass would reduce nitrogen demand. Reciprocally, nitrogen limitation during crop expansion would reduce leaf area index and evaporative demand, and increase the soil evaporation : transpiration ratio. Water and nitrogen interactions are also captured in the water-driven uptake of nitrogen by mass flow and diffusion and in the water-driven processes of nitrogen in soil (e.g. mineralisation).

The paper concludes with suggestions for future research on water-nitrogen interactions.

Introduction

Management practices that increased the availability of nitrogen and water have been a major driver of gains in crop yield on historical time scales (Sinclair and Rufty 2012). Except for some pockets of high-rainfall and fertile soil, water and nutrient scarcity are dominant features of Australian farming (Angus 2001; Connor 2004; Fischer 2009). Interactions between water and nitrogen influence processes from ecosystem to molecular level. Water-nitrogen interactions modulate the geochemical cycling of nitrogen, shape functional diversity of plants and niche segregation, and affect crop yield, grain size and protein, root demography, leaf stoichiometry, photosynthesis and senescence, root-to-shoot translocation and microbial enzyme activity in soil (Bermudez and Retuerto 2014; Cossani et al. 2010; Cossani et al. 2011; Dijkstra et al. 2012; Errecart et al. 2014; Gonzalez-Dugo et al. 2012; Lü et al. 2012; Pregitzer 1993; Sadras 2005; Sadras and Rodriguez 2010; Teixeira et al. 2014; Wang et al. 2015; Wolfe et al. 1988; Ye et al. 2013).

Understanding the interactions between water and nitrogen over a range of organisation levels is important for rainfed cropping systems. Yield gains, however, arise from improved agronomy, better varieties and their synergy (Fischer 2009). For water-nitrogen interactions to be exploited therefore, they must be linked to agronomy, breeding or both. Agronomically, the need to match supply of water and nitrogen is recognised and the interactions have therefore received much attention in both rainfed and irrigated cropping systems worldwide (Albrizio et al. 2010; Angus and van Herwaarden 2001; Asseng et al. 2001b; Cossani et al. 2010; Dalal et al. 1997; Hernández et al. 2015; Sadras 2005). The links between water and nitrogen are less developed in plant breeding (Sadras and Richards 2014). Breeding for drought adaptation has partially focused on nitrogen metabolism, including the use of N isotope signature as a phenotyping tool (Yousfi et al. 2012) and the maintenance of nitrogen fixation in water-stressed legumes (Sinclair 2011; Sinclair et al. 2007). Attempts to

genetically improve the efficiency in the use of nitrogen have paid less attention to the interaction with water (Cao et al. 2007; Huang et al. 2007).

Relationships between water and nitrogen can be additive, whereas synergies can be deduced from definitions (Box 1). In this paper we outline the relationships between nitrogen and water from physiological, agronomic, economic, breeding and modelling perspectives. Environmental aspects of the water-nitrogen interaction are important (e.g. Christianson and Harmel 2015; Norse and Ju 2015), but are not considered. Our primary focus is wheat, the main crop in Australia. We also discuss other species for comparison, including forage crops where advanced notions on the physiology of water and nitrogen have been proposed, sorghum where current understanding of stay-green illuminates some of the connections between nitrogen and water, and legumes, where intra-specific variation in nitrogen fixation under drought seems relevant for crop yield. Directions for further research are identified.

Box 1. Synergies between efficiencies

Efficiency in the use of resources can be defined at different levels of organisation and time scales (Sinclair et al. 1984; Wang et al. 2013). To highlight synergies, here we focus on efficiencies defined as a function of crop shoot biomass (B) as follows: transpiration efficiency, WUE (B,T) is biomass per unit transpiration (T), nitrogen conversion efficiency (NCE) is biomass per unit nitrogen uptake (Nupt) and radiation use efficiency (RUE) is biomass per unit intercepted PAR (PARi). Hence:

$$\text{WUE (B,T,s)} = \text{RUE} \cdot \text{PARi} \cdot \text{T}^{-1} \quad (1a)$$

taking the ratio $\text{T} : \text{PARi}$ as a coarse approximation to canopy conductance g_c (Caviglia and Sadras 2001; Sadras et al. 1991):

$$\text{WUE (B,T,s)} = \text{RUE} \cdot g_c^{-1} \quad (1b)$$

Also:

$$\text{WUE (B,T,s)} = \text{NCE} \cdot \text{Nupt} \cdot \text{T}^{-1} \quad (2)$$

$$\text{NCE} = \text{RUE} \cdot \text{Nupt}^{-1} \cdot \text{PARi} \quad (3)$$

Enhanced radiation use efficiency, e.g. as associated with stay green, sink-driven or nitrogen-driven enhancement of photosynthesis (Stockle and Kemanian 2009) could increase transpiration efficiency, provided canopy conductance does not increase much (eq. 1b). Caviglia and Sadras (2001) provide empirical evidence for the enhancement in water use efficiency driven by higher radiation use efficiency in response to nitrogen supply. Transpiration efficiency can increase with both higher nitrogen conversion efficiency and higher uptake of nitrogen per unit transpiration (eq. 2). Enhanced radiation use efficiency per unit nitrogen uptake can increase nitrogen conversion efficiency for a given PAR interception (eq. 3). In pot-grown plants, transpiration efficiency and nitrogen conversion efficiency both increased with increasing level of ploidy in a comparison of three diploid (*Triticum boeoticum*, AA; *Aegilops speltoides*, BB and *Ae. tauschii*, DD), two tetraploid (*T. dicoccoides*, AABB and *T. dicoccon*, AABB) and one hexaploid (*T. vulgare*, AABBDD) wheats (Huang et al. 2007).

Background: crop yield, soil and climate

Here we provide a brief background to aspects of Australia's climate and soil related to the economies of water and nitrogen of crops. We start this section with definitions of yield necessary to place climate and soil constraints in an agronomic context and to make explicit the elements of yield gap in further sections.

Crop yield and environmental constraints

Yields of individual crops are in a continuum from crop failure to potential and several definitions account for this range (Connor et al. 2011; Evans and Fischer 1999; Fischer 2015; Sadras et al. 2015a; van Ittersum and Rabbinge 1997).

Potential yield is the yield of a current cultivar “when grown in environments to which it is adapted; with nutrients and water non limiting; and with pests, diseases, weeds, lodging, and other stresses effectively controlled” (Evans and Fischer 1999). Potential yield depends on location as it relates to weather but is independent of soil, which is assumed to be physically and chemically favourable for crop growth. Potential yield is constrained by genotypic (e.g. canopy architecture, harvest index) and environmental drivers of crop development, growth and resource partitioning in non-stress conditions. Recognised environmental factors include solar radiation, ambient CO₂ concentration, temperature and photoperiod, as they modulate development and growth (Evans 2013; Fischer 1985; Slafer et al. 2015). The list of environmental factors has been expanded to include proportion of diffuse radiation and vapour pressure deficit (Rodriguez and Sadras 2007). For a given amount of radiation, photosynthesis increases with the proportion of diffuse radiation, that depends on atmospheric conditions and canopy traits (Roderick and Farquhar 2003; Sinclair and Shiraiwa 1993; Spitters 1986). Stomatal conductance and photosynthesis decline with high vapour pressure deficit even in well-watered plants (Ohsumi et al. 2008; Otieno et al. 2012).

Water-limited potential yield is similar to potential yield, except that it is also limited by water supply, and hence influenced by soil type (water holding capacity and rooting depth) and field topography. This is the measure of yield relevant to benchmark rainfed crops. *Actual yield* reflects the current state of soils and climate, average skills of the farmers, and their average use of technology. *Yield gap* is the difference between two levels of yield and the *exploitable yield gap* accounts for both the unlikely alignment of all factors required for achievement of potential or water limited yield and the economic, management and

environmental constraints that preclude, for example, the use of fertiliser rates that maximise yield, when growers' aim is often a compromise between maximising profit and minimising risk at the whole-farm scale, rather than maximising yield of individual crops. To account for this, a factor (< 1) is used to scale potential yield and water-limited yield. A factor = 0.8 has been used to define the exploitable yield gap in some production systems (Lobell et al. 2009); smaller factors apply in riskier systems and higher factors might apply for high-value horticultural crops.

Climate

This section has three parts. First, we consider the climate drivers of potential yield. Next, we focus on rainfall as the main constraint to achieve potential yield; we highlight the value of quantitative patterns accounting for the timing, intensity and duration of stress in relation to the critical period of yield determination. We conclude with a brief discussion of extreme temperatures and their interaction with water and nitrogen.

The photothermal environment

The photothermal environment is the primary limit to potential yield. Fischer (1985) defined a photothermal quotient (PTQ) relating solar radiation (Rad) and mean temperature (Temp) above a base temperature (T_b): $PTQ = Rad / (Temp - T_b)$, and demonstrated correlations between wheat grain yield and PTQ during the critical period for grain set. Associations between yield and PTQ were later verified in barley, pea, chickpea, rice, maize, sunflower and canola (Cantagallo et al. 1997; Didonet et al. 2002; Faraji 2014; Francia et al. 2011; Islam and Morison 1992; Poggio et al. 2005; Sadras et al. 2015b). The robustness of the photothermal quotient as a major driver of yield derives from its physiological basis: it captures the positive association between seed number and radiation, mediated by photosynthesis, and the negative association between seed number and temperature mediated by the shortening of the critical window with increasing temperature. Refinements of this index include corrections for incomplete canopy cover affecting the radiation component (Fischer 1985) and corrections for vapour pressure deficit and the fraction of diffuse radiation as outlined in Section 2.1 (Rodriguez and Sadras 2007). Doherty et al. (2008) mapped vapour pressure deficit and PTQ normalised for vapour pressure deficit and

diffuse radiation at shire-level for the Australian wheat belt, thus highlighting latitudinal and costal variation in climate drivers of potential yield.

Rainfall patterns

In rainfed systems, the amount, seasonality and frequency distribution of rainfall size events have implications for yield as related to the water and nitrogen economy of crops. The amount of precipitation (P), in relation to evaporative demand (E), sets the broad pattern of land use, separating pastoral and cropping areas. Trumbell (1939), defined the limit of safe wheat growth in South Australia based on a $P/E \approx 0.33$ for the period May to September. French (1993) identified the April to October $P/E = 0.26$ based on Minnipa on the upper Eyre Peninsula. An isoline of $P/E = 0.26$ extended around the Australian grains belt effectively fits the current boundary between grain and pastoral land use from West Australia to southern Queensland (Nidumolu et al. 2012). This fit is surprising given the different soil types, seasonality of rainfall and land use policies.

For a given amount of rainfall, seasonality sets the scope of cropping options. In the winter-rainfall areas of southern and Western Australia, cropping is constrained to wheat-based systems in rotation with barley, grain legumes and canola. In the northern grains region, the combination of summer-dominant rainfall and deep soils with high water holding capacity offers the possibility of growing winter and summer crops, as well as opportunistic double cropping, e.g. sorghum - chickpea. Owing to the marked seasonality of rainfall, stored soil water is a larger component of water supply for wheat in the northern region compared to the winter-rainfall regions (Sadras and Rodriguez 2007b). For a given amount and seasonality, size of rainfall events influences the fate of water, i.e. large events favour runoff and deep drainage whereas small events favour soil evaporation (Sadras 2003). High frequency of small events also favours nitrogen mineralisation; Figure 1 illustrates the annual dynamics of nitrogen mineralisation in response to amount, seasonality and size of rainfall events interacting with temperature.

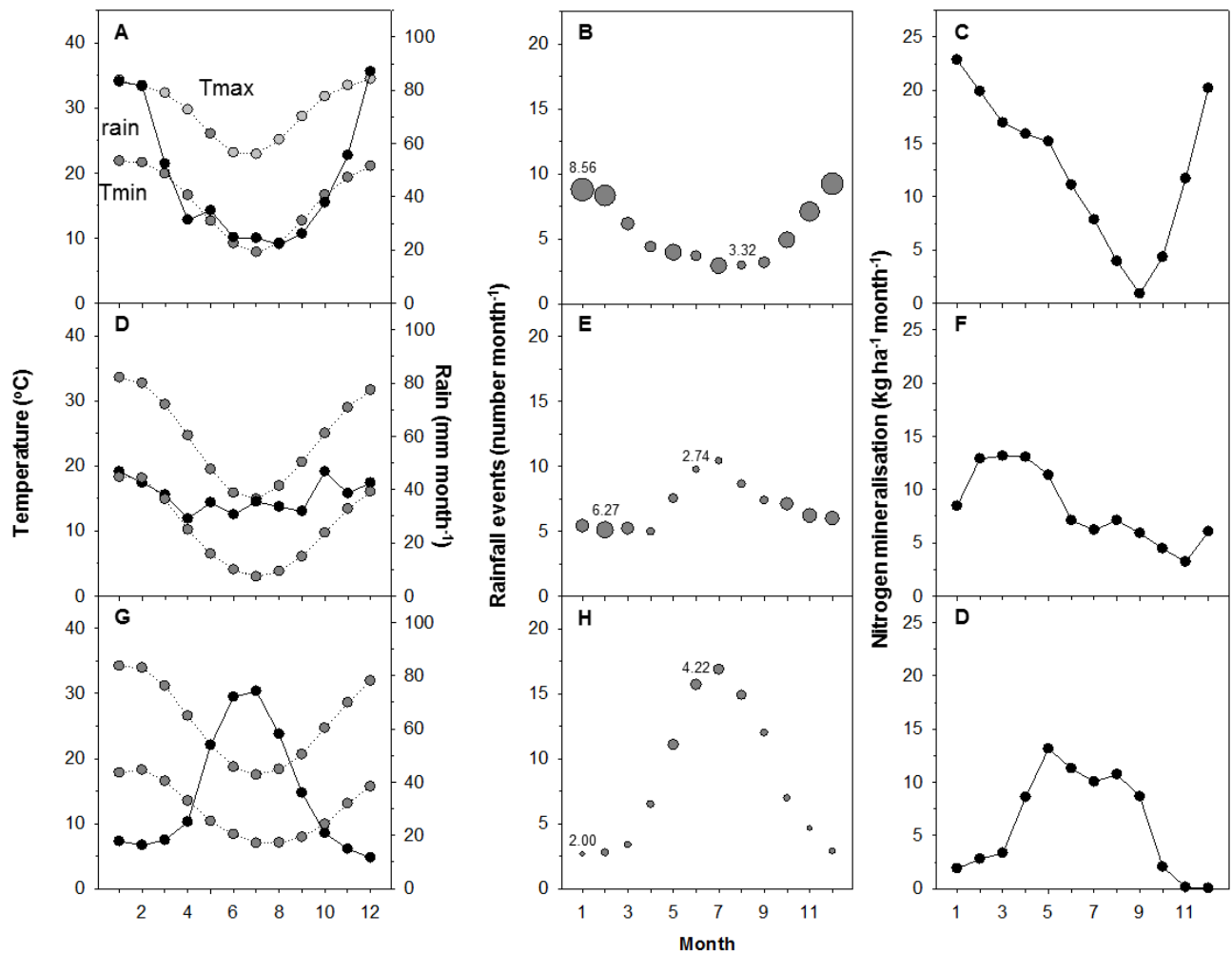


Figure 1 Annual dynamics of modelled nitrogen mineralisation in response to amount, seasonality and size of rainfall events interacting with temperature. Locations represent summer-dominant rainfall (Emerald, 23°50' S, 131° 62' E; annual rainfall: 561 mm), uniform rainfall distribution during the year (Condoblin, 33°02' S, 147°23' E; annual rainfall: 450 mm) and winter-dominant rainfall (West Mora, 30° 64' S, 115° 92' E; annual rainfall: 419 mm). In b-f, the size of the points represents the average size of events, and the numbers indicate the smallest and largest, in mm per event. Mineralisation was modelled with APSIM, assuming an initially dry soil (plant available water = 10% of maximum on 1 January 1957), and a continuous soil water balance for the period 1957-2014. A wheat crop (cv Hartog) was sown according to a rule combining a sowing window (15-May to 10-July) and rainfall conditions (25 mm accumulated in 7 events); if these conditions were not met in a given season, the crop is sown at the end of the window. Stubble is reset to 1 t ha⁻¹ on 1st of January every year and crop fertilisation is set to 150 kg ha⁻¹ at sowing each season. A single soil was used to remove soil effects, and thus capture the climatic drivers of mineralisation.

Rainfall events of different size and frequency drive different biological processes (Schwinning and Ehleringer 2001; Schwinning and Sala 2004). Schwinning and Sala (2004) emphasise the two elements defining “pulse size”: pulse depth, i.e. the depth to which soil water potential is elevated to levels that promote specific biological activities, and pulse duration, i.e. the time over which soil water potential remains at biologically relevant levels. In the space defined by pulse depth and duration, they outline a hierarchy from small, short pulses triggering processes such as nitrogen mineralisation to large, long pulses driving pest outbreaks and shifts in community structure (Figure 2A). Figure 2B maps the size distribution of rainfall events in Australia in the winter semester, highlighting the latitudinal shift from large events in the north to smaller events in the south. The concept of pulses has been used to analyse the fate of water in cropping systems, particularly in relation to the role of stubble (Monzon et al. 2006; Sadras 2003; Verburg et al. 2012). The perspective of water pulse can provide further insight on the connections between the dynamics of water and nitrogen in cropping systems.

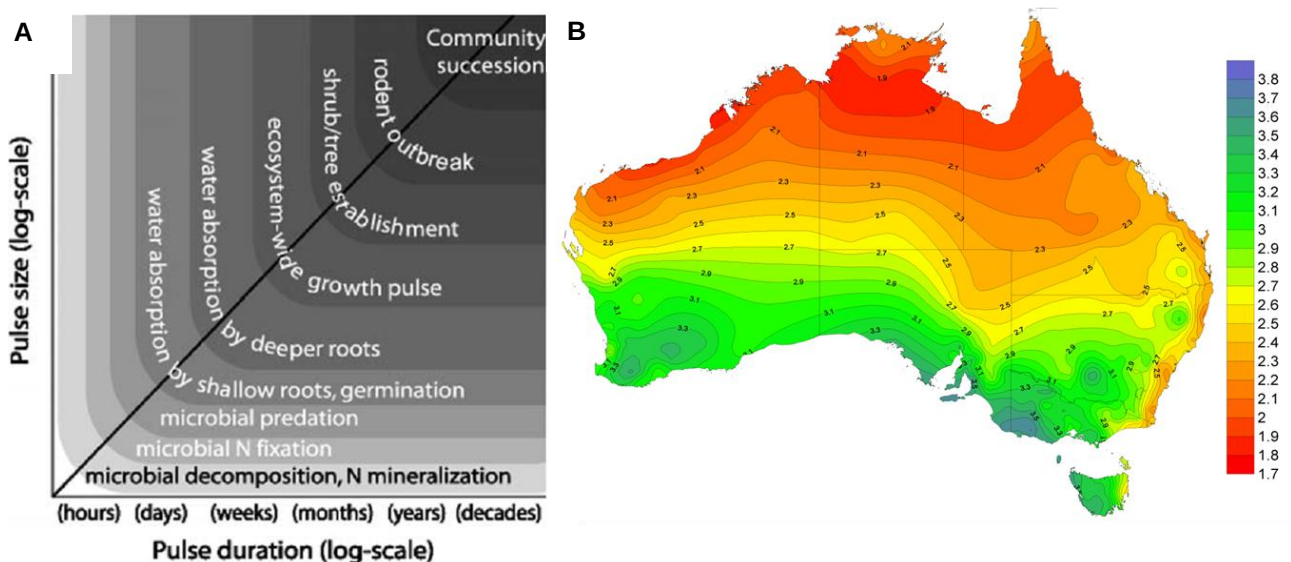


Figure 2. The “water pulse” perspective. A. Response hierarchy to soil moisture pulses of variable size and duration. The solid line shows an approximately linear relationship between size and duration on a log-log scale. Small-short pulses can activate the physiology of microbes at the soil surface. Larger and longer pulses trigger physiological responses of larger organisms, first of soil invertebrates, then of plants. Size of events differentially affects water absorption by shallow or deep roots. Seed germination usually requires smaller pulses than plant establishment. Rainfall clusters, producing pulse events from weeks to months add up to a wet season, which usually triggers ecosystem-wide vegetation growth that could in turn trigger outbreaks of herbivores or granivores, for example, small rodents. Wet periods spanning several years may trigger large-scale shifts of entire communities. B. 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; a high coefficient indicates dominance of small events. Sources: A. Schwinning and Sala (2004). B. Williamson (2007).

Crop response to stress depends on the intensity and duration of stress and the timing in relation to the critical period for yield determination. Adaptive traits and agronomic practices to mitigate the effect of stress thus require an understanding of the probabilistic spatial and temporal patterns of stress in relation to crop development. The pioneering work of Chapman et al. (2000a; Chapman et al. 2000b) modelled the patterns of water supply : demand ratio for sorghum in northern Australia; for example, high frequency of low stress environments is higher in the Darling Downs and Central Queensland, compared to severe terminal stresses in north-western New South Wales and south western Darling Downs. These patterns provide background for ongoing research on crop adaptation (Hammer et al. 2014).

After the early work in sorghum, a similar approach has been used to characterise the patterns of water stress for Australian wheat, maize, field pea and chickpea (Chauhan et al. 2013; Chenu et al. 2013; Lake et al. 2015; Sadras et al. 2012b). For wheat, environment types 3 and 4 in the classification of Chenu et al. (2013) are widespread geographically, represent an important share of the total diversity of environments (50% or more in many important growing regions), and cause the strongest reduction in yield. In both these environment types, the onset of water stress occurs at approximately 500 °Cd before anthesis. This challenges the ambiguous label of “terminal drought” often used to characterise wheat growing environments of Australia and other Mediterranean-type regions (Savin et al. 2015). Chenu (2015) reviewed the methods for quantitative characterisation of water stress patterns, and summarised patterns of other crops and regions worldwide. Similar studies are necessary for other important crops in Australia including canola, lentil, faba bean and lupin.

The spatial and temporal characterisation of the patterns of supply and demand of nitrogen has received less attention (Angus 2001). Modelling tools can be used to relate soil, crop, and climate as illustrated in Figure 1. Next, it would be interesting to link the spatial and temporal patterns of supply and demand for water and nitrogen as background for agronomic, e.g. timing of fertilisation, and breeding studies, e.g. root patterns.

Extreme temperatures

Heat (Asseng et al. 2011; Barlow et al. 2015) and frost (Frederiks et al. 2015; Single 1985; Zheng et al. 2012) events in spring can disrupt reproduction and thus reduce crop yield. The date of the last spring frosts and first heat events vary spatially in the Australian grain-growing regions (Figure 3) and influences the target flowering window that farmers manipulate with sowing date and cultivar choice. The actual response to heat and frost depends on timing, intensity and duration of the event, and their interaction with nitrogen and water supply. For example, a severe heat event around flowering caused no visible damage to well watered wheat crops, whereas in rainfed crops, ear damage ranged from 10% in low density, low nitrogen crops to 60% in their high density, high nitrogen counterparts (Table 1). Factors that favour vigorous canopies including high plant population density and high nitrogen supply might increase vulnerability to frost but the evidence is unclear (Whaley et al. 2004).

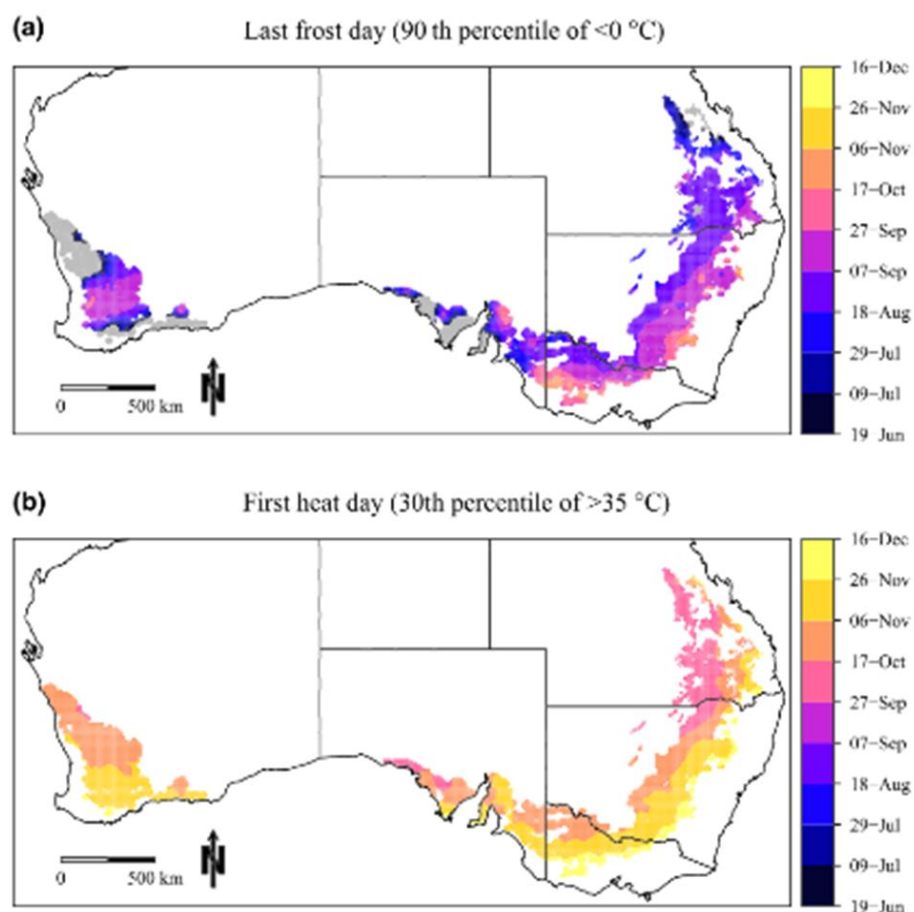


Figure 3. Last day of frost and first day of heat in the Australian grain growing regions. Source: Zheng et al. (2012).

Table 1. Interaction between water and nitrogen supply, sowing density, frost and heat in wheat (Cv Chara) crops on a Grey Vertosol at Horsham, south-eastern Australia (36.65°S, 142.10°W). Rainfed crops received 270 mm and irrigated 390 mm during the growing season. Ear tipping is visual assessment of damaged ears attributable to stress. Growth rate is for the period from 12 days before anthesis to anthesis. Anthesis started at 115 days after emergence (DAE) for all the rainfed crops and irrigated, low nitrogen treatments, and at 121 DAE for the irrigated, high nitrogen plots. At 114 DAE temperature was below zero for about 4 h from midnight. At 115 DAE temperature was above 31°C from 11.40 am until 07.00 pm and peaked at 37 °C; average daily vapour pressure deficit was 1.5 kPa, with an absolute maximum of 6 kPa at 4.00 pm. Yield correlated with ear tipping for rainfed crops ($r^2=0.23$) and with pre-flowering growth rate for the pooled data ($r^2=0.81$). Source: Rodriguez et al. (2005).

Water regime	Sowing density (kg seed ha ⁻¹)	N rate (kg N ha ⁻¹)	Ear tipping (%)	Yield (kg ha ⁻¹)	Growth Rate (g m ⁻² d ⁻¹)
Rainfed	52	0	10	1245	0.0
		16	20	1446	-0.1
		39	27	2043	-4.5
		163	33	1005	0.7
	102	0	22	1341	3.0
		16	28	1537	1.5
		39	37	1845	8.8
		163	60	525	2.0
	52	0	0	4181	16.5
		16	0	4505	12.0
		39	0	3889	12.6
		163	0	3200	10.1
Irrigated	102	0	0	3361	11.0
		16	0	4862	11.6
		39	0	4767	11.2
		163	0	4174	10.9

An important aspect of these spring events is that they occur after most costs have been incurred. Along with rain at harvest, these events contribute to farmer risk aversion on nitrogen fertiliser (GRDC 2014). Under the modelling assumptions of Zheng et al. (2015) the direct effect of frost was about a 10% reduction in yield of the annual Australian wheat crop and a further 10% reduction in yield due to conservative sowing time to avoid frost. These risks are not well simulated in models and decision support systems (Barlow et al. 2015). Zheng et al. (2015) assumed adequate nitrogen fertiliser, so the only indirect cost was delayed sowing. A further indirect cost of spring frost and heat is likely to be conservative nitrogen rates where farmers concerned about these events could reduce crop inputs to reduce the financial loss. The perception that a vigorous crop is more vulnerable to frost damage might further constrain nitrogen rates in frost-prone environments.

Soil

Soil water directly influences the availability of mineral nitrogen for crop uptake and reciprocally nitrogen influences total crop water use but more importantly, canopy size and thus the partitioning of evapotranspiration between unproductive soil evaporation and transpiration. The response to nitrogen of yield per unit water use is larger than the response to water of yield per unit available nitrogen (Albarenque 2015) as discussed later from a physiological perspective. In this section, we discuss the role of soil texture in determining the upper and lower limits for soil water and nitrogen storage and their implications for crop growth. We then turn our attention to water as the primary driver of soil nitrogen mineralisation and to the influence of nitrogen availability on crop water uptake. We then examine coarse regional differences in soils with implications for the water and nitrogen economies of crops.

Soil texture, soil water and soil nitrogen

Potential water storage is a function of soil texture, an inherent soil property which is not under the influence of management except for practices such as clay spreading, which seeks to ameliorate surface water repellence (Mueller and Deurer 2011) and delving, which changes the textural profiles of texture-contrast (or “duplex”) soils (Betti et al. 2015). Owing to the association between clay content and soil porosity, soils with higher clay content have greater total soil water storage capacity than sandy soils. However, clay soils hold on to their water more tightly and there is a trade-off between soil water storage capacity and the availability of that water for crops. The plant available water capacity (PAWC) is the difference between the drained upper limit (DUL), the maximum amount of water a soil can hold against gravity, and the crop lower limit (CLL), the residual amount of water in a soil that is inaccessible to crops. The drained upper limit is a soil property, whereas the lower limit depends on both soil and crop, as the depth, distribution and functionality of roots affect water uptake (Ritchie 1981).

Soils with a clay content $\approx 30\%$ are able to store about double the amount of water of sandy soils (Oliver and Robertson 2009). Such difference is important for crops, however, only when the soil water content is close to the drained upper limit for the sandy soil, at which point finer textured soils become advantageous. Thus under low rainfall, differences in plant available water capacity between soils may not be critical. There is thus an interaction between climate and seasonal conditions with soil texture, which means that in wetter

conditions soil texture may modulate yield, while it exerts less influence under drier conditions. The exception would be under very low rainfall, when soils with lower clay content can be more productive because they hold soil water less tightly.

Soil clay content correlates with soil organic matter, and thus soil organic nitrogen stock. This is because the clays offer physical protection to organic matter, reducing the likelihood that it is broken down by organisms. Thus there is a tendency for finer textured soils to maintain higher organic fertility than coarser textured soils under the same management and climate. Over a single annual cropping season, between 5 and 10% of organic nitrogen might be mineralised (Murphy et al. 1998a), and thus finer textured soils with higher organic matter densities are likely to mineralise more nitrogen within a cropping season than coarse textured soils, even though the organic matter is less protected on the finer textured soil. Finer textured soils thus have a greater hysteresis, more slowly unlocking legacy water and organic nitrogen, and at the same time providing a more buffered mineral nitrogen supply. Soil organic matter also has a small positive influence on the ability of soils to hold and to conduct water, primarily through the formation of soil aggregates, although the effect is only significant at higher soil water content, with soil texture being the primary determinant at lower, perhaps more relevant, soil water content (Saxton and Rawls 2006).

While it is generally thought that nitrogen is primarily taken up from superficial soil layers, deeper soil nitrogen provides an additional source of nitrogen in sandy soils (Anderson et al. 1998), and possibly on some finer textured soils (Page et al. 2003; Smith et al. 1998). Management of nitrogen becomes more critical as PAWC decreases (Oliver and Robertson 2009). Low PAWC soils are typically sandier and more responsive to nitrogen than finer textured soils (Oliver and Robertson 2009; Unkovich 2014), probably because organic nitrogen reserves are lower, the soil is more often dry, and because nitrate cannot be held in the profile against leaching. Fields with low PAWC (<75mm) (Oliver and Robertson 2009) might be most sensitive to nitrogen management on an economic basis, since the margin between nitrogen deficiency, sufficiency or excess is small compared to soils with greater PAWC where there are likely to be greater water and nitrogen buffers.

Soil texture can influence processes leading to loss of nitrogen from the crop-soil system. In soils with low oxygen availability, usually caused by high soil water content, soil nitrate can be denitrified, converted to gaseous N_2O or N_2 , transferred to the atmosphere (Dalal et al. 2003) and thus lost as a crop resource. Because it also requires a readily available supply of carbon for microbial growth, it tends to be a greater problem on finer than coarse textured soils. Waterlogging also causes transient nitrogen deficiency, where recovery is a function of available nitrogen after the waterlogging rather than antecedent nitrogen availability

(Robertson et al. 2009). Coarse textured soils are also more prone to leaching of nitrate (Anderson et al. 1998).

Soil water and nitrogen mineralisation

A strong short-term interaction between available soil water and available nitrogen derives from moisture pulses that sustain the activity of microorganisms involved in the mineralisation of soil organic nitrogen and turnover of microbial biomass and carbon (Murphy et al. 1998a). While small and frequent rainfall events favour superficial soil moisture and encourage nitrogen mineralisation, they also increase water loss through soil evaporation (Sadras 2002a; Sadras and Baldock 2003), resulting in mineralisation of native organic matter and microbial turnover but not decomposition of fresh organic matter (Sparling et al. 1995). Hence soil organic matter stock is likely to be eroded under regular wetting and drying of surface soils. Most (>70%) nitrogen mineralisation is likely to occur in the surface 5 cm of soil (Murphy et al. 1998b) where the organic matter typically resides. Whether modern reduced tillage, stubble retention systems have stratified this organic matter nearer the surface, increasing the potential effects of short wetting and drying cycles on organic matter cycling and nitrogen mineralisation is not clear.

Recently, the primary nitrogen supply for cereal crops in Australia has shifted to fertiliser and away from that mineralised from legumes in rotations (Angus 2001), or from historic soil nitrogen reserves in the northern grain growing regions (Herridge 2013). It is likely that this has also been associated with a decline in soil organic matter stocks. As soil organic matter declines, so does the ability to retain nutrients in the soil via the microbial biomass and other organic matter. Higher temperature (>50°C) favours mineralisation but not immobilisation of nitrogen (Luxhøi et al. 2008), hence there can be a build-up of mineral nitrogen over a warm fallow period if rainfall is received, the magnitude of which may be related to the size of the soil microbial biomass (McNeill et al. 1998). Thus soils with a smaller microbial biomass are likely to accumulate less mineral nitrogen over the fallow period.

Increased available nitrogen can increase the size of the root system directly by stimulation of growth in the vicinity of the nitrogen-rich zone (Officer et al. 2009), and indirectly through crop vigour (Palta et al. 2011). The impact of a nitrogen-driven larger root system on crop water uptake depends on the availability and distribution of water in the soil, the distribution of roots in the soil profile and the crop demand for water. Increased availability of nitrogen can increase crop water extraction but this effect is generally modest in southern Australia (Angus 2001; Norton and Wachsmann 2006; Sadras et al. 2012c), perhaps because of lack of water at depth, soil chemical constraints or a combination. In the Middle East, fertilisation increased seasonal evapotranspiration by up to 16% in rainfed barley (Cooper et al. 1987) and by 8% in irrigated durum wheat (Karam et al. 2009) in relation to unfertilised controls. In environments where crops depend on stored water in deeper soils layers, increased nitrogen availability may have larger effects on rooting depth and total water use. Brown (1971) showed a large response of seasonal evapotranspiration of winter wheat increasing from 221 mm in unfertilised crops to 315 mm in their fertilised counterparts (268 kg N ha⁻¹) on a silt-loam soil developed on deep loess in a summer-rainfall region of US. Soil water extraction was constrained to 0.9 m in the unfertilised crops and increased to 1.8 m under fertilisation. In the deep soils of the Loess Plateau in China, seasonal water use of winter wheat increased up to 19% in response to nitrogen fertilisation, mostly by enhanced water uptake between 1.2 and 2.4 m (Zhong and Zhouping 2014). Increasing water use through improved nitrogen nutrition may increase grain yield (Norton and Wachsmann 2006), but the combinations of crop, soil, climate, and management more likely to be responsive are unknown.

Annual crops tend to root to the depth of available water in rainfed environments of south-eastern Australia (Kirkegaard et al. 2007; Norton and Wachsmann 2006), except where chemical or physical subsoil constraints (McDonald et al. 2013; Nuttall et al. 2003) or disease (Lorimer and Douglas 2001) prevent root growth, problems which are not overcome with additional nitrogen. Rooting depth is thus curtailed in soils with a strong texture contrast (Dracup et al. 1992) or with toxic (Rodriguez et al. 2006; Sadras et al. 2003) or impenetrable (Sadras et al. 2005) layers, regardless of nitrogen nutrition. Inter- and intra-specific variation in rooting depth has been reported (Norton and Wachsmann 2006; Wasson et al. 2014) but the consequences for crop nitrogen uptake have not been explicitly examined.

Regional differences in soils

Although crop yield variation is generally greater between seasons than between soil types within a season (Oliver and Robertson 2009) it is worth considering pertinent differences in soil properties across the Australian cropping zone. We have used the Australian three dimensional soil grid (Rossel et al. 2015) to estimate the soil clay content, bulk density and soil organic carbon stock across the croplands for each State (Figure 4). There is a clear trend of decreasing top-soil clay content from the northeast (Queensland) to the southwest (Western Australia). This correlates with a decrease in soil organic fertility. This gross spatial trend in soil properties is coincident with a shift from summer dominant, to equi-seasonal and then strongly winter dominant rainfall from the north-east to south-west of the cropping zone (see *Climate* section above) (Sadras and Rodriguez 2007a; Unkovich et al. 2009) (Sadras and Rodriguez 2007; Unkovich et al. 2009).

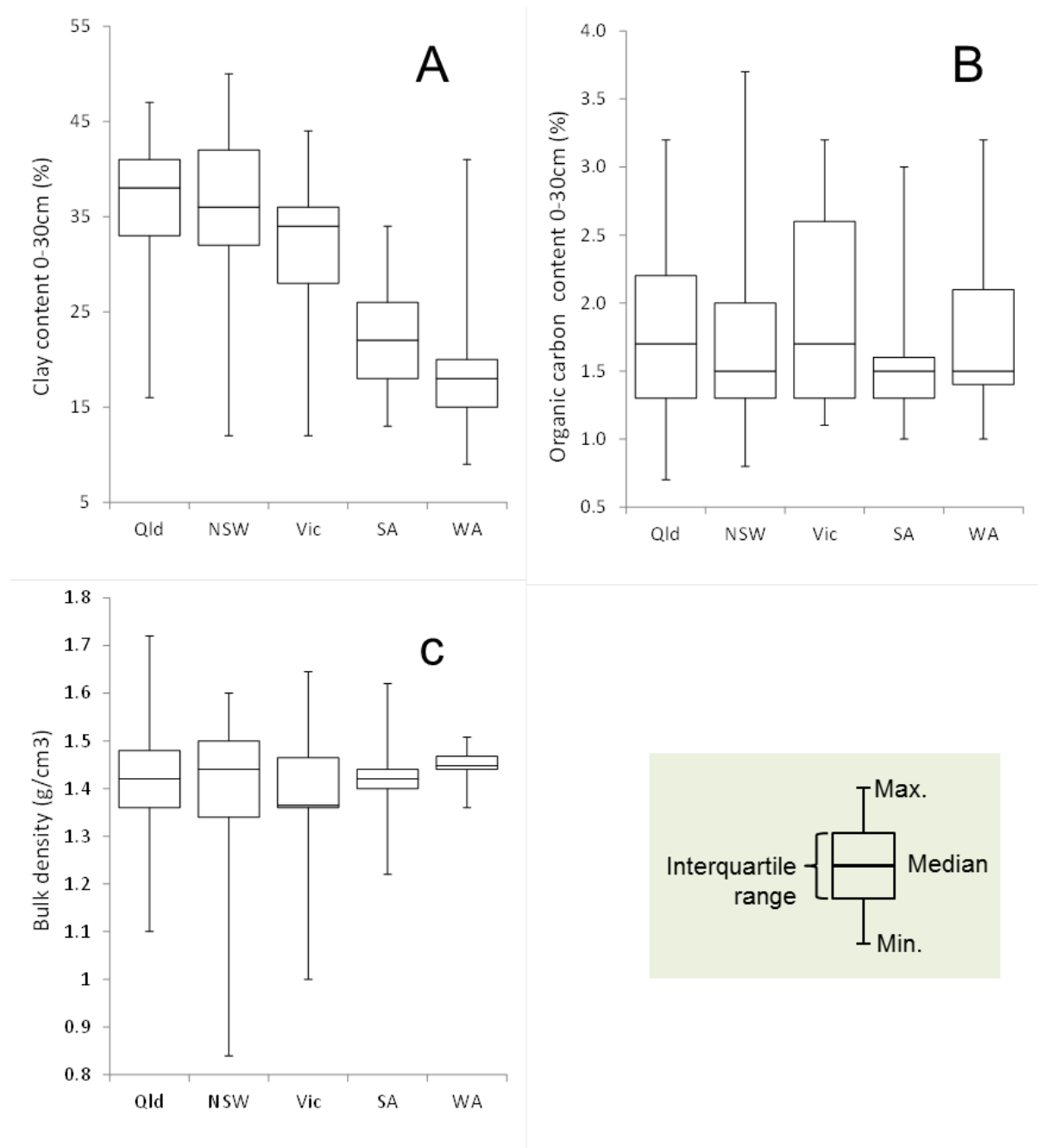


Figure 4 State-level frequency distribution of spatially averaged soil properties for the Australian croplands. (A) Clay content, (B) organic carbon content and (C) bulk density. The croplands are as defined in the national land use map (ABARE 2010b) and the C stock calculated as 0.49 of the C stock (Valzano et al. 2005). Clay and organic carbon are for the top 0.3 m and bulk density for the top 0.1 m.

The implications of these broad changes in soil hydraulic and organic fertility might be that the magnitude of availability and release of soil nitrogen is greater in the east and north and is a pivotal variable which impinges on nitrogen management, whereas in the southern and western regions, the low capacity of soils to store and supply nitrogen and water, and the strong seasonality of rainfall increases the focus on matching fertiliser nitrogen input to seasonal rainfall. The amount of mineral nitrogen required per unit of yield appears to be relatively consistent across the southern and northern cropping regions (Bell et al. 2013). There is a strong tendency for coarse textured soils to produce lower protein wheat, perhaps because those soils have difficulty supplying both nitrogen and water during grain filling, although regional differences in the cultivar grown would also be implicated.

A physiological perspective: co-limitation

Here we address three questions from the perspective of crop physiology: How does nitrogen deficit influence the water economy of the crop? How does water deficit influence the nitrogen economy of the crop? How do combined water and nitrogen deficit affect crop growth and yield?

The effect of nitrogen deficit on the water economy of crops

The effect of nitrogen deficit on the water economy of the crop can be interpreted in the light of the equation (Cooper et al. 1987):

$$WUE(Y, ET, s) = \frac{WUE(B, T, s)}{1 + \frac{E}{T}} \cdot HI \quad \text{eq. (1)}$$

where, using the nomenclature of Sinclair et al. (1984), WUE (Y,ET,s) is yield (Y) per unit evapotranspiration (ET) on a seasonal basis (s), WUE (B,T,s) is biomass (B) per unit seasonal transpiration (T), E is seasonal soil evaporation and HI is harvest index. Owing to the link between foliar nitrogen and radiation use efficiency (Sinclair and Horie 1989; Stockle and Kemanian 2009), and between radiation use efficiency and transpiration efficiency (Box 1), nitrogen deficit reduces biomass per unit transpiration. Brueck (2008) compiled the response of biomass per unit transpiration to nitrogen supply for major crop species. Nitrogen deficit slows canopy growth and increases the ratio of soil evaporation to transpiration (Angus and van Herwaarden 2001; Cooper et al. 1987; Gajri et al. 1993). Often,

shortage of nitrogen reduces crop transpiration, which could be reflected in residual water in the soil at maturity (Angus and van Herwaarden 2001; Brown 1971; Sadras et al. 2012c). Nitrogen deficit can be neutral, positive or negative for harvest index (Albrizio et al. 2010; Bandyopadhyay et al. 2010) and it can respond to the interaction between water and nitrogen, i.e. high nitrogen supply can increase harvest index under favourable water conditions, but decrease it under water deficit (Hernández et al. 2015). The effects of nitrogen on harvest index are, however, small compared to those on biomass in agronomically meaningful conditions (Figure 5BD). Thus, nitrogen deficit reduces yield per unit evapotranspiration (eq. 1) by primarily reducing biomass per unit transpiration, increasing soil evaporation and reducing transpiration, with a minor effect of harvest index reinforcing or partially counteracting this reduction. Owing to the law of diminishing returns, yield per unit nitrogen supply declines with increasing nitrogen supply (Gastal et al. 2015). From these, a nitrogen-driven trade-off between the efficiency in the use of water and the efficiency in the use of nitrogen emerges irrespective of species, soil, climate and management. Experimental and modelling evidence for this trade-off can be found for wheat and barley in Southern Italy, US and Australia (Albrizio et al. 2010; Brown 1971; Sadras and Rodriguez 2010), maize in US and Argentina (Albarenque 2015; Kim et al. 2008), rice in Philippines (Belder et al. 2005), and potato in Egypt (Badr et al. 2012), thus illustrating the universal nature of this trade-off.

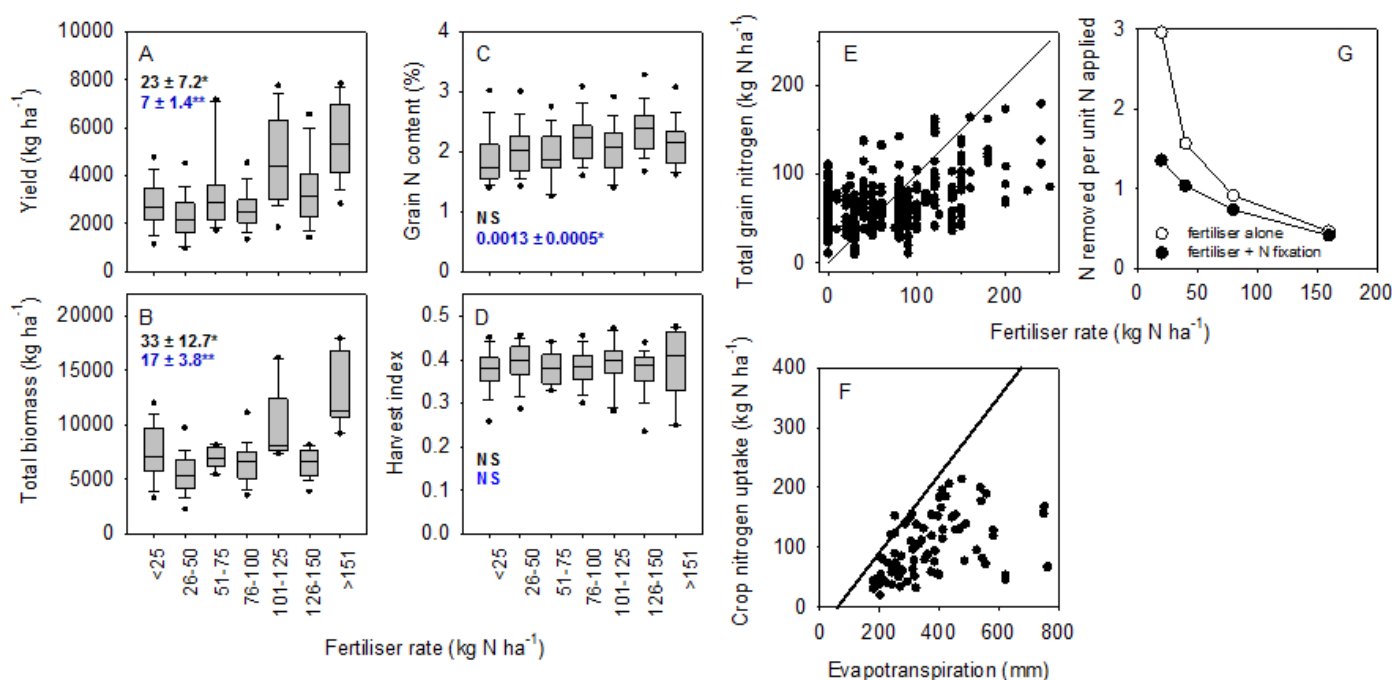


Figure 5. Frequency distribution of wheat (A) grain yield, (B) total biomass, (C) grain nitrogen concentration, and (D) harvest index in relation to nitrogen fertiliser rate. Boxes indicate 5th, 10th, 50th, 90th and 95th percentiles. Numbers are the slope of regression between fertiliser rate and the trait for the 90th (black) and 10th (blue) percentiles with $P < 0.05$ (*) and $P < 0.01$ (**). (E) Relationship between export of nitrogen in grain and input of nitrogen as fertiliser; the reference line is $y = x$. (F) Relationship between crop nitrogen uptake and seasonal evapotranspiration; the reference line has slope = $0.65 \text{ kg N ha}^{-1} \text{ mm}^{-1}$ (French and Schultz 1984b) and x-intercept = 60 mm (Sadras and Roget 2004). (G) Ratio of nitrogen exported in grain and nitrogen input as a function of fertiliser rate in a long-term experiment at Dahlen, Victoria. Data sources: A-F, see Appendix 1; G: Norton et al. (2015).

The effect of water deficit on the nitrogen economy of crops

The effect of water deficit on the nitrogen economy of crops is complex because water deficit affects the growth-driven nitrogen demand (i.e. potential crop biomass x critical nitrogen concentration), critical nitrogen concentration, supply (i.e. nitrogen availability at the root surface), assimilation, and partitioning of nitrogen. Gonzalez-Dugo and colleagues have investigated the influence of water on nitrogen related processes in forages, and advanced a conceptual framework for the interpretation of experiments (Debaeke et al. 2012; Durand et al. 2010; Gonzalez-Dugo et al. 2010; Gonzalez-Dugo et al. 2011; Gonzalez-Dugo et al. 2012; Gonzalez-Dugo et al. 2005). In drying soil, three processes are impaired that collectively can reduce the availability of nitrogen at the root surface: mineralisation, mass flow and diffusion of nitrogen; high root/shoot ratio may partially compensate these effects. In parallel, drying soil reduces crop growth by primarily reducing the capture of resources

(radiation, water and nutrients), hence reducing nitrogen demand. Water deficit can also impair transport of nitrogen from root to shoot and activity of nitrate reductase. Although water deficit could reduce the nitrogen status of plants, the actual response depends on the relative effect of water deficit on growth-driven demand and supply. However, the lack of allometric relationships of nitrogen concentration and biomass under water deficit to derive a reliable nitrogen nutrition index (Sadras and Lemaire 2014) means we have little or no reliable information on the nitrogen status of water stressed crops.

Two gaps thus require attention in relation to the influence of water on nitrogen processes: nitrogen availability and the quantification of crop nitrogen status. The concept of plant available water is well established (see *Soil* section). In contrast, particularly for management purposes, we assume that all inorganic nitrogen in soil is available for the crop. In dry soil, however, part of the inorganic nitrogen may not be available if root growth, nitrogen diffusion and mass flow are constrained. Beyond water, chemical and physical subsoil constraints can also reduce nitrogen availability (Sadras 2005). By analogy with plant available water, the concept of plant available nitrogen needs to be developed for management applications.

Quantification of crop nitrogen status requires dilution curves to account for the allometry between shoot nitrogen concentration and biomass (Gastal et al. 2015). However, nitrogen dilution curves have been parameterised in well-watered crops, whereas theory and limited experimental evidence indicates that the parameters of the curve shift with water deficit (Belanger et al. 2001; Errecart et al. 2014; Gonzalez-Dugo et al. 2010). Further, dilution curves assume two compartments, metabolic with high nitrogen concentration, and structural, with lower concentration (Gastal et al. 2015). In some crops such as wheat, water soluble carbohydrates are an important part of crop biomass, with zero nitrogen concentration. Where cultivar or growing conditions alter the amount of water soluble carbohydrates, dilution curves based on total biomass will be biased; section 5.1 further discusses this topic.

A major gap in the assessment of nitrogen nutrition status of legumes is the lack of appropriate dilution curves ensuring nitrogen supply that maximises growth, as published curves have relied on nitrogen-fixing crops where this condition might not have been met (Divito et al. 2015; Lemaire et al. 1985; Ney et al. 1997).

Combined effect of water and nitrogen deficit on crop growth and yield: co-limitation

Plants in the field are often exposed to multiple stresses (Mooney et al. 1991). As a single limiting factor is unlikely, the Liebig paradigm is generally inappropriate to understand and manage crops (Sinclair and Park 1993). Bloom et al. (1985) used economic analogies to formulate testable hypotheses on plant acquisition and allocation of resources, and proposed that plant growth is maximised when it is equally limited by all resources. This notion was tested in studies combining modelling and experimental data in Mediterranean-type environments of Australia and Spain where it was concluded that, for a given intensity of stress, a high degree of water and nitrogen co-limitation favours wheat grain yield (Cossani et al. 2010; Sadras 2005). Savin et al. (2015) recently reviewed the co-limitation perspective to quantitatively integrate nitrogen and water limitations in small grain cereals.

Albarenque (2015) used the concept of water-nitrogen co-limitation to explore maize response to within-field spatial variation in availability of resources in the eastern Pampas. She combined field experiments and modelling to test two hypotheses: there is variation in water-nitrogen co-limitation at the scale of management zones within paddocks, and yield per unit evapotranspiration is more responsive to co-limitation than yield per unit available nitrogen. The second hypothesis stems from the observation that the response to nitrogen of yield per unit water use is larger than the response to water of yield per unit available nitrogen. Experiments were conducted in two fields (12-14 ha) with either four management zones corresponding to levels of soil erosion or three management zones corresponding to soil types, where each management zone was fertilised with rates from 0 to 210 kg N ha⁻¹. The study supported the working hypotheses, and concluded that co-limitation can be used for zone-management of fertilisation accounting for both water and nitrogen use efficiency.

Current methods to calculate co-limitation require involved experiments, modelling or a combination; practical methods to quantify the degree of co-limitation, e.g. using remote sensing to quantify the nitrogen and water status of the crop, and its application for management are worth exploring.

An agronomic perspective: yield gap and management practices

Many practices influence the fate of both water and nitrogen at scales from field to region. Rotations, tillage, stubble, disease and weed management all can potentially affect the amount of water and nitrogen stored in the soil, their availability to the crop and the partitioning between unproductive losses (e.g. soil evaporation, nitrogen leaching) and productive plant uptake. We start this section with an overview of management practices that makes explicit crop and cropping system perspectives. Next, we look at the interaction between water and nitrogen from the perspective of yield gap. After establishing that shortage of nitrogen is a proximal cause underlying part of the yield gap of wheat crops in Australia, we revise tactical and strategic approaches to manage the water-nitrogen interaction in the winter-rainfall regions of south-eastern and western Australia. We close this section with a brief look at management of crops in northern Australia to highlight agronomic features of this summer-rainfall environment.

Overview

Recent reviews relevant to the agronomy of water-nitrogen interaction include Kirkegaard et al. (2011; 2014) with a primary focus on water and a broad view on management options, Angus and Peoples (2012) assessing the contribution of pastures to the nitrogen economy of annual crops, Angus et al. (2015) on the impact of break crops on wheat yield, including the contribution of nitrogen from previous grain crops, and Scott et al. (2010) on the role of stubble management for water storage. A series of papers analysed soil nitrogen test and its value as a diagnostic tool for fertilisation, primarily based on yield-nitrogen response curves (Bell et al. 2013; Conyers et al. 2013; Watmuff et al. 2013). Gastal et al. (2015) dissect the problems of yield-nitrogen curves and highlight the nitrogen nutrition index as a benchmark for the assessment of crop nitrogen status. Readers are thus referred to these comprehensive reviews.

For a data set of mostly experimental crops across diverse soils, climates and management in Australia, median wheat yield was 2.7 t ha^{-1} and median grain nitrogen concentration 1.7% where fertilisation was below 25 kg N ha^{-1} in comparison to median yield of 5.3 t ha^{-1} and median grain nitrogen concentration 2.1% for their counterparts with more than 151 kg N ha^{-1} (Figure 5AC). Despite this trend, there was large scatter in the response of yield to nitrogen, as expected from the effects of other factors. Likewise, there is well established, large scatter in the relationship between yield and water use (French and Schultz 1984a;

Grassini et al. 2009; Grassini et al. 2010). Variation in yield was mostly related to variation in biomass, whereas median harvest index was relatively stable, ranging from 0.38 with less than 25 kg N ha⁻¹ to 0.41 at 151 kg N ha⁻¹ or more (Figure 5BD).

The data were further analysed using percentile regression to capture the top and bottom boundaries of crop responses to fertiliser (Cade and Noon 2003); this is summarised in the slopes of regressions for the 10th and 90th percentiles in Figure 5AD. Yield and biomass response to fertiliser was 2-3 times larger under favourable conditions (90th percentile) than under stressful conditions (10th percentile). Grain nitrogen concentration correlated with nitrogen fertiliser rate under favourable conditions but not under conditions conducive to low grain protein. The relationship between harvest index and fertiliser had slopes undistinguishable from zero for both 90th and 10th percentiles ($P > 0.60$). Interactions between available soil nitrogen and seasonal water supply may influence harvest index through the so called “haying off” effect (Kirkegaard and Ryan 2014), although the importance of crop water use patterns in this phenomenon is unclear (Savin et al. 2015; Unkovich et al. 2010). In this context, the stability of harvest index in response to nitrogen fertilisation across soils, management, varieties and climates is interesting (Figure 5D).

Comparison of nitrogen export in grain, and the input of nitrogen fertiliser across these environments indicate a cutting point for fertiliser around 50 kg N ha⁻¹ (Figure 5E); below this rate, export exceeds input suggesting likely soil mining. This coarse estimate of partial nutrient balance is consistent with a detailed, long-term experiment at a single site in Victoria where the ratio between nitrogen removed and applied was 1 for rates of fertilisation between 40 and 80 kg N ha⁻¹ (Figure 5G). Empirical information on the rate of nitrogen fertiliser required to match export for specific combinations of sites and management is an interesting reference for management.

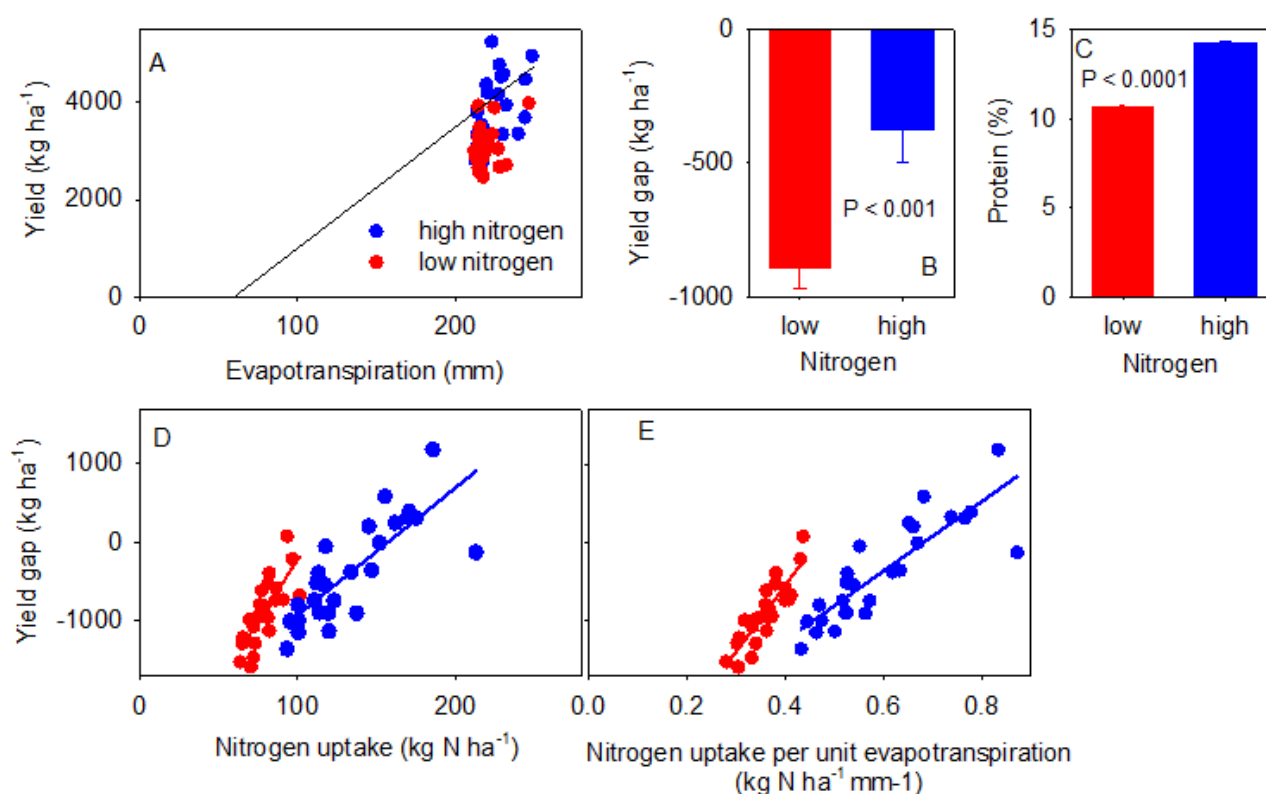


Figure 6. Nitrogen-driven gap between water-limited potential yield and actual yield of wheat. A. Yield and seasonal evapotranspiration compared with a boundary line representing the water-limited potential yield. Parameters of the line are x-intercept = 60 mm (Sadras and Roget 2004) and slope = 25 kg ha⁻¹ mm⁻¹ accounting for the potential of the newest variety in the experiment (Sadras and Lawson 2013). B. Average yield gap across varieties. C. Average protein concentration in grain. Yield gap as a function of D. Nitrogen uptake and E. Nitrogen uptake per unit evapotranspiration. Data from experiments combining low (187 kg N ha⁻¹) and high (284 kg N ha⁻¹) nitrogen availability (initial mineral N + fertiliser), 13 varieties and two locations in South Australia. In B and C, error bars are one standard error. Source: Sadras and Lawson (2013).

Yield gap

The physiological perspective above highlighted the low water use efficiency of nitrogen deficient crops; here we look at the same association from the perspective of yield gaps, as defined in the section *Crop yield and environmental constraints*. Where soils with low fertility combine with uncertain rainfall that make fertiliser investment a risky proposition, nitrogen availability accounts for an important part of the gap between water-limited potential yield and actual yield of wheat (French and Schultz 1984b; Hochman et al. 2013; Hochman et al. 2009a; Sadras and Roget 2004). Nitrogen deficiency also accounts for part of the yield gap in other rainfed systems, e.g. sunflower in Argentina (Grassini et al. 2009) and millet in sub-Saharan Africa (Sadras et al. 2012a). Where irrigation eliminates the uncertainty in water supply, the yield gap attributable to nitrogen can be negligible (Grassini et al. 2010).

Figure 6 illustrates the nitrogen-driven yield gap for an experiment involving two locations in South Australia, two rates of fertiliser and 13 wheat varieties released between 1958 and 2007. For crops with 187 kg N ha⁻¹ in the soil profile at sowing, the yield gap across varieties averaged 890 kg ha⁻¹ and protein concentration in grain 10.7 %; increasing initial nitrogen to 284 kg ha⁻¹ reduced the average yield gap to 375 kg ha⁻¹ and increased protein to 14.3 % (Figure 6 BC). For a given nitrogen supply, varieties with higher capacity to absorb nitrogen had a smaller yield gap (Figure 6 DE); this varietal effect is discussed in the section on plant breeding. Closing the yield gap in the experiments of Figure 6 required 0.7 ± 0.11 kg N ha⁻¹ mm⁻¹ for grain with 14.3% protein, and 0.5 ± 0.07 kg N ha⁻¹ mm⁻¹ for grain with 10.7% protein. For the data of French and Shultz (1984b), yield gaps were closed at an uptake of 0.65 kg N ha⁻¹ mm⁻¹. This ratio is physiologically and agronomically meaningful, and can be explored further for practical applications linking water and nitrogen. Achieving yield close to the water-limited potential requires high nitrogen rates that in turn reduce the yield per unit nitrogen; the nitrogen-driven trade-off between yield per unit water uptake and yield per unit nitrogen uptake requires local solutions in a context of risk, as discussed in the next sections.

Finding the causes of yield gaps is a necessary first step to close them. In this context, it is important to separate the proximate and ultimate causes of gaps. For example, shortage of nitrogen is a common, proximate cause of yield gaps for wheat in Australia and millet in Africa, but the ultimate causes, and therefore the solutions, are different. Shortage of nitrogen inputs in Africa relate to underdeveloped markets and infrastructure, concerns about perceived and realized risks, inaccessibility of input services and credit, and/or inconsistency with personal aspirations (Tittonell and Giller 2013) whereas risk is the main constraint to fertiliser use in Australia (Monjardino et al. 2015; Monjardino et al. 2013).

Wheat in winter-rainfall environments

Seasonal variation in rainfall is a major driver of seasonal variation in yield (Box 2); for example, in a latitudinal transect in the Eyre Peninsula, the coefficient of variation of wheat yield at the shire-level increased from 20-40% in the higher rainfall southern region to 80-100% in the lower rainfall, northern boundary of the grain region (Doherty et al. 2010). Hence, different farming practices have evolved in the low and high rainfall districts of south-eastern and western Australia. We compiled the following information directly from local experts – mostly advisors; this information is largely undocumented, hence the scarcity of supporting references in comparison to the other parts of this paper.

Box 2. Climatology of rainfall and crop yield

Nix (1975) drew attention to the relative importance of rainfall as a climatic constraint in Australian grain production compared to cold temperatures in North America, Europe and Asia and high temperatures and high humidity in India. Australian grain farmers thus face a higher production volatility than most other grain exporting countries (Kimura and C 2011). According to Podbury et al. (1998) the coefficient of variation of de-trended Australian wheat yield from 1960 to 1997 was 19% compared to 7% for the United States. The major source of the year-to-year rainfall variation is the El Niño Southern Oscillation (ENSO) (Manton et al. 2006; McBride and Nicholls 1983; Risbey et al. 2009). Australian national wheat yields were more strongly related to broad-scale ENSO indices than any other major grain crop in the world (Garnett and Khandekar 1992).

Although ENSO is dominant, the Indian Ocean, position of the subtropical ridge and the Southern Annular Mode are additional sources of climate variation for the Australia grains belt (Figure Box 2-1).

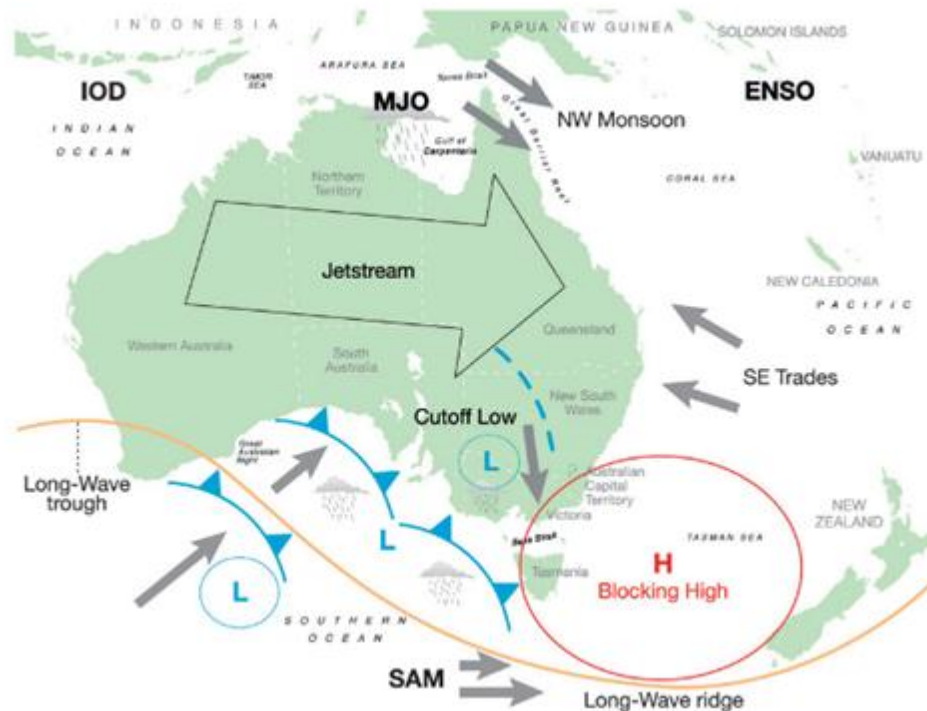
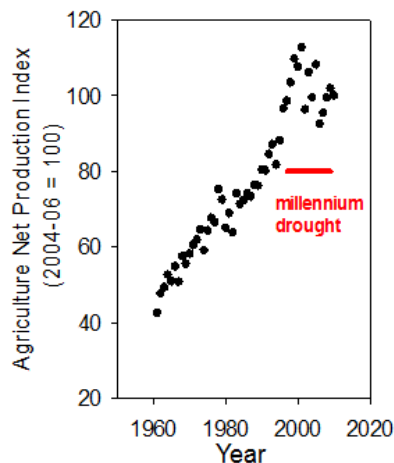


Figure Box 2.1. Main drivers of rainfall variability in Australia. The dominant features originate in the tropics and include El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Madden Jullian Oscillation (MJO). The Southern Annular Mode and blocking modify the impact of these tropical drivers. Other important features include the subtropical jet and a cutoff low shown in a typical position to influence southeast Australian rainfall. In this schematic, the long-wave pattern in the mid-troposphere consistent with the blocking high is also indicated with a trough over Western Australia and a ridge in the Tasman Sea. Dynamic climate models such as POAMA capture some climate drivers and interactions better than others. Improvements will come from better input data of the state of oceans and atmosphere, more accurate representation of processes in the model and improved computing power. Source: Risbey et al. (2009).

Box 2. Continued



A recent manifestation of these multiple sources of variation is the millennium drought from late 1996 to mid 2010, which had a measurable effect on the aggregated output of Australia's agriculture (Figure Box 2-2). While 2002 and 2006 were El Niño years and the southern oscillation index was negative in spring of 2004, there were aspects of this drought that could not be explained by ENSO alone (Timbal et al. 2010; Ummenhofer et al. 2009). Not only has this highlighted the role of the Indian Ocean on rainfall, but it has also raised questions of decadal variability and human induced climate change (Howden et al. 2014; Ummenhofer et al. 2009).

Figure Box 2-2. Time trend in FAO's Net Production Index in Australia highlighting the sustained increase in productivity and the disruption caused by the millennium drought. Source: Sadras et al. (2015a)

Climate change will present further challenges for the Australian grains industry. It will change the interaction between water and nitrogen in complex ways, but is likely to increase pressure on agronomic and genetic improvement in the efficiency of both resources. Confidence from climate science is highest for elevated CO₂, followed by increased temperature and then changes to rainfall (Howden et al. 2010; Karoly 2014). Over the last 150 years the amount of reactive nitrogen on earth's land and freshwater has more than doubled, primarily from anthropogenic sources (Galloway et al. 2008). In common with carbon dioxide, emissions of NO₂ and NO_x have global implications but other aspects of the altered nitrogen cycle (e.g. atmospheric nitrogen deposition) are strongly local. Elevated carbon dioxide would contribute to higher wheat yield and lower grain protein concentration (Bloom et al. 2014; Fitzgerald et al. 2010). The decrease in protein is partially associated with a dilution effect but complicated by reduced nitrogen uptake (Bloom et al. 2014). Warming will have dual impact of hastening crop development and increasing the frequency and intensity of hot days (Sadras and Dreccer 2015). The shifts in phenology may increase the risk of frost at vulnerable reproductive stages (Zheng et al. 2015), and this can be compounded by increased frost risk in parts of southern Australia (Crimp et al. 2014).

The high variability of rainfall on annual and decadal scales makes detection and attribution of trends difficult but recent studies have attributed some of the decline of rain in southern Australia to human induced climate changes (Delworth and Zeng 2014; Timbal et al. 2010). The impact on grain crops of changes to the water balance from rainfall and evaporative demand are relatively well understood and modelled (Potgieter et al. 2013; Yang et al. 2014). The impact and adaptation options arising from changes in seasonality of rainfall and changes to rainfall intensity are an area for future research. How grain crops respond to the interaction of carbon dioxide, temperature, rainfall along with changes in ozone and radiation is an ongoing challenge for modelling (Asseng et al. 2015). Further, we have little understanding of the effects of climate change on crop yield mediated by changes in pests, diseases and soil microorganisms (Sadras and Dreccer 2015). Seasonal variability rather than climate change signals dominate farmer's decisions on fertiliser. However climate change may add a level of uncertainty to a risky decision. For advisers, crop modellers and developers of decision tools, climate change raises questions of appropriate historical time periods to assess the analysis of risk.

In South Australia, low to medium rainfall districts are loosely defined as those areas receiving less than 400 mm annual rainfall and crop yield generally below 2.5 t ha⁻¹ (Doherty et al. 2010). The low rainfall districts of the north and east of Western Australia often feature short growing season, less than 4 months. These regions have been traditionally low users of nitrogen fertiliser. Nitrogen supply up until about 20 years ago has been reliant on rotations incorporating ley pastures, predominantly self-regenerating medics. The widespread replacement of single superphosphate with high analysis fertilisers (di-ammonium phosphate and mono-ammonium phosphate) about 30 years ago has resulted in at least a small amount of starter nitrogen being used on cereal crops at seeding.

In recent decades, nitrogen fixation from pastures across the wheat/sheep zone has declined as the result of reductions in both fixation per unit land area, and the proportion of land allocated to pastures (Angus and Peoples 2012). At the same time, cropping intensity has increased particularly with an increase in cereals at the expense of pastures. In the Mallee and Wimmera regions of south-eastern Australia, land allocated to pastures decreased by 63% whereas cropping increased by 66% between 1975 and 2005 (Duncan and Dorrough 2009). This combination of increased intensification of cropping and reduced nitrogen fixation per unit land has increased the focus on the importance of effective nitrogen management in these environments. Modelling tools such as Yield Prophet (Hochman et al. 2009b) have provided glimpses of the potential which exists in favourable seasons if nitrogen deficiencies can be overcome. Other tools developed with more specific targets include *Select Your Nitrogen*, aimed at nitrogen management for broadacre non-legume cropping farms in Western Australia¹; *Mallee Calculator*², initially tailored to the Murray-Mallee region, and *Nulogic*, which emphasises soil and plant analyses³.

Current advice in low rainfall areas is to apply nitrogen early, either at seeding or by tillering. The main difficulty with this approach relates to the often restricted information available to assess water-limited potential yield. The trend to earlier seeding, which may translate to dry seeding prior to the season break (Fletcher et al. 2015), further compounds these difficulties. A robust approach may be to apply sufficient fertiliser at seeding to meet a predetermined yield threshold then plan on topping up requirements if seasonal conditions are favourable. Those (relatively few) low rainfall regions with longer growing seasons may have more potential to delay applications to gain further climate information.

¹ <http://www.climatekelpie.com.au/manage-climate/decision-support-tools-for-managing-climate/syn-select-your-nitrogen>

² <http://msfp.org.au/tools/mallee-calculator/>

³ <http://www.csbp-fertilisers.com.au/nutrition-services/nulogic-soil-and-plant-analysis>

Advisors increasingly accept the need to overcome the tactical difficulties on nitrogen management in low rainfall environments by a more strategic approach focussing on increased share of high quality, well managed leguminous pastures (Kirkegaard et al. 2014). The current profitability of livestock provides additional impetus for this approach. The adequate share of pastures in the cropping mix remains unresolved - modelling for a cropping farm in southern NSW indicated a pasture intensity of around 40% would overcome historical nitrogen deficiency (Angus and Peoples 2012). In low rainfall cropping areas of South Australia, 25-33% of leguminous pastures are more common. Well managed medic based pastures are widespread, particularly on Eyre Peninsula and the Upper North regions of South Australia. The use of sown vetch for pasture is increasing. In cropping rotations incorporating leguminous pastures, there is an inter-seasonal trade-off between maximising pasture biomass for nitrogen fixation and plant available water for carry-over. The technique of brown manuring involving early termination of a pasture (usually vetch) in spring resulting in some residual carry-over of water can become an important consideration in the nitrogen/water management decisions for the following season.

The increased intensification of cropping noted earlier has seen a decline in the traditional long fallow. However, recent work has highlighted the importance of summer fallow management and its influence on water and nitrogen (Kirkegaard et al. 2014); control of summer weeds is now accepted best practice even after allowing for the reduction in summer grazing from sheep (Hunt et al. 2013).

The shift in cultural practice towards stubble retention and direct drilling has been undertaken to deal with soil erosion and decline in soil structure as well as allowing quicker and earlier crop establishment. Whereas farmers perception is that these practices favour soil water storage through reducing unproductive water loss, the evidence does not fully support this view (Sadras et al. 2012c; Scott et al. 2010; Ward et al. 2009).

In South Australia, high rainfall districts receive above 400 mm annual rainfall. Crop yields are typically above 3.0 t ha⁻¹ (Doherty et al. 2010). The traditional approach has been to apply nitrogen based on target yield, with a substantial portion applied as a separated band at seeding and follow up applications depending on seasonal conditions. In the longer-season, higher rainfall districts of Western Australia, even a third application is considered if the crop is growing well, is free of weed and disease, and water has accumulated in the soil. Current best practice is largely strategic, based initially on testing for nitrogen in the root zone prior to seeding. Logistics and cost means that not all paddocks are tested and therefore untested paddocks require extrapolation from tested paddocks based on rotation history and soil type.

Rates of nitrogen fertiliser in high rainfall environments, up to 120 kg N ha⁻¹, are based on rules of thumb relating to nitrogen requirements and yield - for example, wheat at 11% protein requires 40 kg ha⁻¹ of nitrogen per tonne of grain yield. Yield is analysed by looking at a range of potential outcomes depending on how the season evolves- the use of Yield Prophet giving a yield probability curve is highly regarded, but requires good local soil knowledge for robust outcomes.

Timing of nitrogen application in high rainfall districts relates to managing crop vigour to ensure sufficient plant available water at anthesis, thus the importance of methods to model or measure plant available water. Work undertaken by the Mid- North High Rainfall Group in South Australia has found that a 4 t ha⁻¹ wheat crop requires 50 mm of plant available water at anthesis. Canopy management techniques may include lower seeding rates for early sown crops, delaying nitrogen application, grazing to delay biomass accumulation and the use of plant growth regulators to prevent lodging.

Varieties, fertilisers and logistics

Owing to the large uncertainties in matching nitrogen and water supply, advice and rules have been mostly generic, but there is an emergent interest in tailoring practices to varieties which might reflect the impact of breeding for yield on the nitrogen economy of the crop (see *A breeding perspective*). Further, tailoring nitrogen management to variety might be important to reach malt specifications in barley (Browne and Walters 2015).

Excluding the nitrogen supplied in high analysis NP fertilisers, the predominant fertiliser in south-eastern and Western Australia is urea. Some sulphate of ammonia is used where sulphur is needed or to counter perceived concerns over volatilisation. Liquid UAN (urea and ammonium nitrate solution) is available and is used, but it is generally more expensive than urea.

Recent history involving substantial losses on fertiliser stock held by importers has seen an increased reluctance on behalf of suppliers to hold uncommitted stock resulting in the decline in the flexibility in supply of urea at reseller and farmer level. While actual shortages have been uncommon and only temporary in recent years, there is a trend for (usually) larger users of urea to lock-in supplies early in the season to avoid supply risks. This can compromise flexibility in the face of variable seasons.

Wheat and sorghum in summer-rainfall environments

Present wheat yield gaps in the northern region average $\approx 1.9 \text{ t ha}^{-1}$ showing large potential for improvement (Hochman et al. 2014). For sorghum, trends in yield increase show a large spatial variation (Potgieter et al. 2012), most likely reflecting variation in technology adoption, investment and farmer's skill. Crop selection and rotation may also influence the magnitude of present yield gaps. This is particularly important as we move from a predominantly wheat production systems in the south to the summer-dominant cropping systems in the north featuring summer cropping (sorghum) specialists (Rodriguez et al. 2011).

In the northern region, the shorter seasons associated with higher winter temperature, the reliance on stored soil water and scarce rainfall events in autumn, limit the opportunities for in-crop fertilisation in wheat. Nitrogen fertilisers are usually incorporated up to a month before sowing. Farmers usually decide on the amount to apply based on nitrogen soil tests and available soil water before sowing. There is an increasing interest in the use of green manure crops to reduce nitrogen costs, control herbicide resistance, and improve soils. Preliminary farm trials in the Darling Downs using legumes as cover crops, i.e. brown killed after 60 days of growth, have shown contributions of about 30 kg N ha^{-1} for wheat and sorghum crops, compared to a common fertilisation rate of 100 kg N ha^{-1} . However, trade-offs with water use by the cover crops can be significant particularly in dry seasons (Figure 7A). At Jimbour, summer legumes consumed more than half of the available soil water compared to a bare fallow after 46 days of growth, where dry matter production was 3.7 t ha^{-1} for mungbean, 3.4 t ha^{-1} for lablab, and 2.7 t ha^{-1} for guar (Figure 7A). At the time the cover crop was killed, there was a 59% chance of obtaining a full profile before the winter planting window following mungbean, and 68% in the case of lablab and guar based on current soil moisture and historical climate records.

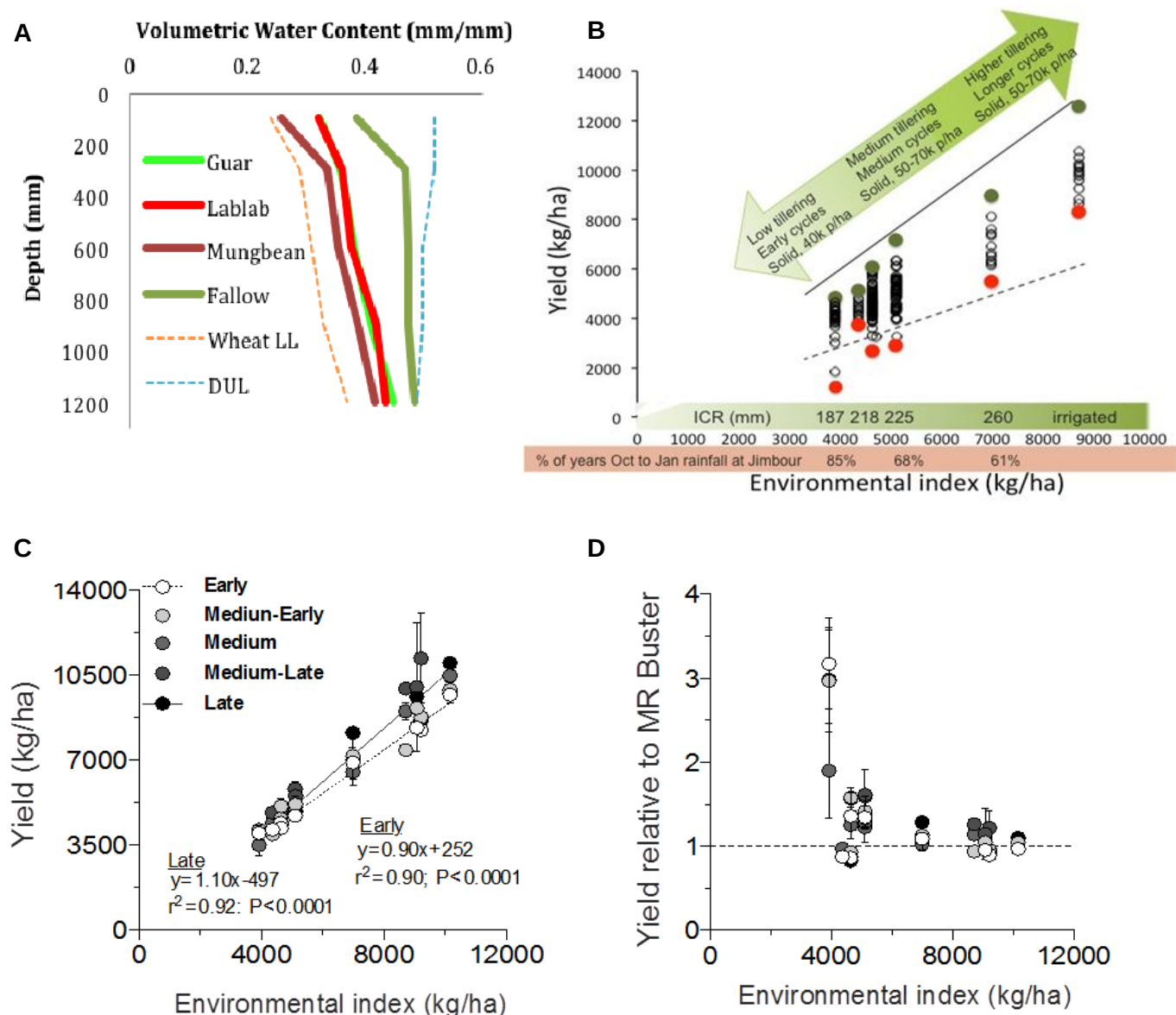


Figure 7. (A) The effects of summer cover crops on stored soil water after 46 days after sowing on a Black Vertosol - Waco Soil at Jimbour, Queensland. The dashed lines are the upper limit and lower limits of soil water content in the profile. Source: McLean and Rodriguez (2014, unpublished data). (B) Relationship between grain yield for each individual G x M treatment, and environmental mean yield for 234 crops in multi-environmental trials. ICR is in crop rainfall, and the arrow indicates the treatments giving the highest yield across environments. Red and green symbols are the crops with the lowest and highest yield, respectively. The boundary lines correspond to $22 \text{ kg ha}^{-1} \text{ mm}^{-1}$ (solid) and $7 \text{ kg ha}^{-1} \text{ mm}^{-1}$ (dashed). The green arrow shows the characteristics of the best performing treatments. (C) Comparison of hybrids of varying phenology in a range from low to high yielding environments. (D). Comparison of current and 20-year old (MR Buster) hybrids in a range from low to high yielding environments. Source: Rodriguez et al. (2015).

Owing to variation in hybrids, environments and agronomic options, there is opportunity for the development of specific G x E x M combinations for sorghum (Hammer et al. 2014). Hybrids vary in tillering (Kim et al. 2010), maturity (Kumar et al. 2009), root angle (Singh et al. 2012), and stay green (see *A breeding perspective* below). Management options including plant population, row configuration i.e. solid, single or double skip row (Whish et al. 2005) and sowing date affect the pattern of canopy development and water use during the growing season. Modelling showed that single and double skip arrangements and reduced plant densities reduced pre-anthesis water use and helped sustain harvest index and yield in years with below-average rainfall (Whish et al. 2005). Low tillering, earlier maturing hybrids planted at low plant populations also performed better at the dryer sites (Figure 7B). Figure 7B shows the treatment mean from a network of sorghum trials across Queensland as a function of the average site yield which is taken as an environmental index for each of the six tested environments. In the wetter environments, the highest yields were achieved with high tillering, long cycles and higher plant populations; while, yield was higher with low tillering, early cycles and lower plant populations in the poorer environments. In-crop-rainfall probability is also shown in the graph for Jimbour, so farmers can better associate their environments with the likelihood of achieving a particular yield, provided best agronomy. The value of this type of information i.e. specific G x E x M combinations, will depend on our capacity to foresee seasonal conditions. Location (i.e. climate and soil) and initial soil moisture at sowing can provide an initial assessment of expected yields (e.g. environmental index), though a seasonal climate forecast of improved accuracy would allow to fully exploit the benefits from matching G and M to expected E; the next section discusses seasonal forecasts in a context of risk.

An economic perspective: dealing with risk

Jobbágy and Sala (2014) quantified the inputs and outputs of nutrients across cropping industries on a global scale. They found that the difference between input and output increases with farm-gate value of produce (Figure 8A). This suggests that a declining share of fertiliser on the total production costs encourages higher fertilisation rates, irrespective of their agronomic benefit and despite their environmental consequences. The largest surplus of both nitrogen and phosphorus corresponds to fruits and vegetables. In comparison, economic return in the grains industry is smaller and the associated nutrient balance is closer to neutral.

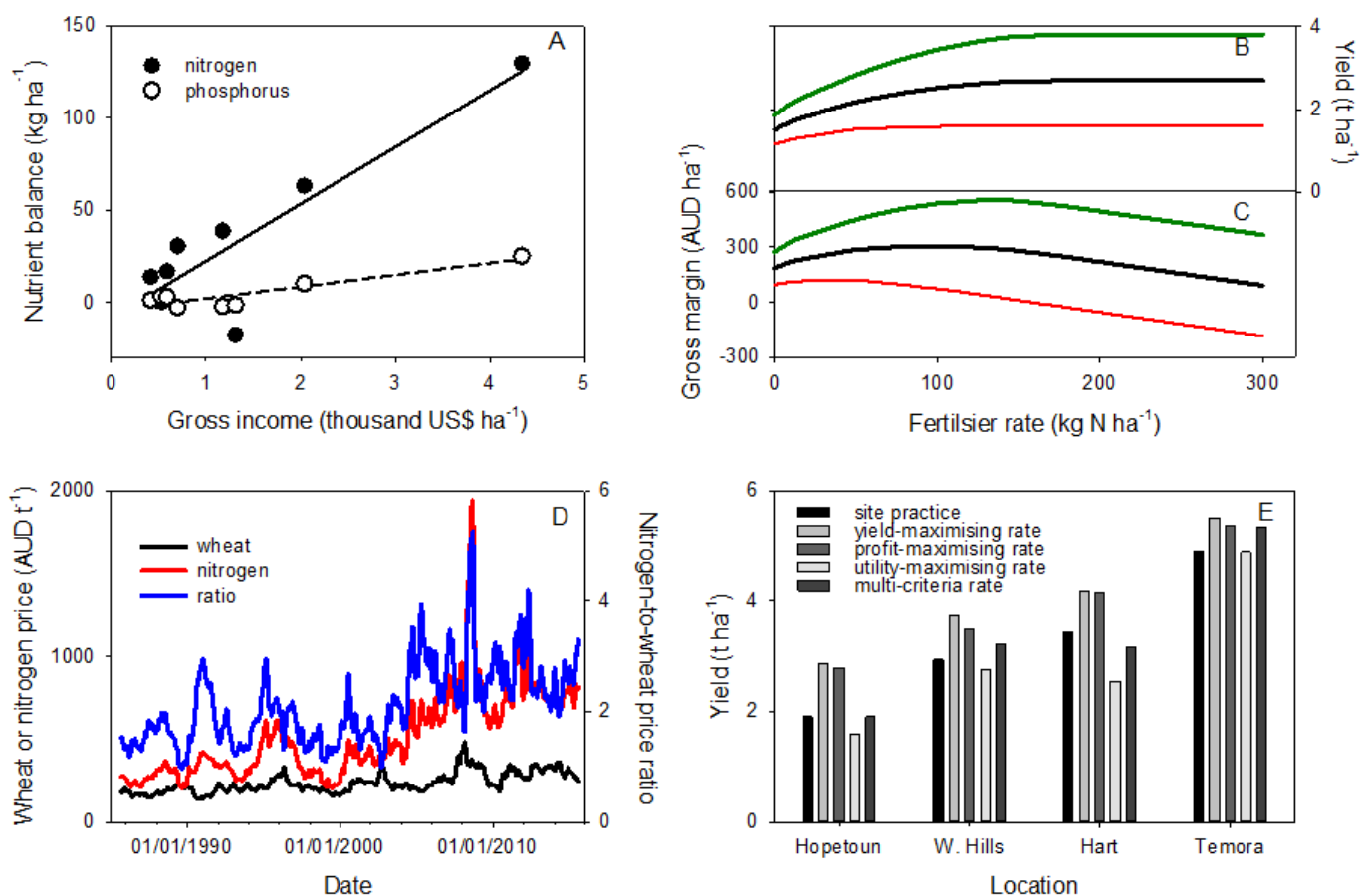


Figure 8. Some economic factors with implications for nitrogen management. A. Association between nutrient balance (fertilisation—withdrawal) and farm-gate value across crops on a global scale. B. Grain price (based on AWS wheat), fertiliser price (based on the cost of urea at 46% N) and nitrogen-to-grain price ratio between 1979 and 2009 in Australia. C. Flat payoff function for nitrogen applications on wheat production, and the direct cost of applying fertiliser. D. Modelled mean (1957–2011) wheat yield with five nitrogen fertiliser rates: site practice (SP), yield maximising (Ymax), profit maximising (Pmax), utility maximising (Umax) and multi-criteria (MC) in four Australian locations. Sources: A. Jobbágy and Sala (2014), B. ABARE (2010a). C. Monjardino et al. (2013). D. Monjardino et al. (2015).

The Australian grains industry is characterised by relatively low inputs of fertiliser due to a combination of 1) relatively low grain yield 2) unsubsidised input costs and output prices, 3) trends of increased farm size and hence more extensive operations and 4) erratic rainfall leading to uncertainty on returns from fertiliser. Not only is nitrogen a significant portion of variable costs, it is an easily observed cost compared to machinery depreciation or even machinery maintenance (GRDC 2014). The overriding influence of economic considerations thus sets the scene for our analysis of nitrogen management in a context of risk, largely driven by uncertain water availability.

In this section, we outline some principles of production economics and risk as background to the specific consideration of the consequences of risk and risk aversion in handling the interactions between water and nitrogen in grain production. We briefly consider the role of seasonal climate forecasts in nitrogen decision making.

Production economics

The relationship between the inputs and the resulting yield output is a response or production function, which conforms to the law of diminishing returns whereby an additional unit of input results in a less than proportional increase in grain production. This is illustrated in simulated yield response to nitrogen in Figure 8B; the divergent yield responses to nitrogen in the years with above or below median rainfall illustrates the influence of water.

When combined with price and cost information, a production function results in a payoff or profit function (Heady and Dillon 1961). The additional income generated by the addition of a unit of input is the marginal return (MR) and the associated additional cost is the marginal cost (MC). The economically optimum nitrogen rate (EONR) occurs when $MR = MC$ (Barnard and JS 1976). For the 30 years in Figure 8BC, the EONR is 100 kg N ha^{-1} and it varies from 140 kg N ha^{-1} in the seasons with above-median rainfall to 40 kg N ha^{-1} in the seasons with below median rainfall.

The EONR varies with climate, soil nitrogen supply and the cost of nitrogen relative to the price of grain. The maximum financial return is achieved at the rate of nitrogen where the slope of the yield response to nitrogen equals the cost/price ratio for nitrogen fertiliser and grain (Kindred et al. 2007). Between 1985 and 2015, there was a five-fold variation in the nitrogen-to-wheat grain ratio (Figure 8D). Global supply and demand is the primary driver of nitrogen price (Prudhomme 2015) which is also influenced by the price of energy and feedstock gas, the exchange rate and shipping costs. Decisions on nitrogen rate thus need to consider the relative price of wheat and cost of nitrogen (Abadi and Farre 2015), in addition to agronomic information (stored soil water and nitrogen, seasonal rainfall prospects).

Although the concept of EONR is common in literature, a rate lower than the profit maximising rate can be justified for two reasons: uncertainty in the coming season, and opportunity costs, i.e. likely better uses of scarce funds than maximising the profit from nitrogen fertiliser. As it is problematic referring to the profit maximising nitrogen rate as economically optimum, for the rest of this paper we will use the term Economic Maximising

Nitrogen Rate (EMNR). Related to an understanding of the EMNR is the benefit cost ratio (BCR) which is the benefit in extra grain yield divided by the cost of applying nitrogen. A BCR of say 2.0 has the straightforward understanding that a farmer will get back \$2 for each \$1 invested in nitrogen. An associated expression is return on investment (ROI) which is the net return found by subtracting the cost of investment from the benefit of the investment and dividing by the cost of investment (commonly expressed as a percentage). Both expressions are valid, and they are related as $ROI = 1 + BCR$. At the EMNR, by definition, the BCR is 1.0 and the ROI is zero. Both ROI (Asseng et al. 2012; McIntosh et al. 2015) and BCR (Angus 1998; Hayman et al. 2015) have been used in economic analysis of nitrogen management; BCR has also been used to assess practices such as weed control (Hunt et al. 2013). The key point is to understand what farmers mean when they refer to requiring a return of say 2 to 1 (Browne and Walters 2015); if the definition is not explicit, this could be interpreted as extra two (BCR) or three (ROI) dollars income from grain per dollar invested in nitrogen.

While the agricultural economics literature emphasises input levels to maximise profit, often large deviations from optimal management make little difference to the payoff – flat payoff functions are a common phenomenon in economic models generally (Anderson 1975; Pannell 2006). For nitrogen, a flat payoff curve means that there is a ‘margin for error’, i.e. a set of alternative rates that are only slightly less attractive than the maximum payoff for nitrogen applications (say, within 5% of the maximum), thereby lowering the risk of not selecting the best rate, or allowing for rate adjustments when considering other factors, such as the environment. However, the flatness of the curve is reduced with increasing price ratio of N to grain. Figure 8C illustrates the relative flatness around the optimal rate of approximately 100 kg N ha⁻¹, suggesting that farmers may be better off taking only informed guesses (based on soil, seasonal and economic indicators) instead of employing costly methods for identifying the appropriate fertiliser rate (Robertson et al. 2008). Further, the degree of flatness depends on soil properties, as discussed for soils with low PAWC where a limited buffering capacity for both water and nitrogen would lead to sharper payoff functions (see *Soil texture, soil water and soil nitrogen*). Overall, the degree of flatness in payoff functions have implications for risk management, precision farming, and the value of research.

Risk and uncertainty

Yield variability, market volatility and financial debt are among the major risks faced by dryland farmers in Australia (Hardaker et al. 2004; Kingwell 2000). The inherent riskiness of

grain production is often high (Hayman et al. 2010) and the variance in wheat revenue has increased between 1992 and 2009 (Kingwell 2011) in response to both climate-drivers and cropping intensification (e.g. less fallow and pasture, higher costs for crop protection) (Llewellyn et al. 2012).

The chance of downside risk is perceived as far greater than that of upside gain in such risky environments. As a result, low-rainfall farmers tend to apply conservative rates of fertiliser to minimise the overall risk of low/variable yields in poor seasons. Nevertheless, additional use of nitrogen fertiliser in these dryland systems may pay off by increasing yield as well as grain quality, and by reducing the probability of missing out in the better years (Asseng et al. 2001a) (Sadras 2002b) (Monjardino et al. 2015; Monjardino et al. 2013). Strategies and tools have been developed to manage the riskiness of nitrogen fertiliser decisions but in highly variable environments, investment in nitrogen fertiliser remains a challenge for farmers (Hochman and Carberry 2011; Lobell 2007).

The average wheat yield gap in Australia around 2.0 t ha^{-1} in the period 1996 to 2012 (Hochman et al. 2012) is partially attributable to intentional under-fertilisation with nitrogen due to risk, risk-aversion and trade-offs between efficiency in the use of nitrogen and water, particularly in low rainfall regions (Monjardino et al. 2015; Sadras and Rodriguez 2010). The role of risk management in yield gaps is illustrated in Figure 8E, which highlights the difference in mean wheat yield response between nitrogen rate according to site practice, a yield-maximising rate, profit-maximising rate, utility-maximising rate and multi-criteria rate in four case-study sites. Here, utility-maximising rate is the nitrogen rate that allows farmers to maximise their utility (or certainty equivalents) for a given level of risk-aversion, and multi-criteria rate is the result of a set of yield-risk-return and risk-aversion criteria that would need to be met for a nitrogen management practice to be selected as the most preferred one (Monjardino et al. 2015). In all cases, the preferred multi-criteria management strategy was neither the yield-maximising nor the profit-maximising strategy; it generated higher mean yield than the utility-maximising strategy, and in three of the four sites it resulted in a similar mean yield to site practice. On average yield-maximising rate was only 3% greater than profit-maximising rate, with the biggest yield gap between these strategies at Wongan Hills. Importantly, site practice and multi-criteria rate achieved approximately 20% less than potential yield, and in two sites yield with site practice was 8% less than with multi-criteria rate, all of which emphasises the role of farmer risk-aversion in limiting the closure of yield and profit gaps in the management of fertilisation. Overall, site practice, particularly at Hopetoun, Wongan Hills and Hart appeared close to optimal when risk is considered.

A discussion of the economics of nitrogen for dryland grains concentrates on the rate of nitrogen as the controlling variable that comes with a cost and often treats the supply of water as zero cost and uncertain. Obviously the supply of water is closely linked to the cost of purchasing or leasing land. Weed control over the fallow is a cost with benefits in water and nitrogen available to the subsequent wheat crop (Hunt et al. 2013). McMaster et al (2015) refer to the process of 'buying a spring' in central NSW with a CBR of up to 8.0 for summer weed control. This increased the CBR of nitrogen topdressing from 1 with no weed control to 3 with complete weed control. Stored soil water at sowing will increase the confidence farmers can have in applying higher rates of N.

Seasonal climate forecasts

Given the risk and costs associated with uncertain seasonal conditions, there is an interest in seasonal climate forecasts (SCF) which are defined as probabilistic statements about the climate of the coming season (WMO 2006). SCF rely on the memory of the climate system captured in the slower moving variable of ocean temperatures especially the Pacific and Indian Ocean (Box 2). SCF are best understood as shifts in probabilities of a variable such as rainfall over the coming growing season. They differ from numerical weather forecasts which use the current state of the atmosphere to predict future states over the next 1-7 days and climate change projections which project the climate in coming decades to centuries for different greenhouse gas forcings. SCF have been available since the 1990s and many studies have shown their potential benefit to agricultural decisions (Crean et al. 2014; Easterling 1999; Hammer 2000; Mase and Prokopy 2014; Meza et al. 2008).

The requirements for a forecast to be beneficial include 1) a climate sensitive decision, 2) a prediction that is skilful and timely 3) the ability to adjust the decision in light of the forecast 4) the communication and support for the forecast (Hansen 2002). Nitrogen fertiliser decisions in the Australian grains industry are a climate sensitive decision and, unlike in many parts of Europe or for sugar cane in Australia, there is no policy setting or industry guidelines constraining the rate of nitrogen used or the time of application. The ongoing challenge is to have acceptable accuracy or skill of the forecast, and in some cases, the timing of the forecast. Closely linked to the skill of the forecast is the effective communication of the forecast. A more accurate forecast would solve many of the communication problems (Ash et al. 2007; Hayman et al. 2007; Lemos et al. 2014; Mase and Prokopy 2014).

Nitrogen decisions on wheat was one of the earlier applications of valuing seasonal climate forecasts. Marshall et al (1996) and Hammer et al (1996) focussed on the grains industry in Queensland using phases of the Southern Oscillation Index (Box 2). Marshall et al (1996) found that a Goondiwindi grain grower benefited from SCF about as much they benefited from wheat breeding (\$3-\$4/ha/year). However, adopting a new wheat variety is likely to provide a modest gain each year, whereas the returns from adopting SCF will have a much wider variability. This is because in some years (for many locations, the majority of years) the forecast will be no different from climatology and when the forecast is emphatic (say 70% chance of exceeding median) there will be a significant minority of years (up to 30%) when acting on the forecast may lead to losses. McIntosh et al (2015) calculated that it took on average between three to eight years for a forecast to be of value in representative grain sites around Australia. Asseng et al (2012) reported on the dynamic climate model POAMA for nitrogen on wheat in West Australia finding benefits of up to \$50 ha⁻¹. Hayman et al (2015) used APSIM to compare two strategies in the medium rainfall zone of South Australia: top-dressing a wheat crop with the same amount of nitrogen every year and tactically changing the rates for top-dressing using information from POAMA. Over the 30 year period from 1981 to 2010, POAMA would have produced the correct guidance 19 times and incorrect guidance 11 times. Under the assumptions of this study, depending on the amount of nitrogen used, following POAMA increased the gross margin by \$23 ha⁻¹ or 9%. A common assumption in these evaluations is that all the benefit of nitrogen is realised in the season when it is applied; however, residual nitrogen in the soil, e.g. in dry seasons, can be of value to the next crop. The soil, climate and management conditions that favour this carry-over of nitrogen need to be identified.

Most analyses of the value of seasonal climate forecast for nitrogen on wheat assume that a farmer has to make the decision prior to the uncertain season. However in-crop application of nitrogen is more common for many farmers in southern and western Australia (see *Agronomic perspective* above). By delaying the application of nitrogen, farmers are applying the principles of Real Options sometimes referred to as purposeful procrastination. The idea of making a decision and then waiting to see what happens compared to waiting to see what is starting to happen and then decide or adjust is central to the intuitive value of Real Options (Luehrman 1998). Real Options have been applied to agriculture and NRM in the Australian context (Hertzler 2007; Nelson et al. 2013; Sanderson et al. 2015). The essence of Real Options is to use the analogy of financial options to consider the value of waiting for better but not complete information. Almost all decisions can be delayed with costs and benefits changing as the delay continues. The obvious benefit of applying nitrogen later in the season is the extra information. This extra information includes 1) the status of the crop

and stored soil moisture, 2) improved information on the rest of the season as the skill of climate forecasts in winter for spring is superior to the low skill in autumn for the coming spring, and 3) more information on the final price of grain. The cost of delaying nitrogen include application costs and the risk of low rates of uptake in a dry season.

A breeding perspective: the water and nitrogen economies of high-yielding varieties

The pioneering experiments of Austin et al. (1980) compared the phenotypes of wheats released in the UK between 1908 and 1978. This approach returns a rate of yield gain, and identifies the traits driving yield improvement. Worldwide comparison of similar studies reinforces the early conclusion that genetic gain in wheat yield is proportional to the potential of the environment (Figure 9). Whilst breeders primarily select for yield and agronomic adaption, this selective pressure can lead to extraordinary changes in phenotype. Using this method, we ask: what are the changes in traits related to the water and nitrogen economy of crops in response to selection for yield? Our primary focus is wheat, and rates of change are calculated as percentage of the newest varieties for comparison of traits (Fischer et al. 2014). We briefly discuss other crops, including sorghum where current understanding of stay-green illuminates some of the connections between nitrogen and water, and soybean where the role of nitrogen fixation under drought has been evaluated in detail.

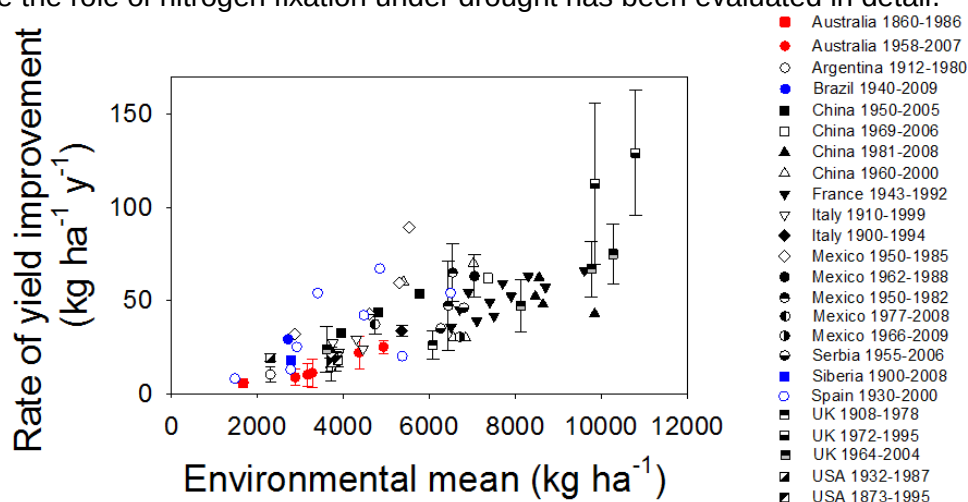


Figure 9. The rate of genetic gain in wheat yield is proportional to the environmental potential. Sources: *Australia*, Siddique et al. (1989), Sadras and Lawson (2011); *Argentina*, Slafer et al. (1989); *Brazil*, Beche et al. (2014); *China*, Zhou et al. (2007), Tian et al. (2011), Zheng et al. (2011), Xiao et al. (2012); *France*, Brancourt-Hulmel et al. (2003); *Italy*, Guarda et al. (2004), Giunta et al. (2007); *Mexico*, Ortiz-Monasterio et al. (1997), Sayre et al. (1997); Waddington et al. (1986), Lopes et al. (2012), Aisawi et al. (2015); *Serbia*, Miadenov et al. (2011); *Siberia*, Morgounov et al. (2010); *Spain*, Sanchez-Garcia et al. (2013); *U.K.*, Austin et al. (1980), Shearman et al. (2005); *U.S.*, Jensen (1978), Cox et al. (1989), Donmez et al. (2001).

Two studies have quantified the changes in the wheat phenotype in the winter-rainfall regions of Australia from early breeding until the mid 1980s (Siddique et al. 1989; Siddique et al. 1990a; Siddique et al. 1990b) and for the period 1958-2007 (Palta and Sadras 2015; Sadras and Lawson 2011; Sadras and Lawson 2013; Sadras et al. 2012d). Yield improvement in Australia over these periods aligns with a global benchmark accounting for the potential of the environment (Figure 9). Richards et al. (2014) provide further insight in an extended assessment of agronomic and breeding contributions to wheat yield improvement in Australia, where they highlight the higher rates of yield gain under more favourable, wetter conditions.

Early selection returned shorter season varieties with better adaptation to local conditions and reduced seasonal evapotranspiration in parallel with shorter cycles (Figure 10A); mean daily evapotranspiration did not vary among varieties ($P = 0.91$) and averaged 1.3 mm d^{-1} . Soil evaporation accounted for by 40% of the seasonal evapotranspiration irrespective of cultivar ($P = 0.50$). Seasonal evapotranspiration remained unchanged for the varieties released between 1958 and 2007 (Figure 10B). As a result of the increase in yield and largely unchanged water use after accounting for phenology, the transpiration efficiency of Australian wheats increased linearly over a century to 2007 (Figure 10C). The $20 \text{ kg ha}^{-1} \text{ mm}^{-1}$ benchmark of French and Shultz (1984a) was largely based on Halberd or earlier cultivars (red point in Figure 10C), hence the need to update this benchmark to account for contemporary varieties, which are close to $25 \text{ kg ha}^{-1} \text{ mm}^{-1}$.

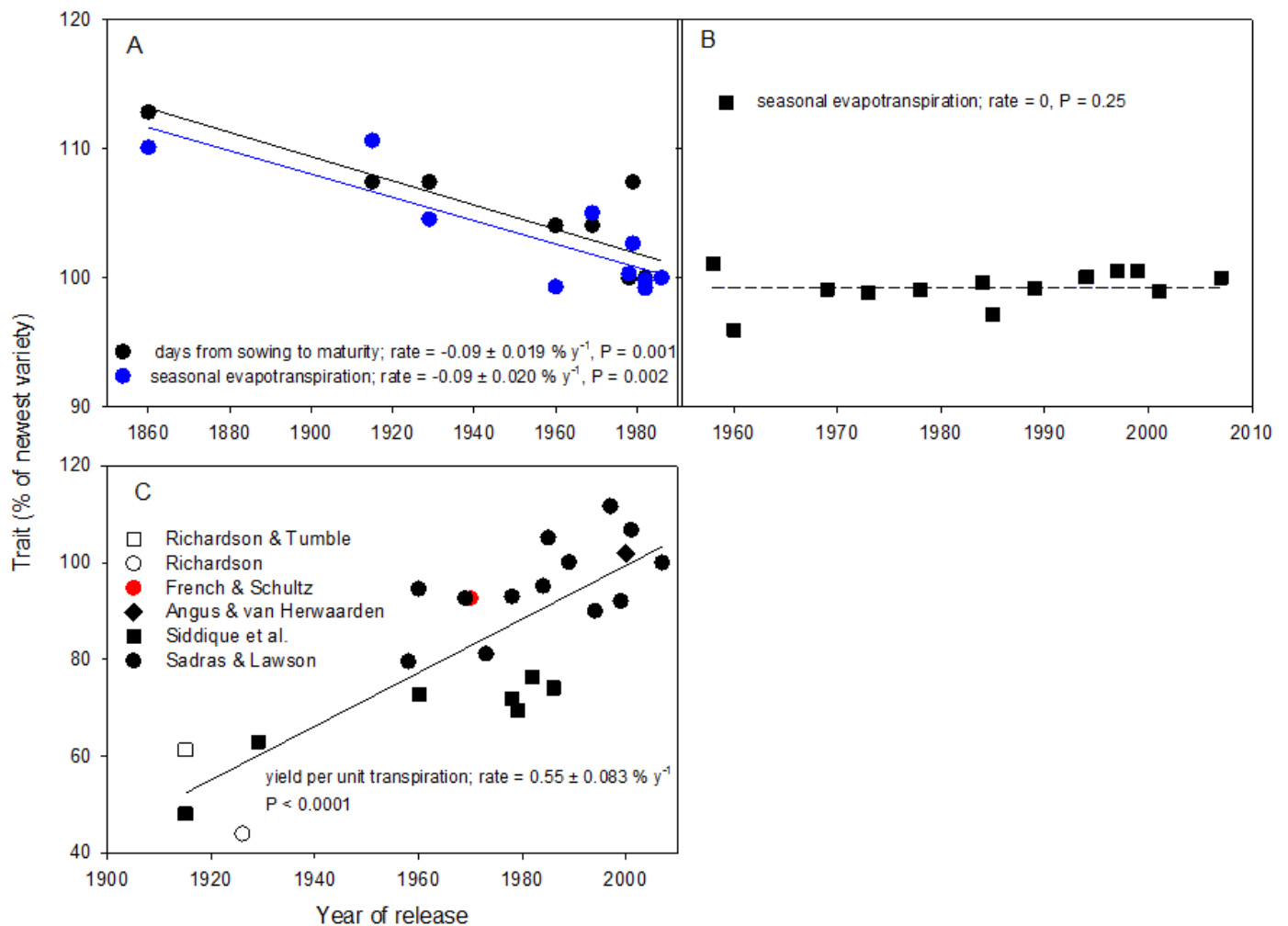


Figure 10. Changes in phenology and water-related traits of bread wheat in response to selection for yield in western and south-eastern Australia. A. Shorter cycle and parallel reduction in seasonal evapotranspiration between 1860 and 1986. B. Stable seasonal evapotranspiration between 1958 and 2007. C. Increase in yield per unit transpiration; the red symbol is cultivar Halberd, with an assumed ratio of $20 \text{ kg grain ha}^{-1} \text{ mm}^{-1}$ (French and Schultz 1984a). Solid lines are regressions with significant slopes, and the dashed line shows slope ≈ 0 . Sources: Richardson (1923), Richardson and Trumble (1928), French and Schultz (1984a), Angus and van Herwaarden (2001), Siddique et al. (1989) and Sadras and Lawson (2011).

Selection for yield between 1958 and 2007 increased wheat stomatal conductance but did not increase the rate of photosynthesis per unit leaf area (Sadras and Lawson 2011; Sadras et al. 2012d). Higher stomatal conductance is a conspicuous response to selection for yield reported for spring and winter bread wheat, durum wheat, rice, cotton and soybean in diverse breeding settings worldwide (Roche 2015). Often, the increase in stomata conductance has been associated with small or no change in photosynthesis, thus the apparent decline in intrinsic water use efficiency (assimilation-to-conductance ratio). Roche analysed the possible causes for these responses (2015) and Sadras et al. (2012e) advanced the hypothesis that where heat stress is prevalent, evaporative cooling, requiring maintenance of stomatal conductance at high vapour pressure, overrides water use efficiency, which requires stomatal closure. In common to cereals, cotton and grapevine,

important physiological and behavioural traits in birds and mammals can be explained in terms of the trade-off between water economy and thermal regulation mediated by evaporative cooling (Piersma and van Gils 2011).

Early selection for yield of wheat in Australia reduced root biomass with no effect on root depth or water uptake (Siddique et al. 1990a). In field-grown crops, root dry matter at anthesis decreased from 397 g m⁻² in the old variety Purple Straw to 280 g m⁻² in the 1986 variety Kulin, and the root:shoot ratio declined from 0.64 to 0.55. Under controlled conditions, root biomass seemed to decline further in response to selection for yield between 1958 and 2007 (Palta and Sadras 2015). These studies focused on varieties adapted to the winter-rainfall environments of western and south-eastern Australia where crops rely primarily on in-season rainfall and stored soil water is minor (section *Climate*). Selective pressure for yield in northern environments where crops rely on soil stored water might have modified wheat phenotype differently, e.g. deeper roots are more likely to be associated with yield in the north and shallower roots are superior in the south (Manschadi et al. 2006). Experiments comparing historic sets of wheat varieties adapted to the northern region would be of interest as a cost-effective means to unravel adaptive traits.

Selection for yield increased shoot water soluble carbohydrates at anthesis in both stressful Australian conditions and high-yielding U.K. environments (Sadras and Lawson 2011; Shearman et al. 2005). Our understanding of the role of carbohydrate reserves is fragmented, particularly in relation to the three way interaction between genotype, water and nitrogen. It is often assumed that reserve carbohydrates contribute to the maintenance of grain size under water stress during grain filling; intra-specific variation for this trait is large, narrow-sense heritability is moderate to high and complex genetic control across up to 10 QTL has been reported (Fischer 2011). Direct selection for water soluble carbohydrates can thus be achieved with genetic tools, high-throughput phenotyping (Dreccer et al. 2014), or a combination. The main impediment to select for this trait is however no technical but conceptual, as its adaptive value remains uncertain in relation to both environmental influences and trade-offs. The role of labile carbohydrate in grain filling under stress needs to be conciliated with the enhancement of this trait in response to selection for yield in wet, high yielding (> 10 t ha⁻¹) environments. Storage of labile carbohydrates involves apparent trade-offs with tillering, grain number, root growth and nitrogen uptake (Dreccer et al. 2013; Dreccer et al. 2009; Lopes and Reynolds 2010; van Herwaarden et al. 1998). Yield response to the interaction between water and nitrogen supply is partially mediated by responses in partitioning of carbon and nitrogen between yield components and reserves (Dreccer et al. 2009; van Herwaarden et al. 1998). Dreccer et al. (2009) showed that resource-based models are insufficient to capture these interactions. This conclusion arises mostly from

studies with lines with different combination of tillering and patterns of resource allocation, and the recognition that the allocation of resources is bounded by the fate of meristems in the plant. Whether a meristem is inactive, grows a new shoot or transitions to reproduction depends on genetic and environment influences, and to some extent the fate of meristems precedes and drives allocation of resources (Bonser and Aarsen 1996; Bonser and Aarssen 2001; Zhang et al. 2008). Understanding the controls of meristem fate and crop morphology, coupled with resource-based models, is thus necessary to untangle these important interactions (Dreccer et al. 2013; Dreccer et al. 2009; Luquet et al. 2006; Luquet et al. 2012).

During the last five decades, the rate of increase in nitrogen uptake of Australian wheats matched the rate of increase in grain yield with breeding; yield per unit nitrogen uptake thus remained stable (Figure 11). In the absence of changes in nitrogen harvest index, protein concentration in grain remained stable. The increase in nitrogen uptake was accompanied by shifts in the profile of foliar nitrogen, whereby newer varieties were greener at flowering, particularly at the bottom of the canopy. The increase in uptake and the shift in the distribution of nitrogen contributed to higher radiation use efficiency, biomass and yield of newer varieties (Sadras et al. 2012d). The large increase in nitrogen uptake in this historic set of varieties is unique. Comparison with breeding for yield of bread wheat in UK and Argentina, and durum wheat in Italy shows that nitrogen uptake did not increase, or where it increased it did not match the rate of yield gain (Figures 12-14). Hence, yield per unit nitrogen increased in all those breeding settings. With little or no increase in nitrogen harvest index, grain protein declined. Figure 15 summarises the four data sets; the condition for the increase in yield per unit nitrogen is that yield increases faster than nitrogen uptake, and this is reflected in a reduction in grain protein content. Reduced grain protein content in response to breeding for yield was also reported for other crops, e.g. maize in the U.S.A. (Egli 2015).

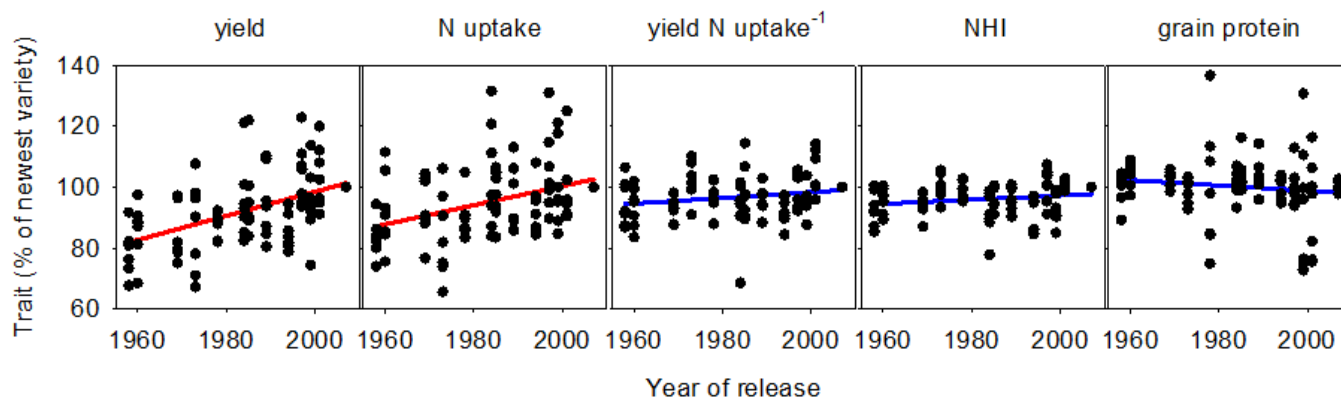


Figure 11. Changes in yield and nitrogen-related traits of bread wheat in response to selection for yield in Australia. Data from experiments comparing 13 cultivars in seven environments of South Australia, including locations, seasons, and nitrogen rates. Traits are relative to the newest variety. Red lines are regressions with non-zero slope ($P < 0.05$) and blue lines are regressions with slope not different from zero ($P > 0.05$). Source: Sadras and Lawson (2013).

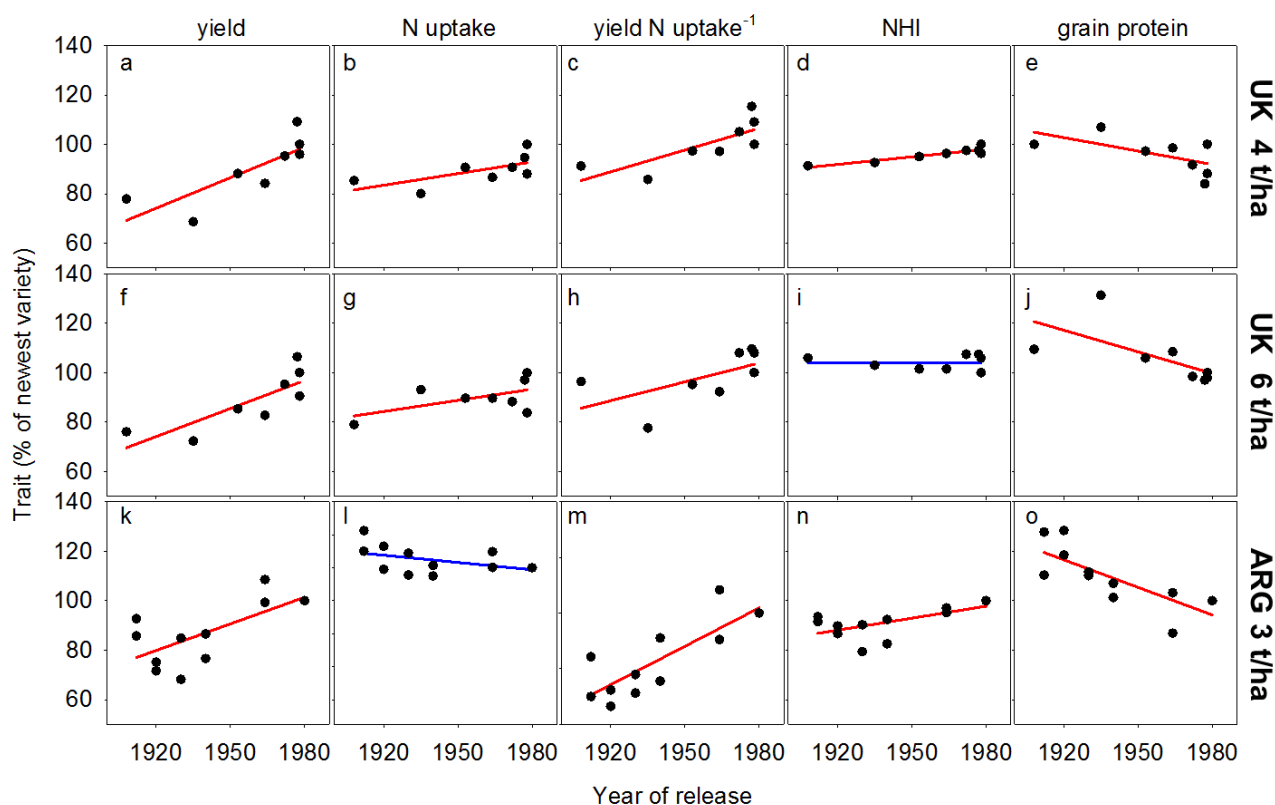


Figure 12. Changes in yield and nitrogen-related traits of bread wheat in response to selection for yield in the UK and Argentina between 1900s and 1980s. The first and second rows are from two fields in the UK, yielding an average of 4 or 6 t ha⁻¹. The third row is the experiment in Argentina where average yield was 3 t ha⁻¹. Traits are relative to the newest variety in each series. Red lines are regressions with non-zero slope ($P < 0.05$) and blue lines are regressions with slope not different from zero ($P > 0.05$). Sources: Austin et al. (1980) and Slafer et al. (1990).

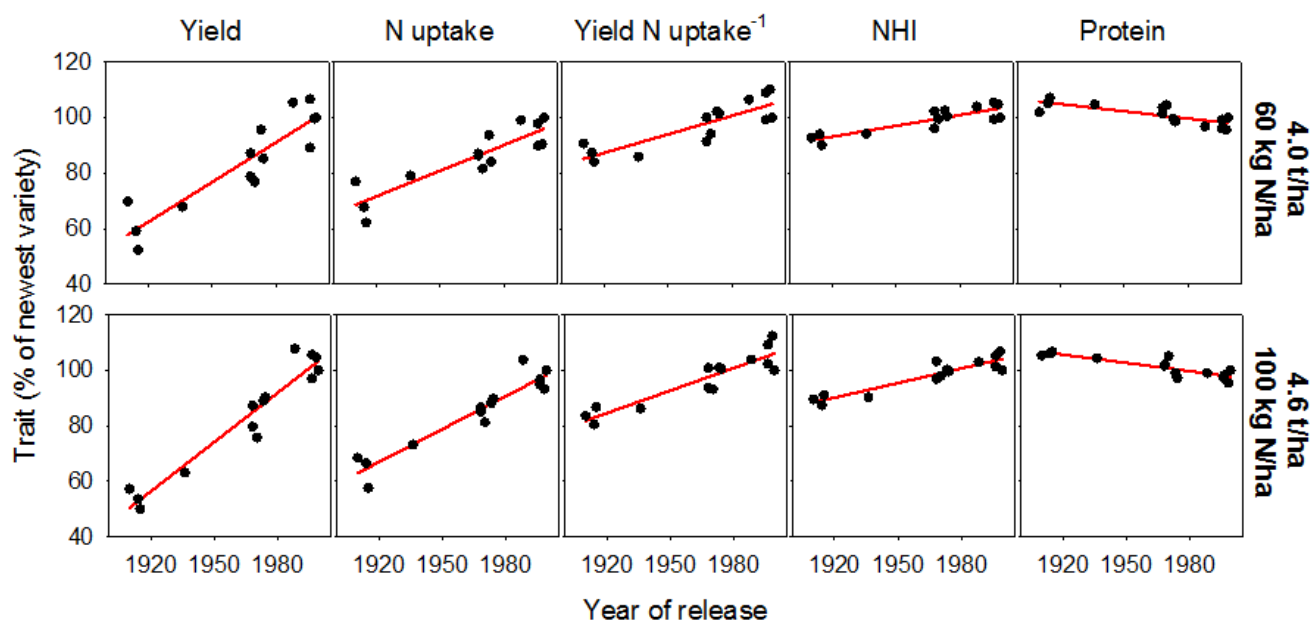


Figure 13. Changes in yield and nitrogen-related traits of durum wheat in response to selection for yield in Italy between 1900s and 1980s. The top row is from crops fertilised with 60 kg N ha⁻¹ and the second with 100 kg N ha⁻¹, returning average yields of 4.0 and 4.6 t ha⁻¹, respectively. Traits are relative to the newest variety. Red lines are regressions with non-zero slope ($P < 0.05$). Source: Giunta et al. (2007).

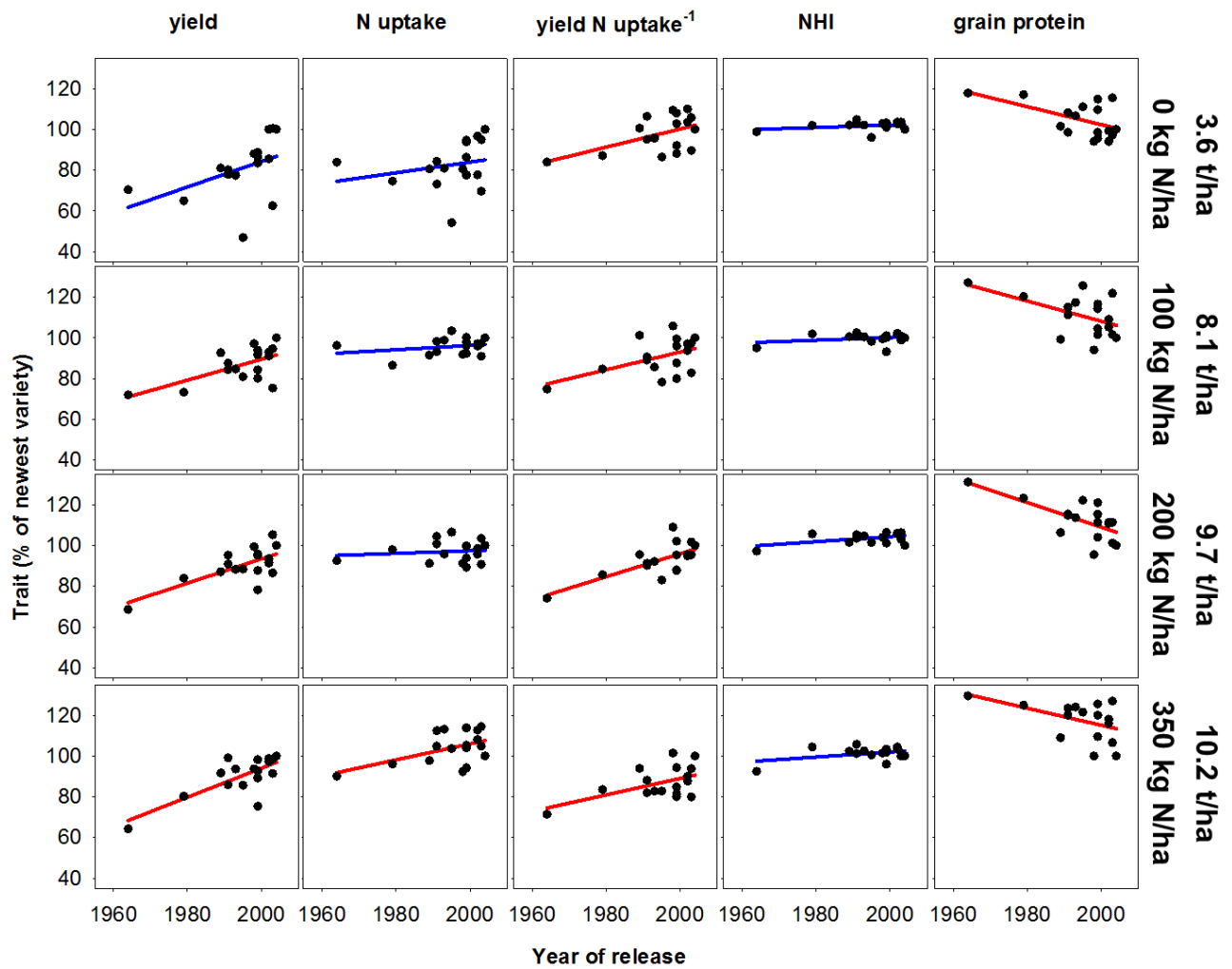


Figure 14. Changes in yield and nitrogen-related traits of bread wheat in response to selection for yield in the UK between 1964 and 2004. Each row is a rate of nitrogen fertiliser and mean yields from 3.6 to 10.2 t ha⁻¹. Traits are relative to the newest variety. Red lines are regressions with non-zero slope ($P < 0.05$) and blue lines are regressions with slope not different from zero ($P > 0.05$). Source: Barraclough et al. (2010).

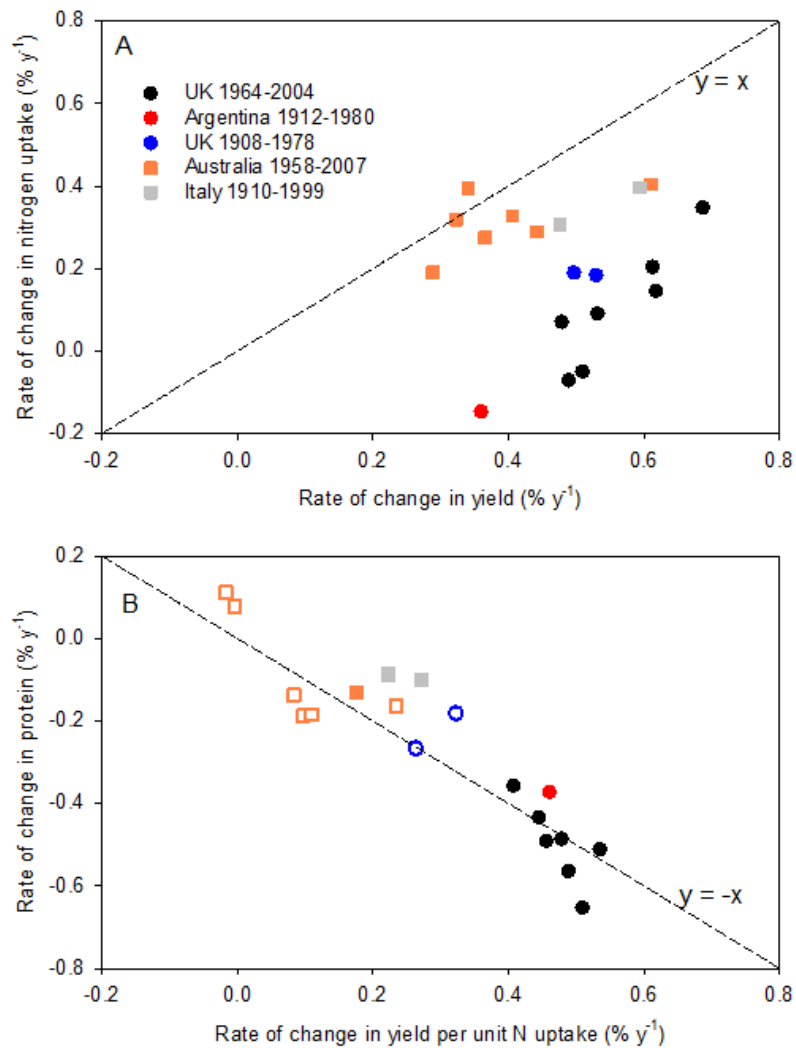


Figure 15. Comparison of rates of change in wheat traits in response to selection for yield. A. Rate of change of nitrogen uptake vs rate of change in yield. B. Rate of change in grain protein concentration vs rate of change in yield per unit nitrogen uptake. In B, open symbols indicate rates of change in protein not different from zero, and solid symbols indicate significant rates ($P = 0.05$). Sources: Austin et al. (1980), Slafer et al. (1990), Giunta et al. (2007), Barraclough et al. (2010), Sadras and Lawson (2013).

In conclusion, selection for yield in the dry, nitrogen-scarce environments of Australia had arguably, a larger impact on the nitrogen economy of the crop than on traits with putative value for adaptation to water deficit. If anything, some of the more consistent trends in water-related traits have been contrary to expectations: stomatal conductance increased with an apparent decline in assimilation-to-conductance ratio, and root biomass decreased. The enhanced capacity for nitrogen uptake despite reduced root biomass in newer varieties is of particular interest in the light of the findings of Liu et al. (2015). They compared two wheat lines, XY107 and XY6, under low and high nitrogen supply in a glasshouse experiment. Despite its lower root biomass particularly in the low nitrogen treatment, XY107 absorbed more nitrogen than XY6 and this was associated with the differential expression of nitrate and ammonium transporter genes, especially *TaNRT2.1*.

Water and nitrogen related traits of other crops

Stay-green in sorghum and nitrogen fixation in legumes involve links between the water and nitrogen economy of the crop that have been summarised recently (Sadras and Richards 2014). Stay-green in sorghum integrates a number of lower level traits and is mostly expressed where water stress during grain fill increases the rate of nitrogen remobilisation and leaf senescence; hence its expression strongly depends on how the trait interacts with other traits, and with environmental and management factors (Jordan et al. 2012). Five combinations of traits and environments would contribute to stay-green in sorghum (Borrell et al. 2003; Borrell et al. 2000; Jordan et al. 2012; Sinclair et al. 2005; van Oosterom et al. 2010; van Oosterom et al. 2011): (1) traits that contribute to water saving and less severe stress during grain fill such as early maturity, small leaves and few tillers, high stomatal sensitivity to drying soil and high vapour pressure deficit; (2) traits that contribute to enhanced water uptake, such as deep roots in the right combination of soil and rainfall; (3) life-history (i.e. high perenniality) or metabolic traits (e.g. higher carbon and nitrogen allocation to roots during grain filling), (4) traits that favour high source:sink ratio (e.g. few grains); (5) developmental traits that change the seasonal pattern of water use for the same maturity type. For plant breeding, strategies 1 and 2, and maybe 3 are of interest, but usually not 4 or 5 as these may involve trade-offs with harvest index and yield.

Selection for yield in the US has often favoured stay-green traits in maize (Duvick 2005). In a comparison of single-cross hybrids released between 1967 and 2006, the rate of yield

increase was 56 kg ha⁻¹ y⁻¹ in unfertilised crops, 79 kg ha⁻¹ y⁻¹ in crops fertilised with 67 kg N ha⁻¹, and 86 kg ha⁻¹ y⁻¹ in crops with 252 kg N ha⁻¹ (Haegerle et al. 2013). The relative increase in nitrogen uptake matched the relative increase in yield at the low fertiliser rate but not at the higher rate, and this was reflected in a reduction in protein content with year of release (Haegerle et al. 2013) in a process similar to that described before for wheat in Europe and Argentina. Modern hybrids require larger fertiliser rates to express their enhanced yield capacity and this is partially related to more subtle changes in the kinetics of nutrient uptake in response to selection for yield. Saccomani et al. (1984) evaluated the two kinetic parameters of sulphate uptake in maize seedlings spanning the period 1930-1975 and found $V_{\max}$ increased 1.37% y⁻¹ and K_m 3.24 % y⁻¹ in relation to the oldest varieties. Thus, the gain in uptake efficiency associated with higher $V_{\max}$ was counteracted by the loss of affinity of the transport system for sulphate, thus explaining why recent hybrids are handicapped respect to older ones at lower nutrient concentration. In common with wheat in Australia, selection for yield of maize in US did not change the seasonal water uptake, hence the yield-driven increase in yield per unit water use (Reyes et al. 2015).

In wheat, breeding for yield returned larger yield gains in more favourable environments indicating larger differences between old and new varieties in potential yield rather than stress adaptation (Figure 9). Limited evidence for sorghum in Australia indicates that breeding for yield might have increased adaptation to stress rather than potential yield (Figure 7D). In contrast to the local breeding effort in sorghum, Australia's maize hybrids derive mostly from lines developed in USA, where maize is usually grown in more favourable environments often at higher plant populations (Grassini et al. 2015). In Australia rainfed maize is sown at wide row spacing and low densities (2.5-3.5 plants m⁻²) where current hybrids produce fertile and infertile tillers, but do not develop a secondary cob in the main stem (Table 2). Unproductive tillering in the current combination of hybrids, environments and management (chiefly crop configuration and population density) is likely to compromise the efficiency in the use of water and nitrogen. A comparative analysis of sorghum and maize would help to understand the differences in plant phenotype in relation to the water and nitrogen economies of the crop and its responses to management.

Table 2. Cobs per plat of maize hybrids sown at 2.2 plants m⁻² on 1.5 rows at Gatton during the 2013/14 season. CRM is the comparative relative maturity and the hybrids are Australian commercial hybrids. Source: Rodriguez, Eyre, and McLean (unpublished).

Hybrid	CRM	Primary cob	Secondary cob	Tiller cobs	Total
624	117	1.0	0.0	0.0	1.0
607IT	118	1.0	0.1	0.8	1.9
1070	110	1.0	0.7	0.4	2.1
1467	114	1.0	0.4	1.1	2.5
727	123	1.0	0.14	1.6	2.74

A genotype-driven link between the maintenance of nitrogen fixation under stress and drought adaptation has been proposed for soybean (Sinclair 2011; Sinclair et al. 2007). Different screening approaches were combined, including coarser methods to screen large numbers of lines (selection for low ureide concentration in petioles, putatively reflecting sensitivity to drought) and more refined methods for fewer lines (acetylene reduction activity). Selected lines with enhanced maintenance of nitrogen fixation were compared with high-yielding commercial cultivars under broad environmental conditions. Two lines were identified that outperformed commercial checks under water deficit, but trade-offs were apparent under high yielding conditions. Line R01-416F out-yielded checks by 17% in environments returning less than 3 t ha⁻¹, whereas R01-581F out-yielded checks by 10% in a narrow environmental window between 2.5 and 3.6 t ha⁻¹. In a glasshouse experiment comparing the normalized acetylene reduction activity of 10 cowpea lines in response to soil drying, the fraction of transpirable soil water at which N fixation rate began to decline ranged from 0.33 in the most sensitive line to another line for which there was no decline in N fixation rate (Sinclair et al. 2015). Whereas the sensitivity to water deficit in legume nitrogen fixation is recognised, the intra-specific variation is significant and has putatively adaptive value. Similar studies are lacking for temperate legumes.

A modelling perspective

Diverse modelling approaches aim to match model complexity, error and applications (Passioura 1996); here we outline aspects of the water and nitrogen economy of crops from a modelling perspective with a primary focus on APSIM (Holzworth et al. 2014; Probert et al. 1998), and briefly discuss other modelling approaches where contrasts are needed.

The typical approach for modelling crop growth and yield is to simulate the potential growth first, followed by its reduction due to water and nitrogen limitations and other stresses (Wang et al. 2002). Net biomass growth or carbon assimilation at whole crop level is modelled using species-specific parameters (e.g. radiation use efficiency or maximum photosynthesis rate, extinction coefficient) together with canopy size (photosynthesising area), CO₂ concentration, radiation and temperature. Potential growth of individual organs (leaf, root, or grain) is mostly temperature driven and defines the demand for biomass or carbohydrates. It can be limited by the partition of available biomass or assimilates (supply), which is controlled by progression of phenological stages driven by temperature and photoperiod. Impact of diffuse radiation is not captured in APSIM; this can be achieved by modifying radiation use efficiency or using a canopy photosynthesis model that distinguish sunlit and shaded leaves (e.g. SUCROS).

Impact of water deficit on growth is simulated by comparing the water demand of the crop and the water supply from the root-soil system on a daily basis. Demand is the amount of water required to maintain potential growth and is determined by crop type, canopy size and weather. APSIM converts the potential biomass growth rate to water demand using the VPD-corrected transpiration efficiency. Other models estimate crop water demand using full or simplified energy balance equations (Penman 1948; Priestly and Taylor 1972) and the energy partition to crop canopy. Water supply is limited by the amount of plant available water in soil and further reduced by the size of root system. APSIM simulates water supply as a fraction of plant available water in the rooted soil layers, considering this fraction and the maximum rooting depth as both crop- and soil-dependent. Other models link water supply to root length density and plant available water. Soil water content at saturation, drained upper limit and crop lower limit control water movement in soil and availability to crops. If water supply cannot meet water demand, biomass growth rate is scaled down from potential by the supply/demand ratio. Impact on processes that are more/less sensitive to water stress (e.g. expansion growth/phenology) is simulated by using a higher/lower threshold of the supply/demand ratio. An alternative approach links water stress to the fraction of available soil water in soil.

Crop nitrogen relations are simulated using a similar supply-demand approach. In current APSIM maximum (N_{cx}), critical (N_{cc}) and minimum (N_{cm}) nitrogen concentrations are defined as species-specific attributes dependent on phenological stages. Crop nitrogen demand is the sum of the demand from the pre-existing biomass to reach critical nitrogen concentration plus the nitrogen required by the new growth to maintain N_{cc} . Nitrogen supply (root N uptake) is the total of N transported into roots via mass flow (passive uptake) and by diffusion (active uptake), with the former linked to transpiration and the latter affected by the fraction of available water in soil, both limited by available mineral nitrogen in rooted soil layers. Actual nitrogen uptake is the smaller one of demand and supply, and is partitioned to different organs proportional to their nitrogen demand. Re-translocation of nitrogen from leaf and stem to grain occurs during grain filling, which can lower the nitrogen concentration in leaves and stems to their minima (N_{cm}). Nitrogen stress is calculated as the relative difference between actual leaf N concentration (N_{ca}) and leaf N_{cc} as $f_N = a(N_{ca} - N_{cm}) / (N_{cc} - N_{cm})$. The f_N with coefficient $a=1.5$ is used to scale down the biomass growth rate, and $a=1.0$ is used for leaf expansion due to its higher sensitivity to nitrogen stress. Available mineral N in soil is updated daily by the soil nitrogen module that simulates soil N processes including N mineralisation, immobilisation, nitrification, denitrification, N movement in soil and N leaching (Probert et al. 1998).

An alternative framework for crop nitrogen dynamics has been implemented in APSIM for sorghum and maize (not yet released). It first calculates the structural stem nitrogen demand using minimum stem nitrogen concentration, then the demand of expanding leaves using a critical specific leaf nitrogen (SLN_c). Any additional nitrogen uptake is allocated to leaves to meet their target SLN (SLN_x) and then to stem. Grain nitrogen demand is simulated using grain number and nitrogen demand per grain. Nitrogen demand per grain is constant during the first part of grain filling due to the accumulation of structural proteins, and is related to grain growth rate during the second half of grain filling. Grain nitrogen demand is met through translocation from stem (plus rachis), and then from leaves; if still insufficient then by senescing leaves. Grain protein content is simulated as consequence of nitrogen supply–demand balance and the carbohydrate supply to the grain. In this approach, all parameters (stem N_{cm} , SLN_c , SLN_x) are genotype specific and independent of stages. It enables a direct link between the rate parameter in the model and genetic controls associated with N translocation processes.

APSIM captures several aspects of the interactions between water and nitrogen. Water and nitrogen are primarily linked by applying the minimum of the water and nitrogen stress to reduce the rate of different processes (tissue expansion, biomass growth). Further, in crops where water limits growth, reduced biomass would reduce nitrogen demand. Reciprocally,

nitrogen limitation during crop expansion would reduce leaf area index and evaporative demand. The modulation of canopy size by nitrogen also impacts on the partitioning of water use between transpiration and soil evaporation. Water and nitrogen interactions are also captured in the water-driven uptake of nitrogen by mass flow and diffusion and in the water-driven fate of nitrogen in soil (e.g. leaching, mineralisation).

The next generation APSIM model (Holzworth et al. 2014) involves updating crop modules using the new Plant Modelling Framework (Brown et al. 2014) that enables the definition of structural, metabolic and non-structural pools for both carbohydrate and nitrogen in the plant organs and flexible implementation and test of alternative approaches for modelling carbon and nitrogen dynamics in plants, such as the impact of increased shoot water soluble carbohydrates and dynamic partitioning of carbon and nitrogen between yield components and reserves. It is expected that the updated model will enhance the predictability of plant phenotype based on its genotype, especially for complex adaptive traits, thus accelerate the progress in molecular plant breeding.

To better support research into impact of water by nitrogen interactions on crop yield and in-season nitrogen management, future work needs to focus on improved simulation of nitrogen mineralisation from different soils and crop residues across climatic regions. Better understanding of genotype-dependent root nitrogen uptake is also needed. These will enable more accurate modelling of nitrogen supply to crops and crop response to applied nitrogen fertiliser. Better capturing the impact of VPD and water stress on canopy temperature and other processes is needed to simulate crop response under drier and hotter environments.

Conclusions: further research

From the previous discussion, the following lines of research are suggested.

1. Yield-soil nitrogen relations are highly scattered because other factors such as water constrain crop responses to nutrients. Plant-based diagnostic tools accounting for nitrogen-biomass allometry remove some of this noise. Thus, we propose to develop nitrogen dilution curves for major crops accounting for by the effects of water deficit, and explicitly including a compartment of water soluble carbohydrates. These dilution curves will allow for unequivocal assessment of the nitrogen status of crops, which are in turn necessary for

calibration of tools for both diagnostic purposes in crop management, and high-throughput methods in breeding.

2. Fertiliser recommendations are generic, but there is an increasing interest in variety-specific differences in response to nitrogen. Thus, we propose to (a) assess the nitrogen demand and responsiveness to fertiliser, in terms of yield and protein, of new wheat and barley varieties and (b) explore the benefits of tailoring fertiliser management to specific varieties.
3. The French & Schultz model has been instrumental in crop management for rainfed systems in Australia. By analogy to the yield-evapotranspiration relationship, we propose to investigate the nitrogen uptake vs evapotranspiration relationship; the nitrogen:water ratio required to close the yield gap, at a certain grain protein, has potential applications in crop management.
4. Growers are familiar with the concept of bucket size for water, but there is no equivalent for nitrogen. We thus propose to develop the concept of plant available nitrogen and field methods to measure it. Practical aspects of soil sampling need some attention, e.g. transport from the farm to the lab, timeliness of lab results to support decisions.
5. There is large variation in the impact of nitrogen supply on water uptake, thus the need to establish the combination of crops, soils and growing conditions where additional nitrogen can contribute further soil water uptake. This is more likely to be relevant in the northern region, where stored soil water is important.
6. Some components of cropping systems (pasture, green manure) contribute nitrogen but may reduce water available to subsequent crops. We therefore need to quantify the trade-offs between nitrogen supply and water consumption by pastures and green manures in different combinations of soil, climate and rotations in both winter- and summer-rainfall regions.
7. Risk analysis of fertiliser decisions generally assumes that all the benefit of nitrogen application is constrained to a single season. Given emerging experimental evidence, we need to (a) determine the size of the carry over effect for different combinations of crop, soil, climate and management and (b) update risk analysis to account for carry-over of nitrogen beyond the application season.
8. Comparison of old and new varieties has been useful in identifying the increasing demand of nitrogen in new wheat varieties. Following on this work, it is of interest to: (a) determine the physiological and genetic basis of

nitrogen uptake in old and new wheat varieties with proven difference in nitrogen uptake in winter-rainfall field conditions and (b) compare water and nitrogen related traits in historic sets of wheat varieties agronomically adapted to grow on stored soil water, e.g. the summer-rainfall environments of northern Australia. The environments were rainfall transitions from summer- to winter-dominant can also be of interest.

9. Superior soybean lines have been selected for maintenance of nitrogen fixation under drought. Research in temperate legumes lags behind soybean and other subtropical species. Hence, there is a need to screen temperate pulses for nitrogen fixation in soil dry-down experiments, and establish the adaptive value (in terms of yield) of this trait.
10. Sorghum is the more important summer cereal in Australia and is supported by local breeding whereas growers rely on putatively less adapted maize hybrids developed overseas. We propose (a) to compare sorghum and maize to understand the differences in phenotypes (e.g. tillering, stomatal sensitivity, response to sowing density) between breeding programs in USA (maize) and Australia (sorghum) and (b) to determine the profitability and risk of different G x E x M combinations for sorghum and maize (hybrids, plant density, row configuration, sowing time, soil type and nitrogen fertilisation).
11. Modelling studies are a cost-effective approach to generate agronomically interesting information across regions and climates. We propose to model and map the nation-wide, probabilistic patterns of supply and demand of water and nitrogen for major crops as background for agronomic, e.g. timing of fertilisation, and breeding studies, e.g. root patterns. Associated with this proposition, there are species-specific gaps as well as gaps related to basic physiology and modelling. Nation-wide patterns of water stress have been produced for wheat, maize, sorghum, field pea and chickpea; remaining crops to be modelled are canola, lentil, lupin and faba bean. Associated with these, the quantification of the critical period of canola, lentil and faba bean need attention. The patterns of demand and supply for nitrogen need to be developed for all crops. To support this, we need improved models of nitrogen mineralisation accounting from variation in soil and crop residues, and better understanding of genotype-dependent root nitrogen uptake.
12. To test and capture the value of soil information (initial water and nitrogen) and POAMA forecasts, we would need to (i) establish a network of real farm case studies representing the North, South and West regions, (ii) compile and integrate soil, genotype, climate and management information, (iii) engage

with growers to discuss these strategies in relation to relevant and actionable decisions, (iv) use APSIM to test the value of initial soil conditions and POAMA, (v) compare APSIM results with long-term (> 5 years) real-farm outcomes, (vi) formalise location-specific recommendations on the relative value of different sources of information.

References

- Abadi A, Farre I (2015) A simple framework for profitable fertiliser use under risk and soil constraints Building Productive, Diverse and Sustainable Landscapes. Proceedings of the 17th ASA Conference www.agronomy2015.com.au, Hobart, Australia
- ABARE (2010a) Farm costs and returns, farm sector. Australian Bureau of Agricultural and Resource Economics, <http://www.abare.gov.au/> [25/11/2011]
- ABARE (2010b) Land use of Australia version 4, 2005-2006. Australian Bureau Agricultural and Resources Economics and Bureau of Resource Sciences, Canberra
- Aisawi KAB, Reynolds MP, Singh RP, Foulkes MJ (2015) The physiological basis of the genetic progress in yield potential of CIMMYT spring wheat cultivars from 1966 to 2009. *Crop Science* 55:1749-1764
- Albarenque SM (2015) Variabilidad espacial de la co-limitación de agua y nitrógeno, efecto sobre la eficiencia de uso de agua y nitrógeno en maíz. M Sc Thesis, Universidad de Buenos Aires
- Albrizio R, Todorovic M, Matic T, Stellacci AM (2010) Comparing the interactive effects of water and nitrogen on durum wheat and barley grown in a Mediterranean environment. *Field Crops Research* 115:179-190
- Anderson GC, Fillery IRP, Dunin FX, Dolling PJ, Asseng S (1998) Nitrogen and water flows under pasture-wheat and lupin-wheat rotations in deep sands in Western Australia 2. Drainage and nitrate leaching. *Australian Journal of Agricultural Research* 49:345-362
- Anderson JR (1975) One more or less cheer for optimality. *Journal of Australian Institute of Agricultural Science* 41:195-197
- Angus J (2001) Nitrogen supply and demand in Australian agriculture. *Australian Journal of Experimental Agriculture* 41:277-288
- Angus JF (1998) Nitrogen fertiliser for wheat - assessing price and weather risks. *Australian Grain* July-August:30-31
- Angus JF, Kirkegaard JA, Hunt JR, Ryan MH, Ohlander L, Peoples MB (2015) Break crops and rotations for wheat. *Crop and Pasture Science* 66:523-552
- Angus JF, Peoples MB (2012) Nitrogen from Australian dryland pastures. *Crop and Pasture Science* 63:746-758
- Angus JF, van Herwaarden AF (2001) Increasing water use and water use efficiency in dryland wheat. *Agron. J.* 93:290-298
- Ash A, McIntosh PC, Cullen B, Carberry P, Stafford Smith M (2007) Constraints and opportunities in applying seasonal climate forecasts in agriculture. *Crop and Pasture Science* 58:952-965
- Asseng S, Dunin FX, Fillery IRP, Tennant D, Keating BA (2001a) Potential deep drainage under wheat crops in a Mediterranean climate. II. Management opportunities to control drainage. *Australian Journal of Agricultural Research* 52:57-66
- Asseng S, Foster I, Turner NC (2011) The impact of temperature variability on wheat yields. *Global Change Biology* 17:997-1012
- Asseng S, McIntosh PC, Wang G, Khimashia N (2012) Optimal N fertiliser management based on a seasonal forecast. *European Journal of Agronomy* 38:66-73
- Asseng S, Turner NC, Keating BA (2001b) Analysis of water- and nitrogen-use efficiency of wheat in a Mediterranean climate. *Plant and Soil* 233:127-143
- Asseng S, Zhu Y, Wang E, Zhang W (2015) Crop modelling for climate change impact and application. In: Sadras VO, Calderini DF (eds) *Crop physiology: applications for genetic improvement and agronomy*, Second Edition edn. Academic Press, San Diego, pp 505-546
- Austin RB, Bingham J, Blackwell RD, Evans LT, Ford MA, Morgan CL, Taylor M (1980) Genetic improvements in winter wheat yields since 1900 and associated changes. *Journal of Agricultural Science* 94:675-689

- Badr MA, El-Tohamy WA, Zaghloul AM (2012) Yield and water use efficiency of potato grown under different irrigation and nitrogen levels in an arid region. *Agricultural Water Management* 110:9-15
- Bandyopadhyay K, Misra A, Ghosh P, Hati K, Mandal K, Moahnty M (2010) Effect of irrigation and nitrogen application methods on input use efficiency of wheat under limited water supply in a Vertisol of Central India. *Irrigation Science* 28:285-299
- Barlow KM, Christy BP, O'Leary GJ, Riffkin PA, Nuttall JG (2015) Simulating the impact of extreme heat and frost events on wheat crop production: A review. *Field Crops Research* 171:109-119
- Barnard C, JS N (1976) *Basic Principles and Concepts In Farm Planning and Control*. Cambridge University Press.
- Barraclough PB, Howarth JR, Jones J, Lopez-Bellido R, Parmar S, Shepherd CE, Hawkesford MJ (2010) Nitrogen efficiency of wheat: Genotypic and environmental variation and prospects for improvement. *European Journal of Agronomy* 33:1-11
- Beche E, Benin G, da Silva CL, Munaro LB, Marchese JA (2014) Genetic gain in yield and changes associated with physiological traits in Brazilian wheat during the 20th century. *European Journal of Agronomy* 61:49-59
- Belanger G, Walsh JR, Richards JE, Milburn PH, Ziadi N (2001) Critical nitrogen curve and nitrogen nutrition index for potato in eastern Canada. *American Journal of Potato Research* 78:355-364
- Belder P, Bouman BAM, Spiertz JHJ, Peng S, Castañeda AR, Visperas RM (2005) Crop performance, nitrogen and water use in flooded and aerobic rice. *Plant and Soil* 273:167-182
- Bell MJ, Strong W, Elliott D, Walker C (2013) Soil nitrogen—crop response calibration relationships and criteria for winter cereal crops grown in Australia. *Crop and Pasture Science* 64:442-460
- Bermudez R, Retuerto R (2014) Together but different: co-occurring dune plant species differ in their water- and nitrogen-use strategies. *Oecologia* 174:651-663
- Betti G, Grant C, Churchman G, Murray R (2015) Increased profile wettability in texture-contrast soils from clay delving: case studies in South Australia. *Soil Research* 53:125-136
- Bloom AJ, Burger M, Kimball BA, Pinter Jr PJ (2014) Nitrate assimilation is inhibited by elevated CO₂ in field-grown wheat. *Nature Climate Change* 4:477-480
- Bloom AJ, Chapin FSI, Mooney HA (1985) Resource limitation in plants - an economic analogy. *Annual Review of Ecology and Systematics* 16:363-392
- Bonser SP, Aarsen LW (1996) Meristem allocation: a new classification theory for adaptive strategies in herbaceous plants. *Oikos* 77:347-352
- Bonser SP, Aarssen LW (2001) Allometry and Plasticity of Meristem Allocation throughout Development in *Arabidopsis thaliana*. *The Journal of Ecology* 89:72-79
- Borrell A, Oosterom Ev, Hammer G, Jordan D, Douglas A (2003) The physiology of "stay-green" in sorghum. In: Unkovich M, O'Leary G (eds) *Solutions for a better environment: Proceedings of the 11th Australian Agronomy Conference*, 2-6 February 2003, Geelong, Victoria, Australia, pp 0-3
- Borrell AK, Hammer GL, Douglas ACL (2000) Does maintaining green leaf area in sorghum improve yield under drought? I. Leaf growth and senescence. *Crop Science* 40:1026-1037
- Brancourt-Hulmel M, Doussinault G, Lecomte C, Berard P, Le Buanec B, Trottet M (2003) Genetic improvement of agronomic traits of winter wheat cultivars released in France from 1946 to 1992. *Crop Science* 43:37-45
- Brown HE, Huth NI, Holzworth DP, Teixeira EI, Zyskowski RF, Hargreaves JNG, Moot DJ (2014) Plant Modelling Framework: Software for building and running crop models on the APSIM platform. *Environmental Modelling & Software* 62:385-398
- Brown PL (1971) Water use and soil water depletion by dryland winter wheat as affected by nitrogen fertilization. *Agron. J.* 63:43-46

- Browne C, Walters L (2015) Nitrogen management: do barley varieties respond differently to nitrogen? Proceedings of the 17th ASA Conference, 20 – 24 September 2015, Hobart, Australia. www.agronomy2015.com.au
- Brueck H (2008) Effects of nitrogen supply on water-use efficiency of higher plants. *Journal of Plant Nutrition and Soil Science* 171:210-219
- Cade BS, Noon BR (2003) A gentle introduction to quantile regression for ecologists. *Frontiers in Ecology and the Environment* 1:412-420
- Cantagallo JE, Chimenti CA, Hall AJ (1997) Number of seeds per unit area in sunflower correlates well with a photothermal quotient. *Crop Sci* 37:1780-1786
- Cao H-X, Zhang Z-B, Xu P, Chu L-Y, Shao H-B, Lu Z-H, Liu J-H (2007) Mutual physiological genetic mechanism of plant high water use efficiency and nutrition use efficiency. *Colloids and Surfaces B-Biointerfaces* 57:1-7
- Caviglia OP, Sadras VO (2001) Effect of nitrogen supply on crop conductance, water- and radiation-use efficiency of wheat. *Field Crops Research* 69:259-266
- Chapman SC, Cooper M, Butler DG, Henzell RG (2000a) Genotype by environment interactions affecting grain sorghum. I. Characteristics that confound interpretation of hybrid yield. *Australian Journal of Agricultural Research* 51:197-207
- Chapman SC, Hammer GL, Butler DG, Cooper M (2000b) Genotype by environment interactions affecting grain sorghum. III. Temporal sequences and spatial patterns in the target population of environments. *Australian Journal of Agricultural Research* 51:223-233
- 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 (2015) Characterising the crop environment - nature, significance and applications. In: Sadras VO, Calderini DF (eds) *Crop physiology: applications for genetic improvement and agronomy*, Second Edition edn. Academic Press, San Diego, pp 321-348
- Chenu K, Dehifard 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
- Christianson LE, Harmel RD (2015) The MANAGE Drain Load database: Review and compilation of more than fifty years of North American drainage nutrient studies. *Agricultural Water Management* 159:277-289
- Connor DJ (2004) Designing cropping systems for efficient use of limited water in southern Australia. *European Journal of Agronomy* 21:419-431
- Connor DJ, Loomis RS, Cassman KG (2011) *Crop ecology: productivity and management in agricultural systems*. Cambridge University Press Cambridge
- Conyers MK, Bell MJ, Wilhelm NS, Bell R, Norton RM, Walker C (2013) Making Better Fertiliser Decisions for Cropping Systems in Australia (BFDC): knowledge gaps and lessons learnt. *Crop and Pasture Science* 64:539-547
- Cooper PJM, Gregory PJ, Tully D, Harris HC (1987) Improving water use efficiency of annual crops in rainfed systems of west Asia and North Africa. *Experimental Agriculture* 23:113-158
- Cossani CM, Savin R, Slafer GA (2010) Co-limitation of nitrogen and water on yield and resource-use efficiencies of wheat and barley. *Crop and Pasture Science* 61:844-851
- Cossani CM, Slafer GA, Savin R (2011) Do barley and wheat (bread and durum) differ in grain weight stability through seasons and water-nitrogen treatments in a Mediterranean location? *Field Crops Research* 121:240-247
- Cox TS, Shogren MD, Sears RG, Martin TJ, Bolte LC (1989) Genetic-improvement in milling and baking quality of hard red winter-wheat cultivars, 1919 to 1988. *Crop Science* 29:626-631
- Crean J, Parton K, Mullen J, Hayman P (2014) Valuing seasonal climate forecasts in a state-contingent manner. *Australian Journal of Agricultural and Resource Economics*:n/a-n/a

- Crimp S, Bakar KS, Kokic P, Jin H, Nicholls N, Howden M (2014) Bayesian space–time model to analyse frost risk for agriculture in Southeast Australia. *International Journal of Climatology*:n/a-n/a
- Dalal R, Wang W, Robertson G, Parton W (2003) Nitrous oxide emission from Australian agricultural lands and mitigation options: a review. *Australian Journal of Soil Research* 41:165-195
- Dalal RC, Strong WM, Weston EJ, Cooper JE, Thomas GA (1997) Prediction of grain protein in wheat and barley in a subtropical environment from available water and nitrogen in Vertisols at sowing
- Australian Journal of Experimental Agriculture* 37:351 - 357
- Debaeke P, van Oosterom EJ, Justes E, Champolivier L, Merrien A, Aguirrezabal LAN, Gonzalez-Dugo V, Massignam AM, Montemurro F (2012) A species-specific critical nitrogen dilution curve for sunflower (*Helianthus annuus* L.). *Field Crops Research* 136:76-84
- Delworth TL, Zeng F (2014) Regional rainfall decline in Australia attributed to anthropogenic greenhouse gases and ozone levels. *Nature Geosci* 7:583-587
- Didonet AD, Rodrigues O, Mario JL, Ide F (2002) Effect of solar radiation and temperature on grain number definition in maize. *Pesquisa Agropecuaria Brasileira* 37:933-938
- Dijkstra F, Augustine D, Brewer P, von Fischer J (2012) Nitrogen cycling and water pulses in semiarid grasslands: are microbial and plant processes temporally asynchronous? *Oecologia*:1-10
- Divito GA, Echeverría HE, Andrade FH, Sadras VO (2015) Soybean shows an attenuated nitrogen dilution curve irrespective of maturity group and sowing date. *Field Crops Research* in press:
- Doherty D, Rodriguez D, Potgieter A, Sadras VO (2008) A national benchmark for the Australian wheat industry: accounting for overlooked climate drivers. In: Unkovich MJ (ed) *Australian Society of Agronomy Conference*, Adelaide, p 95
- 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
- Donmez E, Sears RG, Shroyer JP, Paulsen GM (2001) Genetic Gain in Yield Attributes of Winter Wheat in the Great Plains. *Crop Science* 41:1412-1419
- Dracup M, Belford RK, Gregory PJ (1992) Constraints to root growth of wheat and lupin crops in duplex soils. *Australian Journal of Experimental Agriculture* 32:947-961
- Dreccer F, Chapman SC, Rattey A, Neal J, Song Y, Christopher JT, Reynolds M (2013) Developmental and growth controls of tillering and water-soluble carbohydrate accumulation in contrasting wheat (*Triticum aestivum* L.) genotypes: can we dissect them? *Journal of Experimental Botany*
- Dreccer MF, Barnes LR, Meder R (2014) Quantitative dynamics of stem water soluble carbohydrates in wheat can be monitored in the field using hyperspectral reflectance. *Field Crops Research* 159:70-80
- Dreccer MF, van Herwaarden AF, Chapman SC (2009) Grain number and grain weight in wheat lines contrasting for stem water soluble carbohydrate concentration. *Field Crops Research* 112:43-54
- Duncan DH, Dorrough JW (2009) Historical and current land use shape landscape restoration options in the Australian wheat and sheep farming zone. *Landscape and Urban Planning* 91:124-132
- Durand J-L, Gonzalez-Dugo V, Gastal F (2010) How much do water deficits alter the nitrogen nutrition status of forage crops? *Nutrient Cycling in Agroecosystems* 88:231-243
- Duvick DN (2005) The contribution of breeding to yield advances in maize (*Zea mays* L.). In: Sparks DL (ed) *Advances in Agronomy*, vol 86, pp 83-145
- Easterling WE (1999) Preface. In *Making climate forecasts matter*, ix-xii. National Academy Press, Washington, D.C. In: Easterling WE (ed) *Making climate forecasts matter*. . National Academy Press, Washington, D.C., pp ix-xii

- Egli DB (2015) Is there a role for sink size in understanding maize population - yield relationships? *Crop Science*
- Errecart PM, Agnusdei MG, Lattanzi FA, Marino MA, Berone GD (2014) Critical nitrogen concentration declines with soil water availability in tall fescue. *Crop Science* 54:318-330
- Evans JR (2013) Improving Photosynthesis. *Plant Physiology* 162:1780-1793
- Evans LT, Fischer RA (1999) Yield potential: its definition, measurement and significance. *Crop Science* 39:1544-1551
- Faraji A (2014) Seed number in canola (*Brassica napus* L.): Effects of dry matter, crop growth rate, temperature, and photothermal quotient around flowering. *International Research Journal of Applied and Basic Sciences* 8:2168-2175
- Fischer RA (1985) Number of kernels in wheat crops and the influence of solar radiation and temperature. *J. Agric. Sci.* 105:447-461
- Fischer RA (2009) Farming systems of Australia: exploiting the synergy between genetic improvement and agronomy In: Sadras VO, Calderini DF (eds) *Crop physiology: applications for genetic improvement and agronomy*. Academic Press, San Diego, pp 23-54
- Fischer RA (2011) Wheat physiology: a review of recent developments. *Crop & Pasture Science* 62:95–114
- Fischer RA (2015) Definitions and determination of crop yield, yield gaps, and of rates of change. *Field Crops Research* 182:9-18
- Fischer RA, Byerlee D, Edmeades GO (2014) Crop yields and global food security. Will yield increase continue to feed the world? ACIAR, Canberra
- Fitzgerald G, Norton R, Tausz M, O'Leary G, Seneweera S, Posch S, Mollah M, Brand J, Armstrong R, Mathers N (2010) Future effects of elevated CO₂ on wheat production—an overview of FACE research in Victoria, Australia Food Security from Sustainable Agriculture. 15th Agronomy Conference, 15-18 November 2010, Lincoln, New Zealand. Australian Society of Agronomy, Gosford, NSW
- Fletcher AL, Robertson MJ, Abrecht DG, Sharma DL, Holzworth DP (2015) Dry sowing increases farm level wheat yields but not production risks in a Mediterranean environment. *Agricultural Systems* 136:114-124
- Francia E, Tondelli A, Rizza F, Badeck FW, Li Destri Nicosia O, Akar T, Grando S, Al-Yassin A, Benbelkacem A, Thomas WTB, van Eeuwijk F, Romagosa I, Stanca AM, Pecchioni N (2011) Determinants of barley grain yield in a wide range of Mediterranean environments. *Field Crops Research* 120:169-178
- Frederiks T, Christopher J, Sutherland M, Borrell A (2015) Post-head-emergence frost in wheat and barley: defining the problem, assessing the damage, and identifying resistance. *Journal of experimental botany* 66:3487–3498
- French RJ (1993) Changes in cropping systems at the boundaries of the pastoral and cropping zones in southern Australia. *Rangeland Journal* 15:117-132
- 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. *Aust. J. Agric. Res.* 35:765-775
- Gajri PR, Prihar SS, Arora VK (1993) Interdependence of nitrogen and irrigation effects on growth and input-use efficiencies in wheat. *Field Crops Research* 31:71-86
- Galloway JN, Townsend AR, Erisman JW, Bekunda M, Cai Z, Frenay JR, Martinelli LA, Seitzinger SP, Sutton MA (2008) Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science* 320:889-892
- Garnett ER, Khandekar ML (1992) The impact of large-scale atmospheric circulations and anomalies on Indian monsoon droughts and floods and on world grain yields—a statistical analysis. *Agricultural and Forest meteorology* 61:113-128
- Gastal F, Lemaire G, Durand JL, Louarn G (2015) Quantifying crop responses to nitrogen and avenues to improve nitrogen-use efficiency. In: Sadras VO, Calderini DF (eds)

- Crop Physiology: Applications for genetic improvement and agronomy. Academic Press, San Diego, pp 161-206
- Giunta F, Motzo R, Pruneddu G (2007) Trends since 1900 in the yield potential of Italian-bred durum wheat cultivars. *European Journal of Agronomy* 27:12-24
- Gonzalez-Dugo V, Durand J-L, Gastal F (2010) Water deficit and nitrogen nutrition of crops. A review. *Agronomy for Sustainable Development* 30:529-544
- Gonzalez-Dugo V, Durand J-L, Gastal F (2011) Water Deficit and Nitrogen Nutrition of Crops. *Sustainable Agriculture* 2:557-575
- Gonzalez-Dugo V, Durand JL, Gastal F, Bariac T, Poincheval J, Bardou G, Biron P, Cousson L, Eprinchard A, Millet G, Richard P, Terrasson JP (2012) Restricted root-to-shoot translocation and decreased sink size are responsible for limited nitrogen uptake in three grass species under water deficit. *Environmental and Experimental Botany* 75:258-267
- Gonzalez-Dugo V, Durand JL, Gastal F, Picon-Cochard C (2005) Short-term response of the nitrogen nutrition status of tall fescue and Italian ryegrass swards under water deficit. *Australian Journal of Agricultural Research* 56:1269-1276
- Grassini P, Hall AJ, Mercau JL (2009) Benchmarking sunflower water productivity in semiarid environments. *Field Crops Research* 110:251-262
- Grassini P, Specht JE, Tollenaar M, Ciampitti IA, Cassman KG (2015) High-yield maize-soybean cropping systems in the US Corn Belt. In: Sadras VO, Calderini DF (eds) *Crop Physiology: Applications for genetic improvement and agronomy*. Academic Press, San Diego, pp 17-41
- Grassini P, Thorburn J, Burr C, Cassman KG (2010) High-yield irrigated maize systems in Western U.S. Corn-Belt. II. Irrigation management and crop water productivity. *Field Crops Research* in press
- GRDC (2014) Production Economics - Fact Sheet.
- Guarda G, Padovan S, Delogu G (2004) Grain yield, nitrogen-use efficiency and baking quality of old and modern Italian bread-wheat cultivars grown at different nitrogen levels. *European Journal of Agronomy* 21:181-192
- Haegele JW, Cook KA, Nichols DM, Below FE (2013) Changes in Nitrogen Use Traits Associated with Genetic Improvement for Grain Yield of Maize Hybrids Released in Different Decades. *Crop Sci.* 53:1256-1268
- Hammer G (2000) A general systems approach to applying seasonal climate forecasts. *Applications of seasonal climate forecasting in agricultural and natural ecosystems: the Australian experience* (ed. GL Hammer, N. Nicholls & C. Mitchell):51-66
- Hammer G, Holzworth D, Stone R (1996) The value of skill in seasonal climate forecasting to wheat crop management in a region with high climatic variability. *Crop and Pasture Science* 47:717-737
- Hammer GL, McLean G, Chapman S, Zheng B, Doherty A, Harrison MT, van Oosterom E, Jordan D (2014) Crop design for specific adaptation in variable dryland production environments. *Crop & Pasture Science* 65:614-626
- Hansen JW (2002) Realizing the potential benefits of of climate prediction to agriculture: issues, approaches, challenges. *Agricultural Systems* 74:309-330
- Hardaker BJ, Huirne RBM, Anderson JR, Lien G (2004) *Coping with Risk in Agriculture*. CABI Publishing, Oxford.

Second ed.

- Hayman P, Cooper B, Parton KA, Alves O, Young G, BH H, Scheer C (2015) Can advances in climate forecasts improve the productive and environmental outcomes from nitrogen fertiliser on wheat? A case study using POAMA for topdressing wheat in South Australia. 17th Australian Agronomy Conference, Hobart
- Hayman P, Crean J, Mullen J, Parton K (2007) How do probabilistic seasonal climate forecasts compare with other innovations that Australian farmers are encouraged to adopt? *Australian Journal of Agricultural Research* 58:975-984

- Hayman PT, Whitbread AM, Gobbett DL (2010) The impact of El Niño Southern Oscillation on seasonal drought in the southern Australian grainbelt. *Crop and Pasture Science* 61:677-677
- Heady EO, Dillon JL (1961) Agricultural production functions.
- Hernández M, Echarte L, Della Maggiora A, Cambareri M, Barbieri P, Cerrudo D (2015) Maize water use efficiency and evapotranspiration response to N supply under contrasting soil water availability. *Field Crops Research* 178:8-15
- Herridge D (2013) Managing legume and fertiliser N for northern grains cropping. Grains Research and Development Corporation, Canberra
- Hertzler G (2007) Adapting to climate change and managing climate risks by using real options. *Crop and Pasture Science* 58:985-992
- Hochman Z, Carberry PS (2011) Emerging consensus on desirable characteristics of tools to support farmers' management of climate risk in Australia. *Agricultural Systems* 104:441-450
- Hochman Z, Carberry PS, Robertson MJ, Gaydon DS, Bell LW, McIntosh PC (2013) Prospects for ecological intensification of Australian agriculture. *European Journal of Agronomy* 44:109-123
- Hochman Z, D P, Carberry PS (2014) Crop sequences in Australia's northern grains zone are less agronomically efficient than implied by the sum of their parts. *Agricultural Systems* 129:124-132
- Hochman Z, Gobbett D, Holzworth D, McClelland T, van Rees H, Marinoni O, Garcia JN, Horan H (2012) Quantifying yield gaps in rainfed cropping systems: A case study of wheat in Australia. *Field Crops Research* 136:85-96
- Hochman Z, Holzworth D, Hunt JR (2009a) Potential to improve on-farm wheat yield and WUE in Australia. *Crop & Pasture Science* 60:708-716
- Hochman Z, van Rees H, Carberry PS, Hunt JR, McCown RL, Gartmann A, Holzworth D, van Rees S, Dalgliesh NP, Long W, Peake AS, Poulton PL, McClelland T (2009b) Re-inventing model-based decision support with Australian dryland farmers. 4. Yield Prophet (R) helps farmers monitor and manage crops in a variable climate. *Crop & Pasture Science* 60:1057-1070
- Holzworth DP, Huth NI, deVoil PG, Zurcher EJ, Herrmann NI, McLean G, Chenu K, van Oosterom EJ, Snow V, Murphy C, Moore AD, Brown H, Whish JPM, Verrall S, Fainges J, Bell LW, Peake AS, Poulton PL, Hochman Z, Thorburn PJ, Gaydon DS, Dalgliesh NP, Rodriguez D, Cox H, Chapman S, Doherty A, Teixeira E, Sharp J, Cichota R, Vogeler I, Li FY, Wang E, Hammer GL, Robertson MJ, Dimes JP, Whitbread AM, Hunt J, van Rees H, McClelland T, Carberry PS, Hargreaves JNG, MacLeod N, McDonald C, Harsdorf J, Wedgwood S, Keating BA (2014) APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software* 62:327–350
- Howden M, Schroeter S, Crimp S, Hanigan I (2014) The changing roles of science in managing Australian droughts: An agricultural perspective. *Weather and Climate Extremes* 3:80-89
- Howden SM, Gifford RG, Meinke H (2010) Grains. In: Stokes CJ, Howden SM (eds) *Adapting Agriculture to Climate Change. Preparing Australian agriculture, forestry and fisheries for the future*. CSIRO, Melbourne, pp 21-40
- Huang ML, Deng XP, Zhao YZ, Zhou SL, Inanaga S, Yamada S, Tanaka K (2007) Water and nutrient use efficiency in diploid tetraploid and hexaploid wheats. *Journal of Integrative Plant Biology* 49:706-715
- Hunt JR, Browne C, McBeath TM, Verburg K, Craig S, Whitbread AM (2013) Summer fallow weed control and residue management impacts on winter crop yield though soil water and N accumulation in a winter-dominant, low rainfall region of southern Australia. *Crop and Pasture Science* 64:922-934
- Islam MS, Morison JIL (1992) Influence of solar radiation and temperature on irrigated rice grain yield in Bangladesh. *Field Crops Research* 30:13-28
- Jensen NF (1978) Limits to growth in world food-production. *Science* 201:317-320

- Jobbágy EG, Sala OE (2014) The imprint of crop choice on global nutrient needs. *Environ. Res. Lett.* in press
- Jordan DR, Hunt CH, Cruickshank AW, Borrell AK, Henzell RG (2012) The relationship between the stay-green trait and grain yield in elite sorghum hybrids grown in a range of environments. *Crop Science* 52:1153-1161
- Karam F, Kabalan R, Breidi J, Rouphael Y, Oweis T (2009) Yield and water-production functions of two durum wheat cultivars grown under different irrigation and nitrogen regimes. *Agricultural Water Management* 96:603-615
- Karoly DJ (2014) Climate change: Human-induced rainfall changes. *Nature Geoscience* 7:551-552
- Kim HK, Luquet D, van Oosterom E, Dingkuhn M, Hammer G (2010) Regulation of tillering in sorghum: genotypic effects. *Annals of Botany* 106:69-78
- Kim KI, Clay DE, Carlson CG, Clay SA, Trooien T (2008) Do synergistic relationships between nitrogen and water influence the ability of corn to use nitrogen derived from fertilizer and soil? *Agronomy Journal* 100:551-556
- Kimura S, C LT (2011) Farm level analysis of risk and risk management strategies and policies Technical Note OECD Food, Agriculture and Fisheries. Working Paper No. 48. OECD Publishing. <http://dx.doi.org/10.1787/5kg6z83f0s34-en>
- Kindred D, Smith T, Sylvester-Bradley R, Ginsberg D, Dyer C (2007) Optimising nitrogen applications for wheat grown for the biofuels market. HGCA project
- Kingwell RS (2000) Price risk management for Australian broadacre farmers. *Australian Agribusiness Review* 8
- Kingwell RS (2011) Revenue volatility faced by Australian wheat farmers. 55th Annual Conference of the Australian Agricultural and Resource Economics Society. Melbourne Convention Centre, Melbourne
- Kirkegaard J, Lilley J, Howe G, Graham N (2007) Impact of subsoil water use on wheat yield. *Australian Journal of Agricultural Research* 58:303-315
- Kirkegaard JA, Hunt JR (2011) 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, Lilley JM, Moore A, Verburg K, Robertson M, Oliver Y, Ward PR, Milroy S, Whitbread AM (2014) Improving water productivity in the Australian Grains industry—a nationally coordinated approach. *Crop and Pasture Science* 65:583-601
- Kirkegaard JA, Ryan MH (2014) Magnitude and mechanisms of persistent crop sequence effects on wheat. *Field Crops Research* 164:154-165
- Kumar SR, Hammer GL, Broad I, Harland P, McLean G (2009) Modelling environmental effects on phenology and canopy development of diverse sorghum genotypes. *Field Crops Research* 111:157-165
- Lake L, Chenu K, Sadras VO (2015) Patterns of water stress and temperature for Australian chickpea production. *Crop and Pasture Science*
- Lemaire G, Cruz P, Gosse G, Chartier M (1985) Relationship between dynamics of nitrogen uptake and dry-matter growth for lucerne (*Medicago sativa* L). *Agronomie* 5:685-692
- Lemos MC, Lo Y-J, Kirchhoff C, Haigh T (2014) Crop advisors as climate information brokers: building the capacity of US farmers to adapt to climate change. *Climate Risk Management*
- Liu J, Fu J, Tian H, Gao Y (2015) In-season expression of nitrate and ammonium transporter genes in roots of winter wheat (*Triticum aestivum* L.) genotypes with different nitrogen-uptake efficiencies. *Crop & Pasture Science* 66:671-678
- Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* 132:204-212
- Lobell DB (2007) The cost of uncertainty for nitrogen fertilizer management: A sensitivity analysis. *Field Crops Research* 100:210-217
- Lobell DB, Cassman KG, Field CB (2009) Crop yield gaps: their importance, magnitudes, and causes. *Annual Review of Environment and Resources* 34:179-204

- Lopes MS, Reynolds MP (2010) Partitioning of assimilates to deeper roots is associated with cooler canopies and increased yield under drought in wheat. *Functional Plant Biology* 37:147-156
- Lopes MS, Reynolds MP, Manes Y, Singh RP, Crossa J, Braun HJ (2012) Genetic Yield Gains and Changes in Associated Traits of CIMMYT Spring Bread Wheat in a "Historic" Set Representing 30 Years of Breeding. *Crop Science* 52:1123-1131
- Lorimer M, Douglas L (2001) Effects of wheat management practice on properties of a Victorian red-brown earth. 2. Wheat root distribution and grain yield. *Australian Journal of Soil Research* 39:307-315
- Lü X-T, Kong D-L, Pan Q-M, Simmons M, Han X-G (2012) Nitrogen and water availability interact to affect leaf stoichiometry in a semi-arid grassland. *Oecologia* 168:301-310
- Luehrman TA (1998) Investment opportunities as real options: getting started on the numbers. *Harvard business review* 76:51-66
- Luquet D, Dingkuhn M, Kim H, Tambour L, Clement-Vidal A (2006) EcoMeristem, a model of morphogenesis and competition among sinks in rice. 1. Concept, validation and sensitivity analysis. *Functional Plant Biology* 33:309-323
- Luquet D, Soulie JC, Rebolledo MC, Rouan L, Clement-Vidal A, Dingkuhn M (2012) Developmental Dynamics and Early Growth Vigour in Rice 2. Modelling Genetic Diversity Using Ecomeristem. *Journal of Agronomy and Crop Science* 198:385-398
- Luxhøi J, Fillery IR, Recous S, Jensen LS (2008) Carbon and N turnover in moist sandy soil following short exposure to a range of high soil temperature regimes. *Soil Research* 46:710-718
- Manschadi AM, Christopher Jd, P. , Hammer GL (2006) The role of root architectural traits in adaptation of wheat to water-limited environments. *Functional Plant Biology* 33:823-837
- Manton M, Creighton C, Hayman PT, Hendon H, Mitchell C, Sims J (2006) Workshop on the Science of Seasonal Climate Prediction. National Committee for Earth System Science (NCES) of the Australian National Academy of Sciences, Canberra
- Marshall GR, Parton KA, Hammer GL (1996) Risk attitude, planting conditions and the value of seasonal forecasts to a dryland wheat grower. *Australian Journal of Agricultural Economics* 40:211-234
- Mase AS, Prokopy LS (2014) Unrealized potential: A review of perceptions and use of weather and climate information in agricultural decision making. *Weather, Climate, and Society* 6:47-61
- McBride JL, Nicholls N (1983) Seasonal relationships between Australian rainfall and the Southern Oscillation. *Monthly Weather Review* 111:1998-2004
- McDonald GK, Taylor JD, Verbyla A, Kuchel H (2013) Assessing the importance of subsoil constraints to yield of wheat and its implications for yield improvement. *Crop and Pasture Science* 63:1043-1065
- McIntosh P, Asseng S, Wang E (2015) Profit and risk in dryland cropping: seasonal forecasts and fertiliser management 17th Australian Agronomy Conference, Hobart
- McMaster C, Graham N, Kirkegaard J, Hunt J, Menz I (2015) A simple framework for profitable fertiliser use under risk and soil constraints Building Productive, Diverse and Sustainable Landscapes. Proceedings of the 17th ASA Conference www.agronomy2015.com.au, Hobart, Australia
- McNeill A, Sparling G, Murphy D, Braunberger P, Fillery I (1998) Changes in extractable and microbial C, N and P in a Western Australian wheatbelt soil following simulated summer rainfall. *Australian Journal of Soil Research* 36:841-854
- Meza FJ, Hansen JW, Osgood D (2008) Economic Value of Seasonal Climate Forecasts for Agriculture: Review of Ex-Ante Assessments and Recommendations for Future Research. *Journal of Applied Meteorology and Climatology* 47:1269-1286
- Miadenov N, Hristov N, Kondic-Spika A, Djurico V, Jevtic R, Mladenov V (2011) Breeding progress in grain yield of winter wheat cultivars grown at different nitrogen levels in semiarid conditions. *Breeding Science* 61:260-268

- Monjardino M, McBeath T, Ouzman J, Llewellyn R, Jones B (2015) Farmer risk-aversion limits closure of yield and profit gaps: A study of nitrogen management in the southern Australian wheatbelt. *Agricultural Systems* 137:108-118
- Monjardino M, McBeath TM, Brennan L, Llewellyn RS (2013) Are farmers in low-rainfall cropping regions under-fertilising with nitrogen? A risk analysis. *Agricultural Systems*:37-51
- 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
- Mooney HA, Winner WE, Pell EJ, Chu E (1991) Response of plants to multiple stresses. Academic Press New York:422
- Morgounov A, Zykin V, Belan I, Roseeva L, Zelenskiy Y, Gomez-Becerra HF, Budak H, Bekes F (2010) Genetic gains for grain yield in high latitude spring wheat grown in Western Siberia in 1900-2008. *Field Crops Research* 117:101-112
- Mueller K, Deurer M (2011) Review of the remediation strategies for soil water repellency. *Agriculture Ecosystems & Environment* 144:208-221
- Murphy DV, Sparling GP, Fillery IRP (1998a) Seasonal fluctuations in gross N mineralisation, ammonium consumption, and microbial biomass in a Western Australian soil under different land uses. *Australian Journal of Agricultural Research* 49:523-536
- Murphy DV, Sparling GP, Fillery IRP (1998b) Stratification of microbial biomass C and N and gross N mineralisation with soil depth in two contrasting Western Australian agricultural soils. *Australian Journal of Soil Research* 36:45-56
- Nelson R, Howden SM, Hayman PT (2013) Placing the power of real options analysis into the hands of natural resource managers—Taking the next step. *Journal of environmental management* 124:128-136
- Ney B, Dore T, Sagan M (1997) The nitrogen requirement of major agricultural crops: grains legumes. In: Lemaire G (ed) *Diagnosis of the nitrogen status in crops*. Springer-Verlag, Heidelberg, pp 107–117
- 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
- Nix H (1975) Australian climate and its effects on grain yield and quality. *Aust Field Crops*
- Norse D, Ju XT (2015) Environmental costs of China's food security. *Agriculture Ecosystems & Environment* 209:5-14
- 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
- Norton RM, Walker C, Farlow C (2015) Nitrogen removal and use on a long-term fertilizer experiment. Proceedings of the 17th Australian Society of Agronomy Conference, 20-24 September 2015, Hobart, Australia;
<http://www.agronomy2015.com.au/papers/agronomy2015final00131.pdf>
- Nuttall J, Armstrong R, Connor D, Matassa V (2003) Interrelationships between edaphic factors potentially limiting cereal growth on alkaline soils in north-western Victoria. *Australian Journal of Soil Research* 41:277-292
- Officer SJ, Dunbabin VM, Armstrong RD, Norton RM, Kearney GA (2009) Wheat roots proliferate in response to nitrogen and phosphorus fertilisers in Sodosol and Vertosol soils of south-eastern Australia. *Soil Research* 47:91-102
- Ohsumi A, Hamasaki A, Nakagawa H, Homma K, Horie T, Shiraiwa T (2008) Response of leaf photosynthesis to vapor pressure difference in rice (*Oryza sativa* L) varieties in relation to stomatal and leaf internal conductance. *Plant Production Science* 11:184-191
- Oliver YM, Robertson MJ (2009) Quantifying the benefits of accounting for yield potential in spatially and seasonally responsive nutrient management in a Mediterranean climate. *Soil Research* 47:114-126

- Ortiz-Monasterio RJ, Sayre KD, Rajaram S, McMahon M (1997) Genetic progress in wheat yield and nitrogen use efficiency under four nitrogen rates. *Crop Science* 37:898-904
- Otieno D, Lindner S, Muhr J, Borken W (2012) Sensitivity of Peatland Herbaceous Vegetation to Vapor Pressure Deficit Influences Net Ecosystem CO₂ Exchange. *Wetlands* 32:895-905
- Page K, Dalal R, Menzies N, Strong W (2003) Subsoil nitrogen mineralisation and its potential to contribute to NH₄ accumulation in a Vertisol. *Australian Journal of Soil Research* 41:119-126
- Palta J, Sadras VO (2015) Roots of old and new varieties.
- Palta JA, Chen X, Milroy SP, Rebetzke GJ, Dreccer MF, Watt M (2011) Large root systems: are they useful in adapting wheat to dry environments? *Functional Plant Biology* 38:347-354
- Pannell DJ (2006) Flat earth economics: The far-reaching consequences of flat payoff functions in economic decision making. *Review of Agricultural Economics* 28:553-566
- Passioura JB (1996) Simulation models: science, snake oil, education, or engineering? *Agronomy Journal* 88:690-716
- Penman HL (1948) Natural evaporation from open water, bare soil, and grass. *Proc. R. Soc. London A* 193:120-145
- Piersma T, van Gils JA (2011) *The flexible phenotype*. Oxford University Press, New York
- Podbury T, Sheales TC, Hussain I, Fisher BS (1998) Use of El Nino climate forecasts in Australia. *American Journal of Agricultural Economics*:1096-1101
- Poggio SL, Satorre EH, Dethiou S, Gonzalo GM (2005) Pod and seed numbers as a function of photothermal quotient during the seed set period of field pea (*Pisum sativum*) crops. *European Journal of Agronomy* 22:55-69
- Potgieter A, Hammer G, Rodriguez D, Davis P, Doherty A, Power B, Book P (2012) Forecasting the major crops for Australia and crop yield insurance: an integrated climate, biophysical and remote sensing approach The challenges of index-based insurance for food security in developing countries. A technical workshop organised by JRC & IRI JRC/Ispira, Italy, 2 and 3 May 2012
- Potgieter A, Meinke H, Doherty A, Sadras VO, Hammer G, Crimp S, Rodriguez D (2013) Spatial impact of projected changes in rainfall and temperature on wheat yields in Australia. *Climatic Change* 117:163–179
- Pregitzer K, RL Hendrick, R Fogel (1993) The Demography of Fine Roots in Response to Patches of Water and Nitrogen. *New Phytol* 125: 575-580
- Priestly CHB, Taylor RJ (1972) On the assessment of surface heat flux and evaporation using large scale parameters. *Monthly Weather Review* 100:81-92
- Probert ME, Dimes JP, Keating BA, Dalal RC, Strong WM (1998) APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agricultural Systems* 56:1-28
- Prudhomme (2015) Entering 2015 with shifts in energy markets. What are the possible implications for the fertilizer industry. *Fertilizers and Agriculture. International Fertilizer Association*. May 2015:8
- Reyes A, Messina CD, Hammer GL, Liu L, Oosterom Ev, Lafitte R, Cooper M (2015) Soil water capture trends over 50 years of single-cross maize (*Zea mays* L.) breeding in the US corn-belt. *Journal of Experimental Botany*
- Richards RA, Hunt JR, Kirkegaard JA, Passioura JB (2014) Yield improvement and adaptation of wheat to water-limited environments in Australia-a case study. *Crop & Pasture Science* 65:676-689
- Richardson AEV (1923) The water requirements of farm crops. Influence of environment on the transpiration ratio. *J. Department of Agriculture Victoria* 21:193-284
- Richardson AEV, Trumble HC (1928) The transpiration ratio of farm crops and pasture plants in the Adelaide district. *J. Department of Agriculture South Australia* 32:224-244

- Risbey JS, Pook MJ, McIntosh PC, Wheeler MC, Hendon H (2009) On the remote drivers of rainfall variability in Australia. *Monthly Weather Review* 137:3233-3253
- Ritchie J (1981) Water dynamics in the soil-plant-atmosphere system. *Plant Soil* 58:81-96
- Robertson D, Zhang H, Palta JA, Colmer T, Turner NC (2009) Waterlogging affects the growth, development of tillers, and yield of wheat through a severe, but transient, N deficiency. *Crop and Pasture Science* 60:578-586
- Robertson MJ, Lyle G, Bowden JW (2008) Within-field variability of wheat yield and economic implications for spatially variable nutrient management. *Field Crops Research* 105:211-220
- Roche D (2015) Stomatal Conductance Is Essential for Higher Yield Potential of C3 Crops. *Critical Reviews in Plant Sciences* 34:429-453
- Roderick ML, Farquhar GD (2003) Pinatubo, diffuse light, and the carbon cycle. *Science* 299:1997-1998
- Rodriguez D, de Voil P, Power B, Cox D, Crimp S, Meinke H (2011) The intrinsic plasticity of farm businesses and their resilience to change. An Australian example. *Field Crops Research* 124:157-170
- Rodriguez D, Ferrante A, McLean J, B. G-J, Bielich M (2015) Tactical agronomy for sorghum in the northern region. Australian Summer Grains Conference
<http://www.australiansummergrains.com.au/>
- Rodriguez D, Nuttall J, Sadras VO, van Rees H, Armstrong R (2006) Impact of subsoil constraints on wheat yield and gross margin on fine-textured soils of the southern Victorian Mallee. *Australian Journal of Agricultural Research* 57:355-365
- Rodriguez D, Sadras VO (2007) The limit to wheat water use efficiency in eastern Australia. I. Gradients in the radiation environment and atmospheric demand. *Australian Journal of Agricultural Research* 58:287-302
- Rodriguez D, Sadras VO, Christensen LK, Belford R (2005) Spatial assessment of the physiological status of wheat crops as affected by water and nitrogen supply using infrared thermal imagery. *Australian Journal of Agricultural Research* 56:983-993
- Rossel R, Chen C, Grundy M, Searle R, Clifford D, Campbell P (2015) The Australian three-dimensional soil grid: Australia's contribution to the GlobalSoilMap project. *Soil Research* in press
- Saccomani M, Cacco G, Ferrari G (1984) Changes in the kinetic-parameters of sulfate uptake in maize hybrids during the selection period 1930 through 1975. *Maydica* 29:133-140
- Sadras V, Baldock J, Roget D, Rodriguez D (2003) Measuring and modelling yield and water budget components of wheat crops in coarse-textured soils with chemical constraints. *Field Crops Research* 84:241-260
- Sadras V, 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 (2002a) Influence of size of rainfall events on water budget components and nitrogen mineralisation. In: Villalobos FJ, Testi L (eds) *Proceedings XI European Society of Agronomy Conference, Cordoba, Spain*, pp 137-138
- Sadras VO (2002b) Interaction between rainfall and nitrogen fertilisation of wheat in environments prone to terminal drought: economic and environmental risk analysis. *Field Crops Research* 77:201-215
- 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 (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
- Sadras VO, Baldock J (2003) Soil nitrogen mineralisation as affected by size of rainfall events 11th Australian Agronomy Conference, Geelong

- Sadras VO, Cassman KGG, P., Hall AJ, Bastiaanssen WGM, Laborte AG, Milne AE, Sileshi G, Steduto P (2015a) Yield gap analysis of rainfed and irrigated crops: Methods and Case Studies. FAO, Rome
- Sadras VO, Grassini P, Steduto P (2012a) Status of water use efficiency of main crops. The State of the World's Land and Water Resources for Food and Agriculture, F.A.O. Thematic Report No. 7
http://www.fao.org/fileadmin/templates/solaw/files/thematic_reports/TR_07_web.pdf:41 pp.
- Sadras VO, Lake L, Chenu K, McMurray LS, Leonforte A (2012b) Water and thermal regimes for field pea in Australia and their implications for breeding. *Crop and Pasture Science* 63:33-44
- Sadras VO, Lawson C (2011) Genetic gain in yield and associated changes in phenotype, trait plasticity and competitive ability of South Australian wheat varieties released between 1958 and 2007. *Crop and Pasture Science* 62:533-549
- 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 (2012c) 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, Lawson C, Montoro A (2012d) Photosynthetic traits of Australian wheat varieties released between 1958 and 2007. *Field Crops Research* 134:19-29
- Sadras VO, Lemaire G (2014) Quantifying crop nitrogen status for comparisons of agronomic practices and genotypes *Field Crops Research* 164:54-64
- Sadras VO, Montoro A, Moran MA, Aphalo PJ (2012e) Elevated temperature altered the reaction norms of stomatal conductance in field-grown grapevine. *Agriculture and Forest Meteorology* 165:35-42
- 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, Richards RA (2014) Improvement of crop yield in dry environments: benchmarks, levels of organisation and the role of nitrogen. *Journal of Experimental Botany* 65:1981-1995
- Sadras VO, Rodriguez D (2007a) 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 (2007b) 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, Roget DK (2004) Production and environmental aspects of cropping intensification in a semiarid environment of southeastern Australia. *Agronomy Journal* 96:236-246
- Sadras VO, Vadez V, Purushothamanb R, Lake L, Marrou H (2015b) Unscrambling confounded effects of sowing date trials to screen for adaptation to high temperature *Field Crops Research* 177:1-8
- Sadras VO, Whitfield DM, Connor DJ (1991) Transpiration efficiency in crops of semi-dwarf and standard-height sunflower. *Irrigation Science* 12:87-91
- Sanchez-Garcia M, Royo C, Aparicio N, Martin-Sanchez JA, Alvaro F (2013) Genetic improvement of bread wheat yield and associated traits in Spain during the 20th century. *Journal of Agricultural Science* 151:105-118
- Sanderson T, Hertzler G, Capon T, Hayman P (2015) A real options analysis of Australian wheat production under climate change. *Australian Journal of Agricultural and Resource Economics*

- Savin R, Slafer GA, Cossani CM, Abeledo LG, Sadras VO (2015) Cereal yield in Mediterranean-type environments: challenging the paradigms on terminal drought, the adaptability of barley vs wheat and the role of nitrogen fertilization. In: Sadras VO, Calderini DF (eds) *Crop physiology: applications for genetic improvement and agronomy*, Second Edition edn. Academic Press, San Diego, pp 141-158
- Saxton KE, Rawls WJ (2006) Saxton KE, Rawls WJ (2006) Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. *Soil Science Society of America Journal* 70, 1569-1578. *Soil Science Society of America Journal* 70:1569-1578
- Sayre KD, Rajaram S, Fischer RA (1997) Yield potential progress in short bread wheats in Northwest Mexico. *Crop Science* 37:36-42
- Schwinning S, Ehleringer JR (2001) Water-use trade-offs and optimal adaptations to pulse-driven arid ecosystems. *Journal of Ecology* 89:464-480
- Schwinning S, Sala OE (2004) Hierarchy of responses to resource pulses in arid and semi-arid Oecologia 141:211-220
- Scott BJ, Eberbach PL, Evans J, Wade LJ (2010) EH Graham Centre Monograph No. 1: stubble retention in cropping systems in southern australia: benefits and challenges. Industry & Investment NSW, Orange.
- Shearman VJ, Sylvester-Bradley R, Scott RK, Foulkes MJ (2005) Physiological processes associated with wheat yield progress in the UK. *Crop Science* 45:175-185
- Siddique KHM, Belford RK, Perry MW, Tennant D (1989) Growth, development and light interception of old and modern wheat cultivars in a Mediterranean-type environment. *Australian Journal of Agricultural Research* 40:473-487
- Siddique KHM, Belford RK, Tennant D (1990a) Root-shoot ratios of old and modern, tall and semidwarf wheats in a Mediterranean environment. *Plant and Soil* 121:89-98
- Siddique KHM, Tennant D, Perry MW, Beldford RK (1990b) Water use and water use efficiency of old and modern wheat cultivars in a Mediterranean-type environment. *Aust. J. Agric. Res.* 41:431-447
- Sinclair T, Shiraiwa T (1993) Soybean radiation-use efficiency as influenced by nonuniform specific leaf nitrogen and diffuse radiation. *Crop Sci* 32:1281-1284
- Sinclair T, Tanner C, Bennett J (1984) Water-use efficiency in crop production. *BioScience* 34:36-40
- Sinclair TR (2011) Challenges in breeding for yield increase for drought. *Trends in Plant Science* 16:289-293
- Sinclair TR, Hammer GL, van Oosterom EJ (2005) Potential yield and water-use efficiency benefits in sorghum from limited maximum transpiration rate. *Functional Plant Biology* 32:945-952
- Sinclair TR, Horie T (1989) Leaf nitrogen, photosynthesis and crop radiation use efficiency - a review. *Crop Science* 29:90-98
- Sinclair TR, Manandhar A, Belko N, Riar M, Vadez V, Roberts PA (2015) Variation among cowpea genotypes in sensitivity of transpiration rate and symbiotic nitrogen fixation to soil drying. *Crop Science* in press
- Sinclair TR, Park WI (1993) Inadequacy of the Liebig limiting-factor paradigm for explaining varying crop yields. *Agron. J.* 85:742-746
- Sinclair TR, Purcell LC, King CA, Sneller CH, Chen P, Vadez V (2007) Drought tolerance and yield increase of soybean resulting from improved symbiotic N-2 fixation. *Field Crops Research* 101:68-71
- Sinclair TR, Ruffy TW (2012) Nitrogen and water resources commonly limit crop yield increases, not necessarily plant genetics. *Global Food Security* 1:94-98
- Singh V, van Oosterom EJ, Jordan DR, Hammer GL (2012) Genetic control of nodal root angle in sorghum and its implications on water extraction. *European Journal of Agronomy* 42:3-10
- Single W (1985) Frost injury and the physiology of the wheat plant. *Journal of the Australian Institute of Agricultural Science*

- Slafer GA, Andrade FH (1989) Genetic improvement in bread wheat (*Triticum aestivum* L.) yield in Argentina. *Field Crops Research* 21:289-296
- Slafer GA, Andrade FH, Feingold SE (1990) Genetic-improvement of bread wheat (*Triticum aestivum* L) in Argentina - relationships between nitrogen and dry-matter. *Euphytica* 50:63-71
- Slafer GA, Kantolic A, Appendino M, Tranquilli G, Savin R, Miralles D (2015) Genetic and environmental effects on crop development determining adaptation and yield. In: Sadras VO, Calderini DF (eds) *Crop physiology: applications for genetic improvement and agronomy*, Second Edition edn. Academic Press, San Diego, pp 285-319
- Smith CJ, Dunin FX, Zegelin SJ, Poss R (1998) Nitrate leaching from a Riverine clay soil under cereal rotation. *Australian Journal of Agricultural Research* 49:379-390
- Sparling G, Murphy D, Thompson R, Fillery I (1995) Short-term net N mineralization from plant residues and gross and net N mineralization From soil organic-matter after rewetting of a seasonally dry soil. *Soil Research* 33:961-973
- Spitters CJT (1986) Separating the diffuse and direct component of global radiation and its implications for modelling canopy photosynthesis Part II. Calculations of canopy photosynthesis. *Agricultural and Forest Meteorology* 38:231-242
- Stockle CO, Kemanian AR (2009) Crop radiation capture and use efficiency: a framework for crop growth analysis In: Sadras VO, Calderini DF (eds) *Crop physiology: applications for genetic improvement and agronomy*. Academic Press, San Diego, pp 145-170
- Teixeira AI, George M, Herreman T, Brown H, Fletcher A, Chakwizira E, de Ruiter J, Maley S, Noble A (2014) The impact of water and nitrogen limitation on maize biomass and resource-use efficiencies for radiation, water and nitrogen. *Field Crops Research* 168:109-118
- Tian ZW, Jing Q, Dai TB, Jiang D, Cao WX (2011) Effects of genetic improvements on grain yield and agronomic traits of winter wheat in the Yangtze River Basin of China. *Field Crops Research* 124:417-425
- Timbal B, Arblaster J, Braganza K, Ferabdez E, Hendon HH, Murphy B, Raupach M, Rakich C, Smith I, Whan K, Wheeler M (2010) Understanding the anthropogenic nature of the observed rainfall decline across south-eastern Australia. CAWCR Technical Report No 026, July 2010. Centre for Australian Weather and Climate Research, Melbourne
- Tittonell P, Giller KE (2013) When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Research* 143:76-90
- Trumbell HC (1939) Climatic factors in relation to the agricultural regions of southern Australia. *Transactions of the Royal Society, South Australia* 63:36-43
- Ummenhofer CC, England MH, McIntosh PC, Meyers GA, Pook MJ, Risbey JS, Gupta AS, Taschetto AS (2009) What causes southeast Australia's worst droughts? *Geophysical Research Letters* 36:L04706
- Unkovich M, Baldock J, Forbes M (2010) Variability in harvest index of grain crops and potential significance for carbon accounting in Australian agriculture. *Advances in Agronomy* 105:173-219
- Unkovich M, Baldock J, Marvanek S (2009) Which broadacre crops and pastures should be included in a carbon accounting system for Australia's cropping zone? *Crop and Pasture Science* 60:617-626
- Unkovich MJ (2014) A review of the potential constraints to crop production on sandy soils in low-rainfall south-eastern Australia and priorities for research. Mallee Sustainable Farming Inc., Mildura, p 96
- Valzano F, Murphy B, Koen T (2005) The impact of tillage on changes in soil carbon density with special emphasis on Australian conditions. Australian Greenhouse Office, Canberra, p 164
- van Herwaarden AF, Angus JF, Richards RA, Farquhar GD (1998) '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 Ittersum MK, Rabbinge R (1997) Concepts in production ecology for analysis and quantification of agricultural input-output combinations. *Field Crops Research* 52:197-208
- van Oosterom EJ, Borrell AK, Chapman SC, Broad IJ, Hammer GL (2010) Functional dynamics of the nitrogen balance of sorghum: I. N demand of vegetative plant parts. *Field Crops Research* 115:19-28
- van Oosterom EJ, Borrell AK, Deifel KS, Hammer GL (2011) Does Increased Leaf Appearance Rate Enhance Adaptation to Postanthesis Drought Stress in Sorghum? *Crop Science* 51:2728-2740
- 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
- Waddington SR, Ransom JK, Osmanzai M, Saunders DA (1986) Improvement in the yield potential of bread wheat adapted to northwest Mexico. *Crop Science* 26:698-703
- Wang E, Robertson MJ, Hammer GL, Carberry PS, Holzworth D, Meinke H, Chapman SC, Hargreaves JNG, Huth NI, McLean G (2002) Development of a generic crop model template in the cropping system model APSIM. *European Journal of Agronomy* 18:121-140
- Wang R, Dorodnikov M, Yang S, Zhang Y, Filley TR, Turco RF, Zhang Y, Xu Z, Li H, Jiang Y (2015) Responses of enzymatic activities within soil aggregates to 9-year nitrogen and water addition in a semi-arid grassland. *Soil Biology & Biochemistry* 81:159-167
- Wang Y, Zhang X, Liu X, Zhang X, Shao L, Sun H, Chen S (2013) The effects of nitrogen supply and water regime on instantaneous WUE, time-integrated WUE and carbon isotope discrimination in winter wheat. *Field Crops Research* 144:236-244
- Ward PR, Whisson K, Micin SF, Zeelenberg D, Milroy SP (2009) The impact of wheat stubble on evaporation from a sandy soil. *Crop and Pasture Science* 60:730-737
- Wasson AP, Rebetzke GJ, Kirkegaard JA, Christopher J, Richards RA, Watt M (2014) Soil coring at multiple field environments can directly quantify variation in deep root traits to select wheat genotypes for breeding. *Journal of Experimental Botany* 65:6231-6249
- Watmuff G, Reuter DJ, Speirs SD (2013) Methodologies for assembling and interrogating N, P, K, and S soil test calibrations for Australian cereal, oilseed and pulse crops. *Crop and Pasture Science* 64:424-434
- Whaley JM, Kirby EJM, Spink JH, Foulkes MJ, Sparkes DL (2004) Frost damage to winter wheat in the UK: the effect of plant population density. *European Journal of Agronomy* 21:105-115
- Whish J, Butler G, Castor M, Cawthray S, Broad I, Carberry P, Hammer G, McLean G, Routley R, Yeates S (2005) Modelling the effects of row configuration on sorghum yield reliability in north-eastern Australia. *Australian Journal of Agricultural Research* 56:11-23
- Williamson G (2007) Climate and root distribution in Australian perennial grasses; implications for salinity mitigation School of Earth and Environmental Sciences, vol. Ph D. The University of Adelaide, Adelaide
- WMO (2006) Drought monitoring and early warning: concepts, progress and future challenges. Weather and climate information for sustainable agricultural development. World Meteorological Organisation Number 1006. , Geneva, Switzerland
- Wolfe DW, Henderson DW, Hsiao TC, Alvino A (1988) Interactive water and nitrogen effects on senescence of maize. II. Photosynthetic decline and longevity of individual leaves. *Agron. J.* 80:865-870
- Xiao YG, Qian ZG, Wu K, Liu JJ, Xia XC, Ji WQ, He ZH (2012) Genetic Gains in Grain Yield and Physiological Traits of Winter Wheat in Shandong Province, China, from 1969 to 2006. *crop Science* 52:44–56
- Yang Y, Liu D, Anwar M, Zuo H, Yang Y (2014) Impact of future climate change on wheat production in relation to plant-available water capacity in a semiarid environment. *Theoretical and Applied Climatology* 115:391-410

- Ye Y, Liang X, Chen Y, Liu J, Gu J, Guo R, Li L (2013) Alternate wetting and drying irrigation and controlled-release nitrogen fertilizer in late-season rice. Effects on dry matter accumulation, yield, water and nitrogen use. *Field Crops Research* 144:212-224
- Yousfi S, Dolores Serret M, Jose Marquez A, Voltas J, Luis Araus J (2012) Combined use of d13C, d18O and d15N tracks nitrogen metabolism and genotypic adaptation of durum wheat to salinity and water deficit. *New Phytologist* 194:230-244
- Zhang HX, Zhou DW, Huang YX, Japhet W, Sun DD (2008) Plasticity and allometry of meristem allocation in response to density in three annual plants with different architectures. *Botany-Botanique* 86:1291-1298
- Zheng B, Chapman SC, Christopher JT, Frederiks TM, Chenu K (2015) Frost trends and their estimated impact on yield in the Australian wheatbelt. *Journal of experimental botany:erv163*
- Zheng B, Chenu K, Fernanda Dreccer M, Chapman SC (2012) Breeding for the future: what are the potential impacts of future frost and heat events on sowing and flowering time requirements for Australian bread wheat (*Triticum aestivum*) varieties? *Global Change Biology* 18:2899-2914
- Zheng TC, Zhang XK, Yin GH, Wang LN, Han YL, Chen L, Huang F, Tang JW, Xia XC, He ZH (2011) Genetic gains in grain yield, net photosynthesis and stomatal conductance achieved in Henan Province of China between 1981 and 2008. *Field Crops Research* 122:225-233
- Zhong Y, Zhouping S (2014) Water consumption characteristics and water use efficiency of winter wheat under long-term nitrogen fertilization regimes in Northwest China. *Plos One* 9:e98850
- Zhou Y, He ZH, Sui XX, Xia XC, Zhang XK, Zhang GS (2007) Genetic Improvement of Grain Yield and Associated Traits in the Northern China Winter Wheat Region from 1960 to 2000. *Crop Science* 47:245–253

Chapter 2

The value of soil and climate information to support nitrogen management

Introduction

Australian climate is temporally and spatially variable (Anwar et al., 2007; Rodriguez and Sadras, 2007; Sadras and Rodriguez, 2007), with some level predictability of the occurrence of heat stress (Hudson et al., 2013), and rainfall (Khan et al., 2015). Temporally, the main source of variability are ENSO and the Indian Dipole (White et al., 2013), while spatially north to south and east to west gradients in rainfall, rainfall seasonality and atmospheric demand (Rodriguez and Sadras, 2007) determine achievable yields and set the boundary for potential water use efficiency (Doherty et al., 2010; Rodriguez and Sadras, 2007).

Over the years a large number of tools have been produced to support farmers' and advisors decision-making. Most of these tools are described in the Climate Kelpie website (<http://www.climatekelpie.com.au>) supported by the Managing Climate Variability Program with funding from a range of industry bodies (GRDC, MLA, SRA, CRDC, and RIRDC). The value of decision support tools has been contested (McCown et al., 2009) while others argue that consensus is emerging on how decisions support tools should be developed and scaled out for adoption and impact (Hochman and Carberry, 2011).

Whenever crop nitrogen is in short supply relative to the availability of water, a yield gap emerges often associated to a reduction in profits. Conversely, where nitrogen supply exceeds the requirement to achieve the water-limited yield, the returns on investment in nitrogen will be small or even negative. Therefore, in rainfed cropping matching nitrogen availability to water supply is critical, not only to reduce gaps in productivity but also to increase profits and manage risks.

Focusing on farmers' challenge to adjust fertiliser decisions to season-to-season variation in water and nitrogen, here we analyse decision support tools in their simplest expression. This is, the value of information readily available to farmers from (i) soil sampling for soil water and soil nitrogen at the time of sowing, to decide on nitrogen fertilisation on a wheat crop; and (ii) answer whether the use of POAMA, the latest seasonal climate forecast from the Bureau of Meteorology (<http://poama.bom.gov.au>) would add value to this information. We hypothesised that in rainfed wheat, profit can be increased and risk reduced if nitrogen management is informed by initial soil water (ISW), initial soil N (ISN), and the likely seasonal conditions from POAMA.

Here, we used expert regional crop management and soil knowledge to parameterise the APSIM model (www.apsim.info) and simulate six strategies to inform nitrogen fertilisation practices. Nitrogen management practices were decided based on information of (i) soil water at sowing (ISW); (ii) soil nitrogen at sowing (ISN); (iii) both ISW and ISN; (iv) a seasonal rainfall forecast (POAMA); and two controls, (v) a control where fertiliser decisions were the same every year, i.e. ignoring soil or climate information; and (vi) a control we called perfect knowledge, when the decision of N fertilisation was based on actual rainfall.

Method

We used expert regional crop management and soil knowledge to parameterise the APSIM model (www.apsim.info) and simulate six strategies to inform nitrogen (N) fertilisation practices. Nitrogen management practices were decided based on:

- (i) Soil water at sowing (ISW);
- (ii) Soil nitrogen at sowing (ISN);
- (iii) Both ISW and ISN;
- (iv) A seasonal rainfall forecast (POAMA);
- (v) A control where fertiliser decisions were the same every year, i.e. ignoring soil or climate information; and
- (vi) A control we called perfect knowledge, when the decision on N fertilisation was based on actual rainfall.

Eleven sites across Northern, Southern and Western Australia were selected to capture different climates and soils. The experiment included the six management strategies and rates of nitrogen from zero to 250 kg N ha⁻¹, in 10 kg N ha⁻¹ increments. APSIM was then used to simulate yield, water and N use, water stress index and nitrogen stress index. Efficiency measures were also calculated, including water use efficiency (WUE, yield per unit evapotranspiration), total factor productivity (TFP, yield per unit fertiliser), gross margin (GM, \$ ha⁻¹) and financial risk. Two measures of risk were used: the chance of a negative gross margin (\$ ha⁻¹); and the chance of a return on investment lower than 1.1 (\$ \$⁻¹).

Sites

Eleven sites that represent climatic conditions, soils and cropping systems across Northern, Southern, Western Australia, and Victoria were selected for a simulation experiment. Soil parameters were taken from the APSIM soil database including total organic carbon (TOC),

bulk density (BD), saturated soil water content (SAT), drained upper limit (DUL), and crop lower limit (CLL), on which plant available water capacity (PAWC) was calculated (Table 1). Crop management was obtained from agronomists familiar with each of the regions. Median initial soil water and mineral N at sowing were simulated with APSIM using long-term climate records (n=115) and the soil descriptions as in APSoil (<https://www.apsim.info/Products/APSoil.aspx>) (Table 1).

Table 1. Total organic carbon (TOC), in-crop rainfall, and long-term simulated median initial soil water and soil nitrogen across the eleven sites simulated using APSIM. Source: APSoil (<https://www.apsim.info/Products/APSoil.aspx>)

Sites	TOC (%)	In-crop Rainfall (mm)	Long-term median initial soil water and soil nitrogen	
			Soil water (mm)	Nitrogen (kg ha ⁻¹)
Dalby, QLD	1.2-0.2	159	142	60
Emerald, QLD	1.2-0.4	79	149	117
Goondiwindi, QLD	1.2-0.3	157	141	91
Minnipa, SA	1.3-0.3	148	67	13
Yorke town, SA	4.2-2.1	211	102	54
Merredin, WA	1.0-0.1	133	88	13
Moora, WA	0.5-0.1	192	56	12
Wogan Hills, WA	1.2-0.2	186	95	33
Condobolin, NSW	1.2-0.1	170	104	26
Wagga-Wagga, NSW	1.6-0.1	263	102	17
Birchip, VIC	1.6-0.2	173	87	17

Climate

Daily climate records from 1900 to 2015 were extracted from the SILO patched point data source (<http://apsrunet.apsim.info/cgi-bin/silo>). Figure 1 shows the probability distribution function for in-crop rainfall (mm) for the locations under study. In-crop rainfall was higher in southern and western locations, of a winter rainfall dominant climate and is smaller in the northern locations having a summer-dominant rainfall (Rodriguez and Sadras, 2007). For strategies based on the POAMA forecast we used all available 30 years.

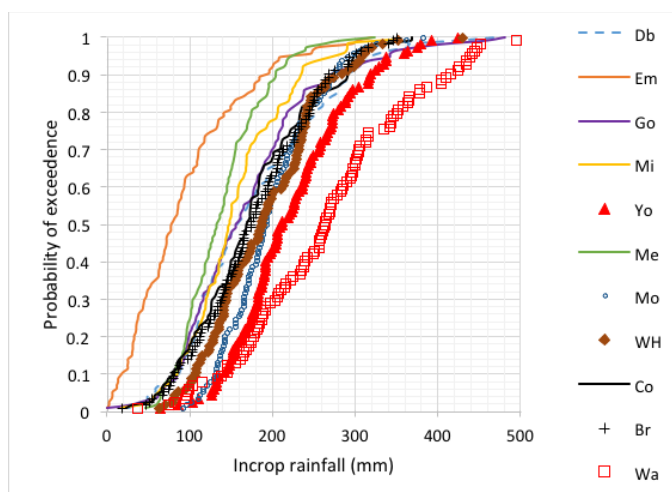


Figure 1. Cumulative distribution function of in-crop rainfall (mm) for Dalby (Db), Em (Emerald), and Goondiwindi (Go) in Queensland; Minnipa (Mi), and Yorketown (Yo) in South Australia; Merredin (Me), Moora (Mo), and Wogan Hills (WH) in Western Australia; Condobolin (Co), and Wagga-Wagga (Wa) in New South Wales; and Birchip (Br) in Victoria, Australia.

Simulated scenarios

The simulated scenarios aimed to examine different nitrogen management strategies based on different types of information. This is, deterministic information from measurement of soil water and mineral nitrogen; stochastic information from a seasonal climate forecast, and two controls, a control when the same amount of N was applied every year, and a control when the amount of N applied was based on the perfect knowledge of seasonal rainfall.

APSIM was first used to estimate the long-term (115 years) median initial soil nitrogen (ISNmedian) and initial soil water (ISWmedian). Long-term medians were calculated from simulating a fallow i.e. starting the simulations on the first of November each year (i.e. after the harvest of the previous wheat crop), and by resetting the ISW to 10% of plant available water capacity, and the ISN to 25 kg N ha⁻¹. Once the ISWmedian and ISNmedian were calculated, they were used to define six N management strategies:

1. *ISW-dependent N rate.* The rule was: if ISW for any given season was smaller than ISWmedian, 50% of the N rate was applied; otherwise, 150% of the N rate was applied. This means that the baseline, say for 100 kg N/ha, was compared with 50 kg N/ha in seasons when ISW was below median, and with 150 kg N/ha in years when ISW was above the median. This allows for comparisons at the same rate of N over the time series.
2. *ISN-dependent N rate.* The rule was: if ISN in any given season was larger than its long-term median (ISNmedian), 50% of the N rate was applied; otherwise 150% of the N rate was applied.

3. *ISW and ISN dependent N rate*: The rule was: (i) if ISW for any given year was larger than ISW_{median}, and ISN was smaller or equal than ISN_{median} then, 150% of the N rate would be applied; (ii) if ISW was smaller than or equal to ISW_{median} and ISN was larger than ISN_{median}, then 50% of the N rate was applied. Otherwise the N applied would be 100%.
4. *Seasonal climate forecast (POAMA) based decision*. The POAMA based rule was: The N application rate was changed every year based on whether the seasonal climate forecast would predict above or below median rainfall at the time of sowing i.e. for the next 5 months. This means that if POAMA forecasted seasonal rainfall below the median, 50% of the N rate would be applied; otherwise, 150% of the N rate was applied.
5. *Same every year (SEY)*. The same amount of N was applied every season; the rate was varied from 10 to 250 kg N ha⁻¹ at steps of 10 kg N/ha, i.e. 25 simulated N treatments.
6. *Perfect knowledge (PK)*. This strategy was devised as a control to assume perfect knowledge, i.e. if the seasonal rainfall for the oncoming season would be known and the N management would be modified accordingly, i.e. if seasonal rainfall was below the long term median, half of the N would be added; and if the seasonal rainfall was above the long term median 150% of the rate would be used.

Economic analysis

The return on investment (ROI, \$ \$⁻¹) and gross margin (GM \$, ha⁻¹) were calculated for each scenario. The cost of seed, labour, and other cultivation practices were considered as fixed costs, and fertiliser cost as variable. Risk was calculated as the likelihood (i.e. percentage of years) of (i) a negative gross margin; and (ii) a ROI smaller than 1.1 \$ \$⁻¹. All the economic data including wheat prices were taken from the GRDC website (May, 2015) (Table 2).

Gross margin in this study was defined as the difference between the gross income (GI) and variable cost (VC):

$GM_i = Y_i \cdot Pr - (VC + N_i \cdot Fpr)$, where

i = year, Y_i = yield of the i -th year, Pr = wheat price in May 2015 (\$ t⁻¹), VC = variable cost (\$ ha⁻¹), N = N rate (kg ha⁻¹), and Fpr = fertiliser price (\$ kg⁻¹).

Table 2. Cost and price data used in the calculation of gross margin and return on investments

Item	Cost
Wheat Price (2015)	250 \$ t ⁻¹
Variable cost excluding N fertilizer	164 \$ ha ⁻¹
Fertiliser	1.24 \$ kg ⁻¹

Data analysis

APSIM simulations provided simulated grain yield, biomass, soil water stress and nitrogen stress at three growth stages, and in-crop rain rainfall from sowing to harvest for each year.

Total Factor Productivity (TFP), Nitrogen Stress Index (NSI), Crop Water Stress Index (WSI), Water Use efficiency (WUE), and down side risk (DSR) were then calculated for each strategy. Total factor productivity was determined as the level of increase in yield per unit of increase in N application. We used 40 kg grain kg⁻¹N applied (40 TFP), as a threshold to indicate whether a strategy would be an efficient treatment. In APSIM, NSI and WSI range between 0 (fully stressed) and 1 (non-stressed crop). NSI was calculated as the difference between the leaf N concentration and leaf minimum and critical nitrogen concentration.

Water Use Efficiency (WUE) was calculated as the grain yield divided by the total crop water use. We used yield of 2.5 t ha⁻¹ and WUE of 10 kg mm⁻¹ ha⁻¹ as thresholds for comparisons. Gross margin vs. risk curves were derived to compare the different strategies.

Results

Yield

Across all the regions (Table 1) maximum yield, more likely yield, and the probability of yield higher than 2.5t ha⁻¹ varied with N supply and the simulated scenarios. In general the two control scenarios provided the most extreme situations, i.e. assuming perfect knowledge and applying the same amount of N every year, provided the highest and lowest yields, respectively. For example, at Dalby (median in crop rainfall 159 mm) the maximum simulated yield was 5.7 t ha⁻¹, with a long-term median between 1.7 to 2.6 t ha⁻¹, depending the simulated strategy and N-rate. At 120 kg N ha⁻¹, the hypothetical perfect knowledge strategy i.e. knowing in advance the value of seasonal rainfall, gave the highest median yield, whereas the ISN strategy had the highest (52%) probability of achieving a yield larger

than 2.5 t ha⁻¹. In general ignoring soil information and applying always the same amount of N fertiliser (SEY) was the least profitable strategy.

Main results for the other locations are summarised below:

At *Emerald* (median in-crop rainfall 79 mm) the median simulated yield was 1.8 t ha⁻¹; differences between strategies were only important at low N rates i.e. below 90 kg N ha⁻¹.

At *Goondiwindi* (median in-crop rainfall 157 mm) the median simulated yield was 2.2 t ha⁻¹. The probability of achieving a yield larger than 2.5 t ha⁻¹, was higher when both information on ISW and ISN were used to decide on N fertilisation, though only for N rates below 90 kg N ha⁻¹.

At *Minnipa* (median in-crop rainfall 148 mm) the simulated median yield was very low (0.6 t ha⁻¹), and differences between strategies were only observed at very low N rates i.e. 10 and 30 kg N ha⁻¹.

At *Yorketown* (median in-crop rainfall 211 mm) yield responses were observed up to 120 kg N ha⁻¹. N management strategies based on ISW and ISN information produced the highest chance of achieving yields over 2.5 t ha⁻¹ though only at low levels of N application. The probability of achieving yields over 2.5 t ha⁻¹ increased with increasing N rate for all strategies.

At *Merredin* (median in-crop rainfall 133 mm) the median yield was less than 2.0 t ha⁻¹ irrespective of the N application strategy. Using information about ISW and ISN gave the highest chances of achieving yields larger than 2.5 t ha⁻¹ though at low levels of N application.

At *Moora* (median in-crop rainfall 192 mm) the median yield increased with the nitrogen application rate up to 2.1 t ha⁻¹. Larger probabilities of achieving more than 2.5 t ha⁻¹ could be achieved using information on ISW and both ISW and ISN to decide on fertiliser rate.

At *Wongan Hills* (median in-crop rainfall 186 mm), yield increased with nitrogen rate up to 120 kg N ha⁻¹. The probability of achieving yields larger than 2.5 t ha⁻¹ was generally higher when information on ISW and ISN were used.

At *Condobolin* (median in-crop rainfall 170 mm) median yield increased up to 60 kg N ha⁻¹. The probability of achieving yields larger than 2.5 t ha⁻¹ was higher when information on ISW and ISN were used though only at the lower levels of N application.

At *Wagga Wagga* (median in-crop rainfall 263 mm) the probability of achieving yields larger than 2.5 t ha⁻¹ was higher when information on ISW and ISN were used, though only for the lower N rates (10 and 30 kg N ha⁻¹). The probability of achieving yields over 2.5 t ha⁻¹ increased from 0 to 62% when information on ISN was used to decide on N fertilisation.

At *Birchip* (median in-crop rainfall 173 mm) the probability of achieving a yield larger than 2.5 t ha⁻¹ was higher when information on ISW and ISN were used, though only at low levels of N application.

Total Factor Productivity

Table 2 shows TFP for different N management strategies at eleven sites across Australia's wheat belt. Both TFP and the probability of achieving a TFP over 40 kg kg⁻¹ decreased as the application of N increased from 10 to 150 kg N ha⁻¹,

Only at one site Yorketown the values of TFP were higher than 40 kg grain kg⁻¹ N above 30kg N ha⁻¹. For all other locations the values of TFP were smaller than 40 at or above 60 kg N ha⁻¹. The perfect knowledge (PK) strategy showed slightly higher TFP though still at low N rates.

Table 2. Comparison of long-term (115 years) median TFP (kg grain kg⁻¹ N) and probability of TFP > 40kg grain kg⁻¹ of N for the simulated strategies and N rates from 10 to 150 kg N ha⁻¹. Strategies are: SEY, same each year; PK, perfect knowledge; ISN, initial soil N strategy; ISW, initial soil water strategy; ISW x ISN, combined strategy informed by soil water and nitrogen. Shaded areas show median and probability values of a TFP > 40kg grain kg⁻¹ of N.

Site	Strategy	Median TFP						Probability of TFP > 40kg/kg					
		10	30	60	90	120	150	10	30	60	90	120	150
Dalby	SEY	170	61	35	25	21	16	0.99	0.86	0.35	0.13	0.08	0.00
	PK	190	73	41	30	23		1	0.91	0.51	0.19	0.04	
	ISN	128	47	29	24	23	21	0.99	0.7	0.31	0.29	0.29	0.22
	ISW	183	66	35	27	21	18	0.46	0.46	0.44	0.42	0.42	0.42
	ISWxISN	151	50	31	24	21	18	0.42	0.31	0.19	0.15	0.13	0.08
Emerald	SEY	169	60	30	20	15	12	0.99	0.85	0.27	0.04	0.00	0.00
	PK	193	70	35	23	18	14	1	0.87	0.4	0.08	0.00	0.00
	ISN	206	72	36	24	17	15	0.98	0.75	0.47	0.24	0.12	0.06
	ISW	184	63	32	22	16	13	0.42	0.41	0.42	0.42	0.41	0.4
	ISWxISN	172	60	30	20	15	12	0.4	0.28	0.14	0.07	0.04	0.02
Goondiwindi	SEY	212	73	37	25	19	15	0.98	0.84	0.44	0.12	0.05	0.00
	PK	217	75	40	28	21	17	0.99	0.89	0.47	0.22	0.10	0.02
	ISN	226	83	42	29	20	17	0.97	0.77	0.51	0.37	0.22	0.12
	ISW	205	70	36	25	19	15	0.46	0.46	0.46	0.46	0.45	0.43
	ISWxISN	217	74	38	26	20	16	0.42	0.3	0.17	0.08	0.04	0.01
Minnipa	SEY	46	26	15	9	7	6	0.58	0.33	0.15	0.04	0.00	0.00
	PK	60	30	17	12	9	8	0.65	0.27	0.05	0.02	0.01	0.01
	ISN	51	28	16	11	8	7	0.58	0.35	0.22	0.15	0.11	0.05
	ISW	53	27	16	11	8	6	0.18	0.18	0.18	0.18	0.19	0.19
	ISWxISN	46	26	14	9	7	6	0.19	0.11	0.05	0.02	0.01	0.00
Yorketown	SEY	361	126	63	43	33	26	1.00	0.99	0.88	0.59	0.15	0.01
	PK	332	115	61	40	30	24	1.00	1	0.87	0.5	0.38	0.35
	ISN	317	114	59	39	27	23	1.00	0.99	0.78	0.49	0.41	0.39
	ISW	345	120	64	43	32	26	0.68	0.68	0.69	0.70	0.70	0.67
	ISWxISN	344	120	62	42	32	26	0.62	0.55	0.44	0.3	0.18	0.12
Merredin	SEY	115	47	30	20	16	12	0.96	0.61	0.12	0.01	0.00	0.00
	PK	113	47	29	21	16	13	0.98	0.66	0.17	0.06	0.00	0.00
	ISN	103	48	30	21	16	14	0.92	0.55	0.4	0.28	0.08	0.06
	ISW	116	47	29	21	15	13	0.32	0.32	0.31	0.31	0.30	0.30
	ISWxISN	113	47	29	20	16	12	0.3	0.17	0.08	0.03	0.01	0
Moora	SEY	64	32	23	19	16	14	0.75	0.33	0.00	0.00	0.00	0.00
	PK	73	36	25	21	18	73	0.63	0.48	0.28	0.09	0.00	0.63
	ISN	67	34	24	19	15	14	0.77	0.36	0.19	0.05	0.00	0.00
	ISW	65	34	25	20	16	14	0.24	0.23	0.23	0.22	0.21	0.21
	ISWxISN	63	33	24	20	17	15	0.21	0.1	0.04	0.01	0.00	0.00
Wogan Hills	SEY	64	32	23	19	16	14	0.75	0.33	0	0	0.00	0.00
	PK	73	36	25	21	18	73	0.63	0.48	0.28	0.09	0.00	0.63
	ISN	67	34	24	19	15	14	0.77	0.36	0.19	0.05	0.00	0.00
	ISW	65	34	25	20	16	14	0.24	0.23	0.23	0.22	0.21	0.21
	ISWxISN	63	33	24	20	17	15	0.21	0.1	0.04	0.01	0.00	0.00
Condobolin	SEY	164	64	33	23	18	14	0.99	0.75	0.36	0.19	0.06	0.00
	PK	170	66	37	26	20	16	1.00	0.84	0.44	0.16	0.04	0.02
	ISN	164	63	37	26	19	16	0.96	0.74	0.46	0.29	0.18	0.16
	ISW	172	66	37	26	20	16	0.43	0.43	0.42	0.41	0.41	0.41
	ISWxISN	163	63	33	24	18	15	0.41	0.29	0.17	0.09	0.04	0.00
Wagga Wagga	SEY	115	53	32	25	20	17	0.98	0.82	0.21	0.00	0.00	0.00
	PK	121	52	34	27	22	19	1.00	0.85	0.36	0.14	0.02	0.00
	ISN	109	52	36	28	23	20	0.98	0.69	0.45	0.31	0.08	0.02
	ISW	105	51	34	26	22	19	0.42	0.41	0.42	0.40	0.38	0.37
	ISWxISN	115	52	34	25	20	17	0.37	0.25	0.12	0.06	0.04	0.01
Birchip	SEY	170	61	35	25	21	16	0.99	0.86	0.35	0.13	0.08	0.00
	PK	190	73	41	30	23	190	1.00	0.91	0.51	0.19	0.04	1.00
	ISN	128	47	29	24	23	21	0.99	0.70	0.31	0.29	0.29	0.22
	ISW	183	66	35	27	21	18	0.46	0.46	0.44	0.42	0.42	0.42
	ISWxISN	151	50	31	24	21	18	0.42	0.31	0.19	0.15	0.13	0.08

Nitrogen Stress Index

As expected the NSI declined with increasing N rates and varied across strategies. NSI varied from 0-0.36 during the period from emergence to GS31, 0-0.44 between GS31-GS65, between 0-0.73 during the GS65 to harvest. Results for the period stem elongation to flowering (GS31-GS65) are shown in Table 3.

Table 3. Comparison of long-term (115 years) median nitrogen stress index (NSI) for the period GS31 to GS65 for different strategies and N rates (10 to 150 kg N ha⁻¹). Strategies are: SEY, same each year; PK, perfect knowledge; ISN, initial soil N strategy; ISW, initial soil water strategy; ISW x ISN, combined strategy informed by soil water and nitrogen. NSI ranges from 0 (no stress) to 1 (maximum stress). Shading highlights N stress.

Strategy	Dalby						Emerald					
	10	30	60	90	120	150	10	30	60	90	120	150
SEY	0.31	0.26	0.16	0.05	0.00	0.00	0.04	0.01	0.00	0.00	0.00	0.00
PK	0.31	0.25	0.15	0.09	0.04	0.00	0.04	0.01	0.00	0.00	0.00	0.00
ISN	0.31	0.24	0.09	0.04	0.01	0.01	0.03	0.00	0.00	0.00	0.00	0.00
ISW	0.32	0.27	0.15	0.07	0.03	0.01	0.04	0.01	0.00	0.00	0.00	0.00
SWxSN	0.32	0.26	0.11	0.03	0.01	0.00	0.03	0.00	0.00	0.00	0.00	0.00
Goondiwindi							Minnipa					
SEY	0.14	0.09	0.03	0.00	0.00	0.00	0.33	0.23	0.11	0.03	0.01	0.01
PK	0.14	0.09	0.03	0.01	0.01	0.00	0.33	0.22	0.10	0.06	0.04	0.03
ISN	0.14	0.07	0.01	0.00	0.00	0.00	0.32	0.24	0.14	0.08	0.04	0.03
ISW	0.15	0.10	0.07	0.04	0.03	0.01	0.33	0.22	0.11	0.07	0.05	0.03
SWxSN	0.14	0.09	0.03	0.00	0.00	0.00	0.33	0.23	0.11	0.04	0.02	0.01
Yorketown							Merredin					
SEY	0.05	0.02	0.00	0.00	0.00	0.00	0.38	0.35	0.19	0.06	0.01	0.00
PK	0.05	0.04	0.02	0.01	0.00	0.00	0.39	0.35	0.20	0.11	0.06	0.03
ISN	0.05	0.01	0.00	0.00	0.00	0.00	0.38	0.33	0.19	0.13	0.07	0.05
ISW	0.06	0.04	0.02	0.01	0.00	0.00	0.39	0.35	0.22	0.14	0.09	0.05
SWxSN	0.05	0.02	0.00	0.00	0.00	0.00	0.39	0.35	0.19	0.08	0.03	0.01
Moora							Wogan Hills					
SEY	0.35	0.34	0.28	0.21	0.16	0.12	0.31	0.27	0.14	0.04	0.01	0.00
PK	0.35	0.35	0.30	0.22	0.16	0.35	0.31	0.27	0.14	0.08	0.04	0.02
ISN	0.35	0.33	0.27	0.22	0.18	0.15	0.31	0.25	0.12	0.08	0.04	0.02
ISW	0.35	0.34	0.28	0.22	0.18	0.15	0.32	0.27	0.17	0.11	0.07	0.04
SWxSN	0.35	0.34	0.28	0.21	0.17	0.14	0.32	0.27	0.13	0.04	0.02	0.01
Condobolin							Waga Waga					
SEY	0.30	0.21	0.09	0.03	0.00	0.00	0.44	0.37	0.22	0.09	0.04	0.02
PK	0.31	0.22	0.12	0.06	0.03	0.02	0.44	0.39	0.22	0.14	0.09	0.05
ISN	0.30	0.20	0.10	0.06	0.03	0.02	0.43	0.36	0.23	0.16	0.09	0.06
ISW	0.31	0.22	0.10	0.04	0.02	0.01	0.44	0.38	0.24	0.16	0.10	0.06
ISWxISN	0.31	0.21	0.08	0.02	0.00	0.00	0.44	0.37	0.23	0.11	0.05	0.03
Birchip												
SEY	0.38	0.30	0.14	0.03	0.00	0.00						
PK	0.39	0.31	0.13	0.07	0.03	0.01						
ISN	0.38	0.29	0.15	0.10	0.05	0.03						
ISW	0.38	0.30	0.17	0.12	0.08	0.04						
ISWxISN	0.38	0.30	0.14	0.04	0.02	0.01						

The degree of N stress varied across sites, levels and strategy of N application. For example little or no stress between stem elongation and flowering was observed in Goondiwindi, Yorketown and Emerald. The highest degree of stress was observed for Moora, which was associated to the lowest level of total soil carbon (Table 1). At the other sites N stress was

higher than 0.1 up to 60-90kg N ha⁻¹. Nitrogen management rules that modified N supply, for example as a function of ISW or ISN, tended to increase the NSI. This could probably be related to the fact that in drier seasons the ISW rules halved the amount of N added as fertilisers, and in addition N mineralisation might have been also reduced, exacerbating the deficiency.

Water Stress Index

Table 4 shows the median WSI for six nitrogen application treatments and five nitrogen management strategies for the period of stem elongation to flowering (GS31- GS65). This is the period of ear growth when the grain number is defined. Irrespective of the N rate or N management strategy, no significant water stress was simulated for Yorketown, while high water stress was observed in Emerald. Overall, water stress increased with the increase of N rates, and strategies that used perfect knowledge, ISW or ISW to modify N rates tended to reduce the intensity of water stress, probably by reducing the amount of N applied in the drier seasons.

Table 4. Water stress index (WSI) from stem elongation to flowering (GS31 to GS65). WSI ranges from 1 (maximum stress) and 0 (no stress).

Strategy	Dalby						Emerald					
	10	30	60	90	120	150	10	30	60	90	120	150
SEY	0.12	0.17	0.26	0.35	0.39	0.41	0.41	0.44	0.44	0.44	0.44	0.44
PK	0.11	0.15	0.23	0.30	0.37	0.41	0.41	0.43	0.44	0.44	0.44	0.44
ISN	0.12	0.19	0.32	0.36	0.39	0.39	0.42	0.44	0.44	0.44	0.44	0.44
ISW	0.11	0.16	0.26	0.32	0.37	0.41	0.41	0.43	0.44	0.44	0.44	0.44
SWxSN	0.12	0.17	0.30	0.36	0.39	0.40	0.42	0.44	0.44	0.44	0.44	0.44
Goondiwindi						Minnipa						
SEY	0.27	0.34	0.39	0.42	0.42	0.42	0.11	0.21	0.27	0.33	0.34	0.34
PK	0.27	0.33	0.39	0.41	0.42	0.42	0.10	0.18	0.27	0.30	0.32	0.33
ISN	0.28	0.35	0.41	0.42	0.42	0.42	0.11	0.20	0.27	0.30	0.32	0.33
ISW	0.27	0.32	0.37	0.39	0.40	0.41	0.10	0.19	0.27	0.29	0.31	0.33
SWxSN	0.27	0.35	0.40	0.42	0.42	0.42	0.11	0.20	0.28	0.32	0.33	0.34
Yorketown						Merredin						
SEY	0.04	0.06	0.07	0.07	0.07	0.07	0.06	0.15	0.30	0.38	0.41	0.41
PK	0.04	0.05	0.06	0.06	0.07	0.07	0.04	0.12	0.25	0.33	0.37	0.39
ISN	0.04	0.06	0.07	0.07	0.07	0.07	0.06	0.17	0.29	0.33	0.37	0.38
ISW	0.04	0.05	0.06	0.07	0.07	0.07	0.04	0.12	0.24	0.32	0.36	0.38
SWxSN	0.04	0.06	0.07	0.07	0.07	0.07	0.05	0.14	0.29	0.37	0.40	0.40
Moora						Wogan Hills						
SEY	0.01	0.03	0.07	0.10	0.13	0.14	0.05	0.12	0.20	0.25	0.27	0.27
PK	0.01	0.02	0.05	0.08	0.11	0.01	0.04	0.10	0.19	0.23	0.25	0.26
ISN	0.01	0.03	0.07	0.09	0.12	0.13	0.06	0.13	0.21	0.23	0.25	0.26
ISW	0.01	0.02	0.07	0.10	0.12	0.13	0.05	0.11	0.18	0.21	0.24	0.25
SWxSN	0.01	0.03	0.07	0.10	0.12	0.14	0.05	0.12	0.21	0.25	0.26	0.26
Condobolin						Waga Waga						
SEY	0.20	0.30	0.40	0.44	0.46	0.47	0.05	0.14	0.26	0.32	0.35	0.36
PK	0.18	0.27	0.37	0.41	0.44	0.45	0.04	0.11	0.22	0.27	0.31	0.33
ISN	0.20	0.31	0.39	0.43	0.45	0.45	0.06	0.15	0.24	0.29	0.33	0.34
ISW	0.18	0.28	0.39	0.43	0.45	0.46	0.04	0.12	0.22	0.28	0.32	0.34
ISWxISN	0.19	0.30	0.41	0.45	0.47	0.47	0.05	0.14	0.25	0.32	0.35	0.36
Birchip												
SEY	0.08	0.16	0.25	0.30	0.31	0.31						
PK	0.06	0.12	0.23	0.27	0.29	0.31						
ISN	0.09	0.17	0.24	0.27	0.29	0.30						
ISW	0.06	0.14	0.22	0.25	0.27	0.29						
ISWxISN	0.08	0.16	0.25	0.29	0.30	0.31						

Water Use Efficiency

Table 5 Water Use Efficiency (WUE kg ha⁻¹ mm⁻¹) across locations for the different simulated scenarios

Site	Strategy	Median WUE						Probability of WUE > 10 kg ha ⁻¹ mm ⁻¹					
		10	30	60	90	120	150	10	30	60	90	120	150
Dalby	SEY	6.8	7.0	7.5	7.9	8.2	7.8	0.00	0.04	0.09	0.19	0.26	0.29
	PK	6.9	7.1	7.4	7.9	8.0	6.9	0.00	0.04	0.22	0.27	0.30	0.00
	ISN	6.9	7.2	7.8	7.9	8.2	8.2	0.00	0.03	0.10	0.20	0.25	0.27
	ISW	6.8	7.0	7.6	7.9	8.1	8.2	0.00	0.02	0.12	0.23	0.23	0.25
	SWxSN	6.8	7.1	7.8	8.1	8.2	8.3	0.00	0.03	0.12	0.21	0.27	0.27
Emerald	SEY	8.3	8.4	8.7	8.7	8.7	8.7	0.18	0.22	0.23	0.24	0.25	0.25
	PK	8.3	8.4	8.6	8.7	8.7	8.7	0.18	0.22	0.25	0.25	0.25	0.25
	ISN	8.2	8.4	8.5	8.7	8.7	8.7	0.18	0.22	0.23	0.24	0.25	0.25
	ISW	8.2	8.4	8.5	8.7	8.7	8.7	0.18	0.23	0.24	0.25	0.25	0.25
	SWxSN	8.2	8.4	8.6	8.7	8.7	8.7	0.18	0.23	0.24	0.25	0.25	0.25
Goondiwindi	SEY	8.3	8.3	8.5	8.7	8.8	8.8	0.15	0.17	0.24	0.28	0.29	0.29
	PK	8.3	8.4	8.7	8.8	8.8	8.8	0.14	0.18	0.28	0.29	0.28	0.28
	ISN	8.3	8.3	8.7	8.7	8.7	8.8	0.14	0.17	0.21	0.25	0.28	0.28
	ISW	8.2	8.3	8.4	8.5	8.6	8.7	0.15	0.17	0.23	0.25	0.25	0.26
	SWxSN	8.2	8.2	8.5	8.7	8.8	8.8	0.15	0.17	0.23	0.28	0.28	0.28
Minnipa	SEY	2.6	4.0	4.8	4.9	4.9	4.9	0.00	0.00	0.06	0.14	0.19	0.21
	PK	2.5	3.3	4.2	4.6	4.9	5.1	0.00	0.00	0.17	0.20	0.21	0.21
	ISN	2.6	3.9	4.6	4.8	5.0	5.1	0.00	0.00	0.04	0.07	0.12	0.14
	ISW	2.6	3.4	4.2	4.6	4.6	4.8	0.00	0.01	0.13	0.16	0.16	0.16
	SWxSN	2.6	3.9	4.7	4.9	4.9	4.9	0.00	0.00	0.08	0.14	0.17	0.19
Yorketown	SEY	14.8	14.9	14.7	14.8	14.7	14.7	0.91	0.93	0.93	0.93	0.93	0.93
	PK	14.8	14.7	14.3	14.3	14.5	14.5	0.91	0.91	0.92	0.92	0.93	0.93
	ISN	14.7	14.7	15.1	14.9	14.7	14.7	0.91	0.93	0.93	0.93	0.93	0.93
	ISW	14.5	14.8	14.8	14.7	14.7	14.7	0.91	0.91	0.92	0.92	0.93	0.93
	ISWxISN	14.7	14.8	14.8	14.9	14.9	14.7	0.91	0.93	0.93	0.93	0.93	0.93
Merredin	SEY	6.2	6.8	8.2	8.5	8.6	8.6	0.01	0.01	0.07	0.21	0.29	0.31
	PK	6.4	7.2	8.1	8.3	8.5	8.5	0.02	0.02	0.22	0.25	0.27	0.30
	ISN	6.4	7.1	7.5	8.0	8.5	8.6	0.01	0.01	0.06	0.12	0.19	0.22
	ISW	6.1	6.9	7.3	7.9	8.4	8.6	0.02	0.02	0.17	0.23	0.24	0.26
	ISWxISN	6.3	6.9	8.0	8.4	8.5	8.6	0.01	0.01	0.08	0.21	0.27	0.30
Moora	SEY	2.2	3.3	4.6	5.5	6.4	7.0	0.00	0.00	0.00	0.03	0.10	0.15
	PK	2.0	3.2	4.5	5.5	6.2	2.0	0.00	0.00	0.00	0.01	0.03	0.00
	ISN	2.2	3.2	4.7	5.6	6.3	6.5	0.00	0.00	0.02	0.06	0.10	0.12
	ISW	2.2	3.4	4.9	5.6	6.4	6.7	0.00	0.00	0.01	0.06	0.08	0.10
	ISWxISN	2.2	3.3	4.8	5.6	6.4	6.6	0.00	0.00	0.00	0.04	0.10	0.14
Wogan Hills	SEY	7.4	8.5	9.9	10.7	11.3	11.7	0.00	0.13	0.47	0.65	0.71	0.71
	PK	7.4	8.8	9.8	10.7	11.2	11.5	0.00	0.21	0.55	0.61	0.64	0.68
	ISN	7.5	8.7	9.6	10.5	11.2	11.4	0.00	0.13	0.42	0.57	0.64	0.67
	ISW	7.3	8.3	9.4	10.2	10.5	10.9	0.01	0.21	0.40	0.56	0.63	0.69
	ISWxISN	7.4	8.6	9.9	10.7	11.3	11.7	0.00	0.14	0.47	0.65	0.70	0.72
Condobolin	SEY	7.5	8.2	8.6	8.9	9.2	9.3	0.06	0.13	0.30	0.31	0.37	0.39
	PK	7.7	8.3	8.5	8.9	8.9	9.0	0.07	0.20	0.33	0.36	0.39	0.39
	ISN	7.8	8.3	8.8	8.9	8.9	9.0	0.04	0.13	0.18	0.29	0.36	0.37
	ISW	7.8	8.0	8.7	9.0	9.1	9.1	0.06	0.19	0.25	0.32	0.36	0.37
	ISWxISN	7.7	8.2	8.8	9.0	9.1	9.2	0.06	0.14	0.27	0.32	0.37	0.39
Waga Waga	SEY	5.9	7.1	8.5	9.2	9.8	10.5	0.00	0.00	0.06	0.34	0.46	0.56
	PK	5.9	7.1	8.2	9.1	9.7	10.0	0.00	0.01	0.32	0.38	0.46	0.50
	ISN	5.9	6.9	7.7	8.5	9.1	9.4	0.00	0.00	0.12	0.23	0.33	0.38
	ISW	5.9	7.0	8.0	8.8	9.2	9.5	0.00	0.00	0.20	0.34	0.39	0.46
	ISWxISN	5.9	7.1	8.3	8.9	9.6	10.0	0.00	0.00	0.10	0.33	0.43	0.51
Birchip	SEY	6.5	7.9	9.0	10.0	10.5	10.9	0.04	0.09	0.33	0.50	0.56	0.58
	PK	6.8	8.1	9.0	9.7	10.1	10.6	0.04	0.19	0.45	0.49	0.51	0.52
	ISN	6.8	7.9	8.8	9.1	9.8	10.1	0.04	0.10	0.26	0.39	0.47	0.50
	ISW	6.5	7.7	8.5	8.6	9.3	9.7	0.04	0.19	0.34	0.41	0.45	0.49
	ISWxISN	6.6	8.0	8.9	9.8	10.4	10.5	0.04	0.11	0.35	0.48	0.53	0.54

Median WUE increased with the availability of N (Table 5 and Figure 2), though results varied across N management strategies. The median WUE under the different strategies and sites was lower than $14.8 \text{ kg ha}^{-1}\text{mm}^{-1}$, though the maximum achieved WUE was close to the

All sites except Yorketown and Birchip had median values of WUE below $10 \text{ kg ha}^{-1} \text{ mm}^{-1}$. Changes in the probability of WUE over $10 \text{ kg ha}^{-1} \text{ mm}^{-1}$ with management strategies were location- and N-rate dependent. The largest response in WUE as a function of N was observed at Moora, WA, a site where the water stress index was relatively low, and the nitrogen stress index was relatively high (Tables 3 and 4). The reason why WUE at Minnipa did not respond as much as at the other locations requires further analysis. Yorketown in SA had the highest WUE and the lowest response to N, consistent with the lack of nitrogen stress (Table 3).

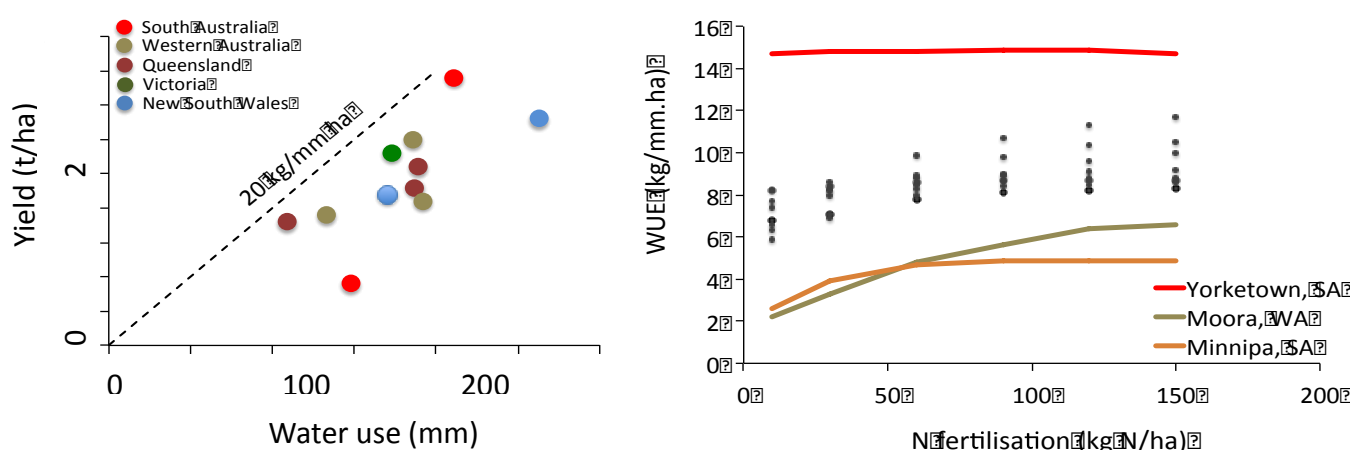


Figure 2. (a) Simulated maximum yield as a function of water use across all simulated sites. The dotted line shows water use efficiency equivalent to $20 \text{ kg mm}^{-1} \text{ ha}^{-1}$. (b) Median water use efficiency for the strategy where both ISW and ISN were used decided on the level of N fertilisation, as a function of level of applied N (kg ha^{-1}). Lines are for the extreme responses, and small dots for the rest of the sites.

Managing profit and risk using soil information and a seasonal climate forecasting

The value of the different types of information i.e. ISW, ISN and POAMA, to support N management decisions was different across the locations and N rates. An example for three sites is presented in Figure 3, which shows the value of the different strategies and that of POAMA to support N fertilisation decisions at sowing of wheat at Condobolin (WA), Dalby (QLD) and Wongan Hill (WA).

At Dalby and Wongan Hills the POAMA forecast was as good as knowing in advance seasonal rainfall for levels of N fertilisation between 60 and 150kg N/ha. This is highly encouraging as information on initial soil conditions was only valuable, in general at low N rates. At Condobolin the benefits were smaller (upper row in Figure 3).

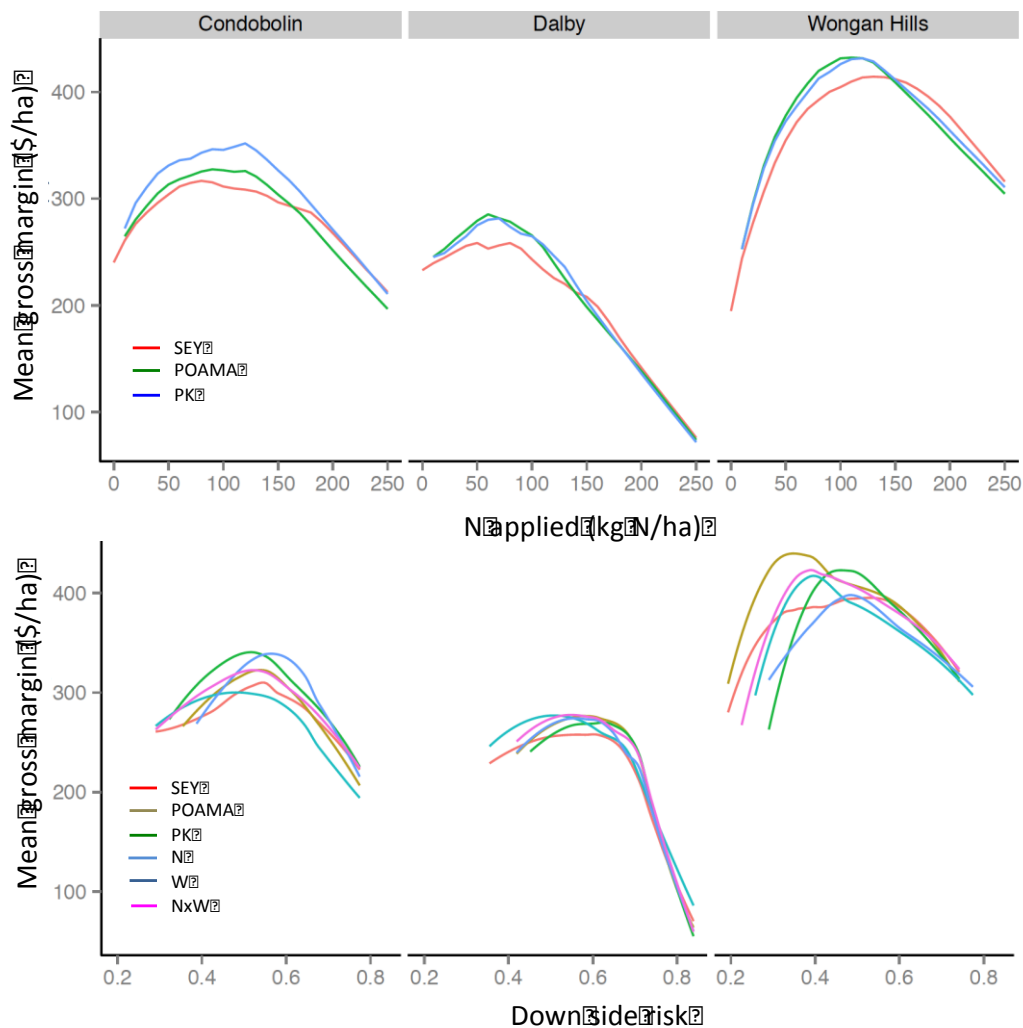


Figure 3. Simulated mean gross margin (\$/ha) as a function of N applied (kg N/ha) and down side risk for Condobolin (NSW), Dalby (Qld) and Wongan Hills (WA). Down side risk is the probability of a return in investment (\$/\$) lower than 1.1.

When all the sources of information were combined and compared to the controls i.e. same management each year (SEY), and perfect knowledge (PK) on seasonal conditions (see lower row of plots in Figure 3), different types of information appeared to have different importance across the different locations and levels of N supply.

However we can generalise that in most cases using soil water or soil N at sowing to decide on N management was more effective than the strategy that applied the same amount of N every year (SEY). At Dalby for example profits could be increased and or risks reduced at the lower levels of N supply if information about soil N at planting would be used. The increase in gross margins was as high as 50\$/ha from sampling the soil before planting and sending the samples to determine soil mineral N. Considering that the cost per soil test is

close to 20\$/sample, the benefits from modifying N management based on knowing the initial soil N would be paid with just one ha of crop planted. At Wongan Hills the use of POAMA would allow farmers to significantly increase profits and reduce risks, this is a significant result as in WA the skill and value of the 5 SOI phase system can be considered close to zero. In Condobolin information about both ISN and ISW proved to be valuable across the range of levels of N tested.

The results for Victoria and South Australia were less clear; this might be due to the way APSIM was set up, or the description of the soils that were used in the simulations. Though before we have shown how different intensities of both water and nitrogen stress (Tables 3 and 4) affected efficiency measures such as WUE (Figures 2a and b). The analysis of the potential value for the Southern states merits detailed analysis that is beyond the scope of this report.

Discussion

Our simulations highlighted complex interactions among soil type, initial water and nitrogen conditions, N management, and seasonal conditions.

The sites having the highest in crop rainfall were Wagga-Wagga followed by Yorketown and Moora. In about 70% of seasons, in crop rainfall in Wagga-Wagga was between 200 and 500 mm. In Emerald and Merredin, the driest sites in our study, in crop rainfall was less than 200 mm in 90% of seasons.

Simulated long-term median yields showed a clear response to nitrogen fertilizer in each strategy. The probability of achieving yields of more than 2.5 t ha⁻¹ was generally higher for the ISWxISN strategy though usually for rates of N application to 60 kg N ha⁻¹ across most of the sites. Differences between SEY and information-based strategies faded at higher N rates. Thus, at lower levels of investment in fertiliser having additional information on initial soil nitrogen would appear to increase profit and reduce risk, while information about initial soil water appeared to be particularly useful at higher N investment.

Owing to the law of diminishing returns, TFP declined with increasing fertiliser rate. TFP also varied between strategies and sites. In most of the sites, the chance of TFP over 40 kg kg⁻¹ was higher for SEY, PK, ISN strategies at rates from 10 to 60 kg N ha⁻¹. The ISW strategy returned higher TFP at 90 kg N ha⁻¹ or higher rates.

As expected NSI declined with increasing N rate, and varied between strategies and sites. It varied from 0-0.36 in the period emergence-GS31, 0-0.44 in GS31-GS65 and 0-0.73 in the GS65 to harvest. In the same way that patterns of supply and demand of water has been established for wheat across the grain belt, location-specific patterns of supply and demand of nitrogen are needed (Chapter 1).

WSI decreased with the increase of N rates. Overall, WSI did not differ between strategies and N rates for the period emergence-GS31. This is consistent with the low demand of water in small crops. In Wagga Wagga, Merredin, Wongan Hills and Birchip, a large drop in WSI in the period GS31-GS65 was observed when the N application rate was increased from 30 to 60 kg N ha⁻¹.

Maximum WUE corresponded to the maximum grain yield. WUE increased with increasing N rate for each strategy and varied with the management strategy. The median WUE under the different strategies and sites was lower than 14.8 kg ha⁻¹mm⁻¹. All the sites except Yorketown and Birchip had a median WUE of less than 10 kg ha⁻¹ mm⁻¹. Higher water use efficiencies were observed at 150 kg N ha⁻¹, though the probability of achieving values of WUE larger than 10 kg ha⁻¹ mm⁻¹ were different between sites and strategies. For Dalby the probability of achieving WUE greater than 10 kg ha⁻¹ mm⁻¹ was higher for the strategy that required both ISW and ISN at 120 kg N ha⁻¹. At Emerald, the different information strategies and the addition of N did not affect WUE. At Yorketown ISN at 60 kg N ha⁻¹ produced the highest WUE. The lowest WUE was simulated for Minnipa and Moora, where the probability of achieving values of WUE greater than 10 kg ha⁻¹ mm⁻¹ were near zero for all strategies receiving 60 kg N ha⁻¹ or less.

The gross margin vs risk curves were strongly site-dependent. For example, at Dalby the GM increased with increasing N-rates to 110 kg N ha⁻¹. The return on investment (ROI) was higher at low rates of investment in N (10-30 kg N ha⁻¹), as expected from diminishing returns in yield. A rate of 100 kg N ha⁻¹ provided higher GMs with an associated risk of 47%. The highest GM was obtained from using both information about ISW and ISN *i.e.* 344 \$ ha⁻¹ at a 46% probability of low ROI.

The value of POAMA to support N management decisions differed greatly across Australia's grains regions, and across levels of investment in N fertilisers. The clearest results were observed at Dalby, Wongan Hills and Condobolin where using POAMA forecasts to decide on N fertilisation significantly reduced risk and increased profit. The results from POAMA in Victoria and South Australia might be affected by the way soils were parameterised.

However, in rainfed cropping, yield and consequently farmers' profits, depend not only on the nitrogen nutrition of the crop, but also on farmers' capacity to match genotype and management to the growing environment and expected seasonal conditions. Thus, the full potential from using soil and POAMA information can only emerge from integrating this information with information about:

- Genotype: Maturity, tillering, stay green type, early vigour, transpiration efficiency, root patterns, disease and lodging tolerance, and quality traits (protein, screenings).
- Crop management: Monitoring and forecasting tools (soil water and N, POAMA, PredictaB), weed control, tillage and stubble management, sowing window, plant density and row configuration, N and P management (rate, timing, placement); micronutrients as required
- Environment: Soil, including depth, plant available water, chemical and physical constraints; Climate, including rainfall patterns and risk of extreme temperatures (frost and heat stress).

Here we propose that future investments should aim to quantify the value of ISW, ISN and POAMA by:

- (i) Establishing a network of real farm case studies representing the North, South and West regions,
- (ii) Compiling and integrating soil, genotype, climate and management information,
- (iii) Engaging with growers to discuss these strategies in relation to relevant and actionable decisions,
- (iv) Using APSIM to test the value of initial soil conditions and POAMA,
- (v) Comparing APSIM results with real-farm outcomes,
- (vi) Formalising location-specific recommendations on the relative value of different sources of information.

References

- Anwar, M.R., O'Leary, G., McNeil, D., Hossain, H., Nelson, R., 2007. Climate change impact on rainfed wheat in south-eastern Australia. *Field Crops Research* 104, 139–147. doi:10.1016/j.fcr.2007.03.020
- Carberry, P.S., Hochman, Z., Hunt, J.R., Dalgliesh, N.P., McCown, R.L., Whish, J.P.M., Robertson, M.J., Foale, M.A., Poulton, P.L., van Rees, H., 2009. Re-inventing model-based decision support with Australian dryland farmers. 3. Relevance of APSIM to commercial crops. *Crop Pasture Sci.* 60, 1044–13. doi:10.1071/CP09052
- Doherty, A., Sadras, V.O., Rodriguez, D., Potgieter, A., 2010. Quantification of wheat water-use efficiency at the shire-level in Australia. *Crop Pasture Sci.* 61, 1–11. doi:10.1071/CP09157
- Hochman, Z., Carberry, P.S., 2011. Emerging consensus on desirable characteristics of tools to support farmers' management of climate risk in Australia. *Agricultural Systems* 104, 441–450. doi:10.1016/j.agsy.2011.03.001
- Hudson, D., Marshall, A.G., Yin, Y., Alves, O., Hendon, H.H., 2013. Improving Intraseasonal Prediction with a New Ensemble Generation Strategy. *Mon. Wea. Rev.* 141, 4429–4449. doi:10.1175/MWR-D-13-00059.1
- Khan, M.Z.K., Sharma, A., Mehrotra, R., Schepen, A., Wang, Q.J., 2015. Does improved SSTA prediction ensure better seasonal rainfall forecasts? *Water Resour. Res.* 51, 3370–3383. doi:10.1002/2014WR015997
- McCown, R.L., Carberry, P.S., Hochman, Z., Dalgliesh, N.P., Foale, M.A., 2009. Re-inventing model-based decision support with Australian dryland farmers. 1. Changing intervention concepts during 17 years of action research. *Crop Pasture Sci.* 60, 1017–14. doi:10.1071/CP08455
- Rodriguez, D., Sadras, V.O., 2007. The limit to wheat water-use efficiency in eastern Australia. I. Gradients in the radiation environment and atmospheric demand. *Aust. J. Agric. Res.* 58, 287–16. doi:10.1071/AR06135
- Sadras, V.O., Angus, J.F., 2006. Benchmarking water-use efficiency of rainfed wheat in dry environments. *Aust. J. Agric. Res.* 57, 847–10.
- Sadras, V.O., Rodriguez, D., 2007. The limit to wheat water-use efficiency in eastern Australia. II. Influence of rainfall patterns. *Aust. J. Agric. Res.* 58, 657–13.
- White, C.J., Hudson, D., Alves, O., 2013. ENSO, the IOD and the intraseasonal prediction of heat extremes across Australia using POAMA-2. *Clim Dyn* 43, 1791–1810. doi:10.1007/s00382-013-2007-2

