Farmer risk-aversion limits closure of yield and profit gaps: A study of nitrogen management in the southern Australian wheatbelt

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ABSTRACT

Nitrogen (N) is the most limiting nutrient in cereal crop production and is an important requirement in closing the gap between potential and achieved water limited yield. However, N fertiliser management in broadacre cereal cropping can be risky for farmers operating in dryland regions because of variability of rainfall and price. Farmers typically respond to this situation by making risk-averse decisions that are neither yield- nor profit-maximising. Here we use a set of case-study sites across the southern Australian wheatbelt to examine the risk-return profile of a range of N management options and show the extent to which the economics of N fertiliser decisions and the farmers’ attitude to risk can determine N rates in a way that limits closure of yield gaps. Using a risk-return framework that incorporates crop simulation response to N application, probability theory, finance techniques, and risk-aversion analysis, we were able to better demonstrate how farmers might select N management practices that manage the trade-off between maximising economic net return and risk exposure using a risk-aversion analysis across four case-study sites.

1. Introduction

Agricultural practices that close yield gaps between actual and potential crop yields are receiving increased global attention in an effort to improve food security (Abeledo et al., 2008; Mueller et al., 2012; Van Ittersum et al., 2013). Reducing this gap is often achieved through the intensification of agronomic management and reduction of important constraints to water-limited crop performance such as nutrition, weeds, disease and pests (Hochman et al., 2012; Lobell et al., 2009; Van Ittersum et al., 2013). However, the maximisation of water-limited yield does not necessarily result in the maximisation of profit or the preferred level of exposure to risk for dryland cropping farmers, particularly where large fertiliser costs are involved (Lobell, 2007; Lobell et al., 2009).

In Australia, farmers in dryland cropping regions need to select fertiliser rates for their cereal crops in the face of high variability of seasons (CSIRO, 2010), as well as grain and input prices (ABARE, 2010; FAO, 2010; Price, 2009). Deciding on the best rate of fertiliser is influenced by many factors, including grain prices, fertiliser prices, farm logistics, available finance and the crop potential yield, which is in turn controlled by available water, soil fertility, weed and pest burdens, and land use history (Angus, 2001; Chen et al., 2008; McDonald, 1989). The inherent riskiness of grain production is often high (Hayman et al., 2010; Sadras, 2002) and a two-fold increase in variance in wheat revenue over the past two decades has been recorded in some major Australian cropping regions (Kingwell, 2011), partly in consequence of climate-related yield variance and partly due to system change towards continuous cropping (e.g. less fallow/pasture) (Llewellyn and D’Emden, 2012).

The most commonly limiting nutrient and largest fertiliser cost for Australian farmers is nitrogen (N) (Chen et al., 2008). In low-rainfall environments, such as the wheatbelt, there is an N-driven trade-off between yield per unit N and yield per unit water use (Sadras and Rodriguez, 2010). The yield-N response curve (diminishing returns) means that the common practice of applying low N rates can be interpreted as an approach that maximises N use efficiency (NUE), at the expense of achieving their full water-limited yield potential. As a result, N has been described as a risk-increasing input, a theory with resonance worldwide (Broun, 2007; Just and Pope, 1979; Leathers and Quiggin, 1991; Lobell, 2007; McDonald, 1989; Picazo-Tadeo and Wall, 2011; Quiggin and Anderson, 1979; Rajsic et al., 2009; Roosen and Hennessy, 2003; Russell, 1968; Sadras, 2002; Sadras and Richards, 2014; Van Herwaarden et al., 1998). Exceptions are higher rainfall regions with high yield potential where over-application of N (i.e. more than necessary to attain a given yield target) has been associated with farmer risk-aversion (Gandorfer et al., 2011; Rajsic and Weersink, 2008; Rajsic et al., 2009).

Strategies and tools have been successfully developed to manage the riskiness of N fertiliser decisions (Hochman and Carberry, 2011). Nevertheless, in the highly variable dryland environments of...
Australia, where a high level of risk (and risk-aversion) provides extra incentives for farmers to reduce their risk-exposure (Bardsley and Harris, 1987; Bond and Wonder, 1980; Chavas and Holt, 1996; Kingwell and Pannell, 2005; Kingwell, 1994; Leathers and Quiggin, 1991; Monjardino et al., 2013; O’Connell et al., 2003; Pannell et al., 2000), many wheat farmers are known to adopt particularly low rates of N (based on average local industry recommendations) and thereby are likely to miss out on greater returns from more intense cropping in more favourable production years (Asseng et al., 2001; Cossani et al., 2010; SADARS; Sadras and Rodriguez, 2010; Sadras and Roget, 2004; Sadras et al., 2012). Therefore, since investment in N fertiliser remains a highly challenging decision for farmers, we question their practice of consistently under-fertilising based on the premise that it can be modified when attitude to risk is considered, because farmers with different degrees of risk-aversion are likely to have different preferences for N strategies (Arrow, 1971; Hardaker et al., 2004a; Kingwell, 1994; Lambert, 1990; Leathers and Quiggin, 1991; Pannell et al., 2000; Pratt, 1964).

In a previous study, we explored the effect of adopting these low N input strategies on profit-risk outcomes across soil zones in one case-study site in south-eastern Australia (Monjardino et al., 2013). In this paper, we expand the analysis to identify the role of risk and risk-aversion in determining preferred N fertiliser rates (including in-season applications) and the consequent constraints to closing yield gaps and achieving water-limited potential yield across a range of Australian cropping environments.

The extent to which both risk and risk-aversion affect yield- and profit-maximisation is tested using a risk-return framework that incorporates crop simulation response to N application, probability theory, finance techniques, and risk-aversion analysis. This is applied with the aim of providing insight into the ability to improve profitability and productivity within decision-making contexts with varying levels of risk-aversion and cropping risk, and, ultimately, of influencing farmer practice in the quest for the sustainable intensification of agriculture.

2. Methods

2.1. Case-study sites

This study focuses on four sites across several Australian grain-growing regions in four states. In the low-rainfall region (below 350 mm), the focus is on Hopetoun (~35,734, 142.237) in the Victorian Mallee. This site has a winter-dominant low rainfall pattern, resulting in cereal crops that are often exposed to varying degrees of moisture stress, including terminal drought (Sadras, 2003; Sadras and Baldock, 2003). In the winter-dominant medium-rainfall region (350 to 500 mm) the focus is on Hart (~33,753, 138.416), located in mid-north of South Australia, and on Wongan Hills (~30.88, 116.71) in the central wheatbelt of Western Australia where, due to the low soil water holding capacity, summer rainfall events provide little water to winter-grown crops. The focus site in the high-rainfall region (above 500 mm) is Temora (~34,533, 147.57) in New South Wales where rainfall is distributed relatively equally over the four seasons with significant reliance on stored soil water from the fallow period for crop growth. Annual and April–October rainfall is given for each site in Table 1 together with current typical N fertiliser rates based on consultation with local advisors.

Assumed current site practice for nitrogen fertiliser applications based on expert local advice is shown in Table 1. Importantly, we recognise that the current site practice rates referred to here may reflect the risk farmers have experienced over only part of the historical period modelled. This is particularly relevant after a longer drier period (in the lower rainfall site), when the memory of the recent dry years likely affects management, hence contributing to more conservative site practice rates (Alem et al., 2010; Picazo-Tadeo and Wall, 2011). While for clarity we focus on the use of single site practice rates in this study, it should be noted that this does not recognise the broad range of N rates used by farmers over the range of soils and situations in a region, including those using variable rate fertiliser application within-fields.

2.2. Crop yield simulation

The Agricultural Production Systems Simulator (APSIM v.7.3) (Keating et al., 2003) was used to model water- and N-limited grain-yield over the 1950 to 2010 growing seasons using the climate files described in Table 1. All nutrients other than N and the effects of pests, disease, weeds, and heat or frost shock were not modelled and assumed to be non-limiting. APSIM has been widely tested and validated in Australian cropping systems for the simulation of wheat and soil water and N response to different seasons and N management strategies (Hochman et al., 2009; Hunt and Kirkegaard, 2011; Jones and Whitbread, 2010; Probert et al., 1998; Sadras and Rodriguez, 2010; Verburg et al., 2007). To simulate yields, the APSIM wheat module was used in conjunction with the soil-water module (SOILWAT 2), the soil-N module (SOIL N) and the surface-residue model (RESIDUE) (Oliver and Robertson, 2009; Probert et al., 1998).

To validate APSIM, the measured yield data for Hopetoun were sourced from field trials described by Hunt et al. (2013), for Wongan Hills the data were sourced from DAFWA field trials (1983 and 1996) described by Delroy and Bowden (1986) and Pluske (1998), for Hart the data were sourced from Hart Field site trials (unpublished data 2005–2010, Hooper, P) and for the Temora site the data were sourced from Hunt et al. (2012).

Table 1

<table>
<thead>
<tr>
<th>Site</th>
<th>State</th>
<th>Annual rainfall (mm)</th>
<th>Apr–Oct rainfall (mm)</th>
<th>Climate station number</th>
<th>APSOIL No.</th>
<th>Soil type</th>
<th>Site practice (kg N ha⁻¹)</th>
<th>Input costs (AUD ha⁻¹)</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hopetoun</td>
<td>VIC</td>
<td>330</td>
<td>213</td>
<td>77018</td>
<td>717</td>
<td>Duplex Sandy loam over clay (chromosol)</td>
<td>20 sown + 30 in-season</td>
<td>127</td>
<td>S. Craig, C. Browne, H. van Rees, R. Kingwell, Y. Oliver, M. Robertson, J. Braun, P. Hooper, J. Hunt</td>
</tr>
<tr>
<td>Wongan Hills</td>
<td>WA</td>
<td>350</td>
<td>270</td>
<td>8137</td>
<td>400</td>
<td>Loamy sand (kandosol)</td>
<td>25 sown + 10–15 in-season</td>
<td>185</td>
<td></td>
</tr>
<tr>
<td>Hart</td>
<td>SA</td>
<td>400</td>
<td>270</td>
<td>21007</td>
<td>286</td>
<td>Light Clay over Medium Clay (calcitosol)</td>
<td>30 sown + 30 in-season</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Temora</td>
<td>NSW</td>
<td>520</td>
<td>281</td>
<td>73038</td>
<td>179</td>
<td>Sandy clay loam over light clay (brown chromosol)</td>
<td>10 sown + 50 in-season</td>
<td>203</td>
<td></td>
</tr>
</tbody>
</table>

*Daily climate data from the SILO historical climate database for each site.

APSOIL No. refers to the soil no. for identifying the relevant soil characterisation on the APSOIL database (available from: http://www.apsim.info/wiki/APSolashx).

Input costs include seed and dressing, herbicides, fungicides, fertilisers excluding N, fuel and oil, repairs and maintenance, labour, levies, insurance, interest on variable costs (8%), depreciation (10% of $200 ha⁻¹ machinery investment) from the data sources listed.
Table 2

APSIM soil, sowing and fertiliser settings by site.

<table>
<thead>
<tr>
<th></th>
<th>Hopetoun</th>
<th>Wongan Hills</th>
<th>Hart</th>
<th>Temora</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st April N to 1 m (kg ha(^{-1}))</td>
<td>50</td>
<td>18</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>1st Jan profile water (mm)</td>
<td>12</td>
<td>6</td>
<td>31</td>
<td>138</td>
</tr>
<tr>
<td>Rooting depth restricted (cm)</td>
<td>No</td>
<td>No</td>
<td>75</td>
<td>No</td>
</tr>
<tr>
<td>Soil N mineralisation modifier</td>
<td>No</td>
<td>Yes(^a)</td>
<td>No</td>
<td>Yes(^b)</td>
</tr>
<tr>
<td>Summer cona(^c)</td>
<td>2</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Summer U(^d)</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Winter cona</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>Winter U</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Minimum available soil water (mm)</td>
<td>12</td>
<td>6</td>
<td>31</td>
<td>65</td>
</tr>
</tbody>
</table>

\(^a\) N mineralisation for sand modifier used which was sourced by using APSIM v.7.4 (Asseng et al., 1998).

\(^b\) N mineralisation modifier described by Verburg et al. (2007).

\(^c\) Cona is the second stage evaporation as a fraction of the square root of time since the end of first stage evaporation.

\(^d\) U is first stage evaporation as cumulative evaporation since soil wetting, before soil supply becomes limiting.

With the exception of Temora, the soil water for each site was reset to crop lower limit on the 1st of January in every season, which coincides with the average observation of soil moisture at crop harvest in a Mediterranean-type climate, and soil water was allowed to accumulate over the remainder of the fallow period. For Temora the soil water was reset to the mean modelled post-harvest soil water content due to the non-seasonal even distribution of rainfall across a calendar year. Soil N and soil organic matter values were reset on the 1st of April (Table 2). The soil N values were informed by soil test values measured at each site in the 2009–2011 growing seasons. The mid-maturity wheat cultivar, Yitpi, was planted at 150 plants m\(^{-2}\) in every season at 250 mm spacing and 30 mm depth, between 25th April and 14th July, following 10 mm of rainfall within a five-day period and was forced to sow on the 14th of July if 10 mm of rain did not fall within this window.

A number of APSIM settings were site-specific and these are given in Table 2. Of note, Temora and Wongan Hills required modified soil N mineralisation functions, and Temora had modified soil water resets due to the difference in seasonal rainfall dominance.

The simulation treatments comprised a factorial experiment of N fertiliser applied as urea at sowing (upfront) at rates of 0, 7.5, 15, 30, 60, 90, 120 and 150 kg N ha\(^{-1}\) and, in-season N rates of 0, 7.5, 15, 30, 60, 90, 120 and 150 kg N ha\(^{-1}\) applied at Zadoks crop growth stage 31–40 (GS31–40) (Zadoks et al., 1974) when soil water (Table 2), soil N (profile N did not exceed 100 kg ha\(^{-1}\)) and rainfall rules were met (>10 mm rainfall in a three day period). The scenarios were selected for coverage of the typical crop yield–N rate response curve in these environments (i.e. yield plateaus beyond –100 kg N ha\(^{-1}\)) and the site practice rates. Because crop yield potential was not known when the tactical N application treatment was triggered, there were some seasons where the eventual crop yield potential was too low to warrant extra N addition but the GS31–40 conditions triggered N application, or GS31–40 conditions did not trigger N application but eventual yield potential was adequate to warrant extra N application. The average proportion of seasons with no tactical N applied was 33%, 15%, 14% and 20% for Hopetoun, Wongan Hills, Hart and Temora, respectively.

2.3. Data sets

In addition to the 60-year time-series wheat-yield data sets generated in APSIM for all scenarios, two farm-gate-price datasets were created, one for Australian Standard White (ASW) wheat and the other for N fertiliser (urea, 46% N) from a range of data sources including historical pool returns (AWB, 2010), commodity statistics (ABARE, 2010), farm budget guides (Rural Solutions SA, 2011) and consultant and state government agricultural staff advice. The highly versatile ASW wheat with medium-to-low-protein white wheat grain is represented best in APSIM, even though protein, which partly determines the price received for wheat, is not considered in this analysis due to lack of accuracy. Real prices (in Australian dollars, AUD\(^1\)) at farm gate were used to capture long-term deflation over the 40 years from 1970 to 2010 (adjusted to 1998, using the consumer price index) (Fig. 1).

For each price series we calculated the mean price of wheat (AUD 210 t\(^{-1}\)) and N (AUD 1030 t\(^{-1}\)) over that period, along with the relative variances (0.16 and 0.22, respectively). Wheat prices were found to be logistically distributed, whereas N prices best fitted a Beta General distribution, which is positively skewed and best captures the increasing price volatility observed in the past decade.

A correlation coefficient of +0.12 between grain and fertiliser prices reflects a relatively weak relationship because grain price depends primarily on global grain supply and N price is affected by the cost of energy (Kingwell, 2000). Consequently, possible estimation bias arising from auto-correlation was not incorporated (Sarris, 2000) and so, based on the correlated price distribution, 1000 random draws were generated using @RISK\(^\text{™}\) (Palisade Corporation, 2002). These price distributions were used in calculating economic net returns from growing wheat at a range of N fertiliser rates applied at sowing and in-season.

2.4. Crop yield variability

APSIM-generated frequency distributions of wheat yields were produced for each of the N treatments. We then fitted probability density functions to the frequency distributions to characterise climate-induced variability in yield outputs using the @RISK software. The yield frequency distributions were fitted using probability density functions (PDF) of various forms including Invgauss, Weibull, Pearson\(s\), normal, logistic, uniform and beta distributions. We chose the Anderson–Darling statistics test (Anderson and Darling, 1952) to measure the goodness of fit of each distribution (Monjardino et al., 2013). The probability density function with the best fit as measured by the Anderson–Darling statistic test was selected for use in Monte Carlo simulation of crop yield.

\(^1\) AUD = Australian Dollar. At the time of writing 1.00 AUD = 0.77 USD and 1.00 AUD = 0.68 EUR.
2.5. Profit function

We used a profit function described in Monjardino et al. (2013) to calculate economic net returns for wheat. As in the previous study (for a different site), we quantified variability in net returns for each scenario by using @RISK to generate 1000 Monte Carlo simulations of net returns using random samples for the yield parameter drawn from the modelled probability density functions for yields, as well as random samples for the price parameters based on the correlated distributions of these prices over the defined period. Frequency distributions were then developed for net returns under all scenarios. As for yield, we fitted probability density functions to them and selected the best using goodness of fit and Anderson–Darling test (Anderson and Darling, 1952).

In summary, economic net returns for wheat were calculated via a profit function as shown in Equation 1, with the prices and costs (in AUD) obtained from a range of sources (ABARE, 2010; Rural Solutions SA, 2011).

\[
NRn = (Yn \times Pw) - ((Rn1 + (Rn2 + f)) \times Pn) - (Ct \times f) - Co
\]  

where \(NRn\) is net returns by total N rate \(n\) (AUD ha\(^{-1}\)); \(Yn\) is crop yield by total N rate \(n\) (kg ha\(^{-1}\)); \(Pw\) is price of ASW wheat grain (AUD kg\(^{-1}\)); \(Rn1\) is rate of N applied at sowing (kg N ha\(^{-1}\)); \(Rn2\) is rate of N applied in-season (kg N ha\(^{-1}\)); \(Pn\) is price of N (i.e. price of urea/0.46) (AUD kg\(^{-1}\) N); \(Ct\) is operational cost of applying extra fertiliser in-season (AUD ha\(^{-1}\)); \(f\) is frequency of seasons with tactical N application in-season; and \(Co\) is other costs (AUD ha\(^{-1}\)). Other costs, assumed unchanged over time, include variable costs of growing wheat (e.g. seed purchase and treatment, herbicides, fuel and oil, and fertilisers other than N), fixed costs of production apportioned on an AUD ha\(^{-1}\) basis (e.g. repairs and maintenance, labour, insurance and levies), interest on variable costs (8%), and depreciation of machinery investment (10% of AUD 200 ha\(^{-1}\) in machinery investment).

2.6. Farmers’ aversion to risk

A purely economic assessment of nutrient management strategies is expected to be modified when attitude to risk is considered, because farmers with different degrees of risk-aversion are likely to have different preferences for N strategies (Hardaker et al., 2004a, Kingwell, 1994; Leathers and Quiggin, 1991; Pannell et al., 2000). In other words, when risk matters, an individual’s objective shifts from maximising expected profit to maximising expected utility, or overall satisfaction (Arrow, 1971; Lamberto, 1990; Pratt, 1964).

As described in Monjardino et al. (2013), N fertilisation preferences under risk were revealed through a Stochastic Efficiency with Respect to a Function (SERF) analysis (Hardaker et al., 2004b). In summary, SERF ranks alternative strategies (N fertilisation application rates and methods in this case) in terms of Certainty Equivalents (CE), representing the willingness to pay for a certain return, for a specified range of risk attitudes of the farmer. The risk attitude range can be measured by the Constant Absolute Risk Aversion (CARA) coefficient, which is based on the magnitude and spread of the distribution of net returns and a pooled variance–covariance matrix for the relevant type of farming (i.e. dryland cereal cropping) (Abdullahi et al., 2003; Hardaker et al., 2004a; Lien, 2002). The selected measure of risk-aversion, CE, is calculated under a utility function of a decision-maker with wealth (based on mean NR) as the performance criterion (Hardaker et al., 2004a, 2004b). In this case, assuming that mean net return is the equivalent to the farmer’s total wealth, even if not strictly correct, is an acceptable simplification given the specific (i.e. fertilisation per hectare) nature of the analysis (Anderson et al., 1977). The choice of a negative exponential utility function is particularly relevant for evaluating marginal risky investments that are small relative to the equity of the business, such as risks affecting only next year’s income (Hardaker and Lien, 2007) (Equation 2).

\[
U(W) = 1 - e^{-cW}
\]

where W is wealth or income expressed as a wealth equivalent and c is the Constant Absolute Risk Aversion (CARA) coefficient ($c > 0$).

In SERF analysis, simultaneous comparison of strategies by their utility determines the most efficient strategy for a farmer with a particular risk attitude. The CARA coefficient typically varies between 0.0 (risk neutral) and 0.0266 (very risk averse), based on the relative risk aversion scale of 0.0 to 4.0 (Hardaker et al., 2004a, 2004b). Here, we use wider absolute risk aversion bounds, from 0.0 to 0.035, to give a better illustration of the impact of ranking alternatives (Hardaker et al., 2004a).

2.7. Multi-criteria measures of yield-risk-return and risk-aversion

We used a range of indicators to quantify the expected magnitude and variability of net returns from each scenario, modified from Kandulu et al. (2012) and Monjardino et al. (2013), and relative to farmer’s risk-aversion and water-limited yield potential. These are:

1. Mean of expected net returns, i.e. the magnitude of net returns;
2. Standard deviation of net returns (SD), a measure of variance or dispersion from the mean;
3. Coefficient of variation (CV), i.e. a measure of dispersion of a probability distribution (SD/mean);
4. Probability of break-even [\(P NRi,d \geq 0\)], i.e. the probability of returning a profit;
5. Conditional value at risk of the lowest 10% of possible outcomes (CVaR\(_0.1\)), i.e. the mean of the lowest 10% net returns or, in other words, the scale of extreme financial loss associated with unfavourable events (Chavas and Holt, 1996);
6. Return on total N fertiliser investment at risk (\(R\_\_\)) i.e. a measure of the investment in total N fertiliser made with the least certainty of return;
7. Change in CE, i.e. the effect of increased farmer’s risk-aversion;
8. Proportion of the water-limited yield potential.

Calculation of the return on total N fertiliser investment at risk (\(R\_\_\)) was included to assess the marginal value of the N fertiliser applied and to help define the boundaries of acceptable level of risk to the farmer. Calculating the probability of break-even and CVaR\(_0.1\) allows for a more clear estimation of magnitude and risk of net returns, as well as probabilities of low-end net returns from alternative options (Rockafellar and Uryasev, 2002; Uryasev and Rockafellar, 2001).

3. Results and discussion

3.1. Yield-maximising N rate (\(Y_{\text{max}}\))

The observed yields used for model testing ranged from 0.5 to 6.6 t ha\(^{-1}\) dependent on the site yield potential (Fig. 2). The model explained 65% of the variation in yield, with a root mean squared error (RMSE) of 0.82 t ha\(^{-1}\). The evaluation of model fitting by individual sites did result in a lower RMSE for sites with lower yield potential (0.4 t ha\(^{-1}\) for Hopetoun, 0.6 t ha\(^{-1}\) for Wongan Hills, 1.2 t ha\(^{-1}\) for Hart, and 1.2 t ha\(^{-1}\) for Temora). For the Hart site, the simulated yields are consistently higher than observed, likely due to the presence of constraints other than N. This could cause the site N practice to appear more sub-optimal than it should as the site yield potential with current practice is likely lower than that modelled.
The mean and deviation in wheat yield response to N fertiliser at sowing shows the variation in responsiveness across the sites (Fig. 3). The level of yield responsiveness rapidly diminished as the soil N (derived from soil and fertiliser N) increased above 100 kg N ha\(^{-1}\) in the top metre of the soil profile. At very high rates of N there were yield penalties caused by a change in the distribution of water use causing water shortage at later growth stages. In addition, the figure demonstrates the water-limited yield potential with the lowest rainfall site (Hopetoun) having the lowest yield with nil N and the highest rainfall site (Temora) having the highest yield potential with nil N (Fig. 3). The downside yield risk in modelled output is likely to be less than that which occurs at farm level. This is due to a number of factors including the inability of the model to accommodate the effects of pests, diseases and other limiting nutrients and that the most timely management of sowing and N application is simulated which is not necessarily achievable at the whole-farm level.

Fig. 4 illustrates the variance in the yield gap between the water- and N-limited potential yield (Fig. 4, max yield) and the minimum yield where no N was applied (Fig. 4, min yield) across the 60-year simulation. The figure demonstrates the potential role for N in closing the yield gap at all of these sites but not in every season type. The yield achieved with site practice N fertilisation (SP) was equivalent to potential or maximum yield at Temora but significant yield gaps remained between site practice yield and potential or maximum yield in many seasons at the three other sites (Fig. 4) with an average yield gap of 1.05 t ha\(^{-1}\) at Hopetoun, 0.74 t ha\(^{-1}\) at Wongan Hills and 0.79 t ha\(^{-1}\) at Hart.

Overall, yield-maximising N rates involved a combination of very high up front N and in-season N inputs relative to site practice. It is notable that, even as there are very small increases in yield for large inputs of N after a certain point, we have chosen to refer to maximum yield rather than some interpretation of attainable yield (where the yield curve plateaus, for example).

### 3.2. Profit-maximising N rate (P\(_{\text{max}}\))

For each site we initially compared the N rate applied as site practice with all other N strategies using the basic parameters of mean net return, standard deviation from the mean and coefficient of variation. Due to the large set of results generated in this study, results are in the appendix (Appendix: Supplementary Tables S1 to S4) as part of the online supplementary data. Overall, across all four sites, mean annual net returns varied between AUD 67 ha\(^{-1}\) (0 N ha\(^{-1}\)) in Hopetoun (Table S1) and AUD 832 ha\(^{-1}\) (90 + 15 kg N ha\(^{-1}\)) in Temora (Table S4). The highest returns on N input generally occurred with rates greater than 30 kg N ha\(^{-1}\). The lowest returns resulted from nil or very low N input, especially in the lowest rainfall site of Hopetoun. At low fertility, sites optimising mean NR required the addition of some N at sowing to meet the early N requirement of crops growing in low fertility soils in order for in-season N to positively influence mean NR. This relationship diminished at sites with higher inherent fertility (e.g. Hart and Temora). High rates of N (i.e. greater than 60 kg N ha\(^{-1}\)) applied in-season often resulted in reductions in mean net returns and increases in the CV of the mean net return (Tables S1 to S4), likely due to a plateau in the level of yield responsiveness. In addition, the fact that in-season applications are
triggered by a range of in-season soil and agronomic conditions in our APSIM-based analysis does not guarantee that the in-season N is being applied to a crop with high yield potential. As a result of this trend of increasing risk on returns from relying on high in-season N fertilisation, only selected results up to 90 kg N ha\(^{-1}\) applied in-season are presented in the appendix tables.

Based on the results shown in Tables S1 to S4, the magnitude and variance of economic net returns for the selected scenarios across the four sites suggest that:

1. The N rates that generated the probability of highest returns with relatively low levels of risk ranged between 7.5 and 30 kg N ha\(^{-1}\) applied both up front and in-season;
2. For similar total amounts of N, split applications often generate a higher mean net return than up front applications, but rely on adequate early N nutrition for their best effect.

In general, over 60-year runs, the probability of maximising profit involved N rates higher than the site practice, but considerably lower than the yield-maximising N rates, including in-season. The profit-maximising N rates (\(P_{\text{max}}\)) are: 150 + 0 kg N ha\(^{-1}\) for Hopetoun, 90 + 0 kg N ha\(^{-1}\) for Wongan Hills, 120 + 15 kg N ha\(^{-1}\) for Hart, and 60 + 30 kg N ha\(^{-1}\) for Temora. These high rates reflect the influence of gaining high yields in high potential seasons (Fig. 4) on average profit.

The profit-maximising N rate (\(P_{\text{max}}\)) (i.e. the N rate with the highest mean net return) and its associated standard deviation were compared with those generated for the yield-maximising N rate (\(Y_{\text{max}}\)) and the site practice N rate (SP) for each case-study. It is clear that at all four sites there is not a financial incentive to achieve water-limited yield potential by using increasing rates of fertiliser N to close yield gaps, because lower \(P_{\text{max}}\) were more attractive economically and the yield gap between \(Y_{\text{max}}\) and \(P_{\text{max}}\) was relatively small across

Fig. 4. Maximum or potential yield (achieved with optimal N fertiliser application), yield achieved with site N fertiliser practice, and minimum yield (achieved with nil N fertiliser) for simulated 1950–2010 growing seasons at each case study site. While we have used a line for visual representation, each season was modelled discretely without carryover from the preceding season.
all sites (i.e. profit-maximising yield greater than 93% of yield potential). However, even though the risk associated with \( P_{\text{max}} \) was lower than that of \( Y_{\text{max}} \), it remained relatively high across most sites (Table 3 and Appendix: Supplementary Tables S1 to S4).

3.3. Utility-maximising N rate under risk-aversion (\( U_{\text{max}} \))

The risk-return results generated so far are in line with risk-neutral behaviour where maximising average profit is the objective regardless of variance. However, it has been demonstrated that Australian farmers are typically averse to risk (Bardsley and Harris, 1987; Bond and Wonder, 1980; Kingwell and Pannell, 2005; Kingwell, 1994; Monjardino et al., 2013; Pannell et al., 2000, 2006, Bond and Wonder, 1980). By comparison, lower levels of risk-aversion have been attributed to farmers (Monjardino et al., 2013; Pannell et al., 2000, 2006, Bond and Wonder, 1980; Kingwell and Pannell, 2005; Kingwell, 1994; Monjardino et al., 2013; Pannell et al., 2000, 2006). By comparison, lower levels of risk-aversion have been attributed to farmers (Monjardino et al., 2013; Pannell et al., 2000, 2006, Bond and Wonder, 1980; Kingwell and Pannell, 2005; Kingwell, 1994; Monjardino et al., 2013; Pannell et al., 2000, 2006).

To account for farmers’ aversion to risk, the results were analysed using the SERF framework and each N strategy re-ranked according to their certainty equivalent based on utility to farmers on a scale of risk-aversion. \( U_{\text{max}} \) is described here as the N rate that allows farmers to maximise their utility (represented as CE) for a given level of risk-aversion, but for the sake of simplification we focus on the \( U_{\text{max}} \) at the coefficient of constant absolute risk aversion (CARA) in the middle of the scale (−0.015), which relates to farmers with a moderate level of risk-aversion. In most cases this is also the \( U_{\text{max}} \) for higher CARA levels. These utility-maximising N rates (\( U_{\text{max}} \)) are: 15 + 15 kg N ha\(^{-1}\) for Hopetoun, 30 + 7.5 kg N ha\(^{-1}\) for Wongan Hills, 7.5 + 15 kg N ha\(^{-1}\) for Hart, and 15 + 60 kg N ha\(^{-1}\) for Temora.

Given the demonstrated unfeasibility of using yield-maximising N rates (\( Y_{\text{max}} \)), SERF results for \( P_{\text{max}} \) and \( U_{\text{max}} \) under risk-aversion are illustrated in Fig. 5 for each case-study. CE is largely negative for \( P_{\text{max}} \) at moderate levels of risk-aversion, and is relatively low for SP in medium rainfall sites. For the lower risk, higher rainfall site of Temora, the SERF results confirm a continuous preference for higher in-season N rates, while less in-season N is preferred in the other three sites. Overall, it is clear that a shift occurs from higher input strategies to lower input strategies as risk-aversion increases, suggesting that the more risk-averse farmers (\( >0.005 \)) in southern Australia would be prepared to accept a low-risk, low-return outcome. This result supports the premise that most farmers will perceive N fertiliser as a risk-increasing input.

Even though certainty equivalents provide a good indication of the utility of each N strategy to farmers with a range of attitudes to risk, we argue that there are other aspects of risk that a risk-averse person or a risk-neutral person may be interested in, or depend on, that are not covered by the SERF framework, such as the probability of break even, downside risk and marginal return on N investment. Therefore, to best utilise the combined analysis of yield-risk, profit-risk and the effect of risk-aversion, we proceeded to develop a set of yield-risk-return and risk-aversion criteria that would need to be met for an N management practice to be selected as the most preferred practice. The multi-criteria N rate (MC) was required to meet all of the following criteria, which were assumed to be sufficiently realistic (e.g. ‘rules-of-thumb’, expert opinion) across the systems represented in this analysis:

- Mean \( NR \geq \text{Mean } NR_{SP} \) in that soil (SP = site practice)
- \( CV \leq 2.0 \)
- \( P(NR \geq 0) \geq 50\% \)
- \( CV_{\text{Umax}} \geq -\text{AUD } 150 \) ha\(^{-1}\)
- \( R_{0} \geq \text{AUD } 2.0 \) per dollar of total N invested
- \( \text{Change in } CE \leq -\text{AUD } 1000 \) ha\(^{-1}\) resultant from an increase in risk-aversion
- \( \text{Yield } \geq 50\% \) of water-limited yield potential

The probability of breaking even was very high (around 100%) in most simulated scenarios in the sites with higher rainfall (greater than 350 mm) (Tables S2 to S4), and greater than 80% for most
simulated scenarios in the site with lower rainfall (lower than 350 mm) of Hopetoun (Table S1).

Downside risk using CVaR0.1 generated values up to −AUD 200 ha\(^{-1}\) (i.e. high downside risk) at N rates well below those required to achieve yield potentials (i.e. at least 150 kg N ha\(^{-1}\) applied up front). There were no positive CVaR0.1 values for all management strategies in the riskier, lower rainfall site of Hopetoun, and the smallest negative values were calculated for low sowing N rates at this site, which could include the site practice rate (Table S1). Downside risk was low (e.g. more positive CVaR0.1 values) in the other three sites with higher rainfall, with the highest CVaR0.1 value of AUD 345 ha\(^{-1}\) calculated for the scenario 60 kg N ha\(^{-1}\) in Temora (an improvement of around AUD 113 ha\(^{-1}\) when compared with the site practice of 15 + 60 kg N ha\(^{-1}\), Table S4).

Considering both yield and price risk, the best value for money invested in total N fertiliser at the start of the season occurred in Hart when 7.5 kg of N was applied in-season, with AUD 6.7 net return for each dollar of N purchased (Table S3).

Comparing across the set of yield-risk-return and risk-aversion metrics for the selected N strategies presented in Table 3, for example the Wongan Hills site showed an increase of AUD 42 ha\(^{-1}\) in mean net return, no change in CV and in the probability of break even, a slight decrease in downside risk (AUD 1 ha\(^{-1}\)), an increase of 8% in yield, and only a very moderate decrease of AUD 0.2 net return for each dollar of N purchased and in CE change due to risk-aversion (−AUD 46), as a result of adopting the MC risk-return strategy, which is only slightly lower than the site practice and favours up front N fertilisation. In other words, there is a potentially small profit gain accompanied by a small fall in risk premium for the Wongan Hills farmers when moving from 30 + 15 to 60 kg N ha\(^{-1}\) on the soil studied here. Conversely, the Temora site increased its mean net return by AUD 19 ha\(^{-1}\), decreased its downside risk by AUD 97 ha\(^{-1}\), increased its value of N fertiliser by AUD 1.5, while only decreasing yield loss by 2% and decreasing farmer uncertainty by around AUD 2000 from a total reduction of 30 kg N ha\(^{-1}\) and a shift of N fertiliser applied in-season to upfront (i.e. best rate compared to site practice). For the other sites, there was no great advantage in changing the site practice, with the exception of Wongan Hills where all N inputs should be applied upfront.

A comparison of the distribution of mean net return outcomes for SP, \(Y_{\text{max}}\), \(P_{\text{max}}\), \(U_{\text{max}}\) and MC management strategies is made in Fig. 6. The downside risk associated with yield- and profit-maximising N management strategies is apparent at the lower rainfall site of Hopetoun. Conversely, this site had the biggest upside gain (albeit a risky one) from \(Y_{\text{max}}\) and \(P_{\text{max}}\) compared with SP, \(U_{\text{max}}\) and MC in the higher rainfall seasons. The multi-criteria risk-return practice (MC) at the medium-high rainfall sites of Hart and Temora appears to have a lower net return than SP in higher rainfall seasons (represented in the highest net return, <0.2 probability section of the graph).

Fig. 5. Certainty equivalents on a scale of farmer aversion to risk (Constant Absolute Risk Aversion coefficient) for the site practice N rate (SP), the profit-maximising N rate (\(P_{\text{max}}\)) and the utility-maximising N rate (\(U_{\text{max}}\)) applied to a wheat crop for each of the five case-study sites (risk neutral CARA ~0.00, risk averse CARA ~0.015, very risk averse CARA ~0.035, not shown).
Using the mean wheat yield to illustrate the difference between SP, \( Y_{\text{max}} \), \( P_{\text{max}} \), \( U_{\text{max}} \) and MC management strategies, a number of interesting relationships become apparent (Fig. 7). In all cases, the multi-criteria risk-return N management strategy is neither the yield-maximising nor the profit-maximising strategy, it generates higher mean yield than the utility-maximising strategy, and in three of the four sites it results in a very similar mean yield to SP. On average \( Y_{\text{max}} \) is only 3% greater than \( P_{\text{max}} \), with the biggest yield gap between \( P_{\text{max}} \) and \( Y_{\text{max}} \) at Wongan Hills. Importantly, SP and MC achieve approximately 20% less than potential yield, and in two sites SP yield is 8% less than MC yield, all of which emphasises the role of farmer risk-aversion in limiting the closure of yield and profit gaps in the management of N fertilisation.

Overall, site practice, particularly at Hopetoun, Wongan Hills and Hart appears close to optimal when risk is considered (Table 3). This analysis is consistent with our previous work on the economic benefits of adopting higher N rates and/or tactical N by soil zone in farms located in Karoonda in the Mallee region of southern Australia (Monjardino et al., 2013), as well as with a range of other studies demonstrating the economic benefits of tactical N management (Angus, 2001; Broun, 2007; Kingwell et al., 1993; Lobell, 2007; McDonald, 1989; Moeller et al., 2009; Nordblom et al., 1985; Oliver and Robertson, 2009), agricultural intensification of marginal cropping land (Asseng et al., 2001; Babcock, 1992; Bryan et al., 2014; Good, 2004; Sadas, 2002; Sadas and Rodriguez, 2010; Sadas and Roget, 2004; Spiertz, 2010). Importantly, our results demonstrate the value of applying a range of research tools, such as crop growth simulation models in combination with economic-risk measures and risk-aversion theory. The MC approach enables options...
for the management of yield and profit gaps (Hochman et al., 2012; Lobell et al., 2009; Van Ittersum et al., 2013) to be considered within the context of farmer considerations of risk.

4. Conclusions

This analysis investigates the effect of economic-risk trade-offs and farmer risk-aversion on the use of N fertiliser to close the gap between actual and potential yield and profit across four farm risk profiles in Australia. Our study builds on the work conducted by Lobell et al. (2009) on the importance, magnitude and cause of crop yield gaps by overlaying an economic-risk-aversion analysis to their conclusions. In particular, we were able to demonstrate the role of nitrogen in closing yield and profit gaps using a series of N-defined fertilisation scenarios from which yields and associated profit and risk profiles were selected that aligned with site practice, water-limited yield potential, profit-maximisation and best risk practice. This process allowed us to consider the risk-return trade-offs in environments with differing levels of N-related yield gaps. In addition, we were able to further explore the N fertilisation decision-making process by considering a scale of farmer risk-aversion.

The analysis demonstrated that for four dryland cropping sites spread across the southern wheatbelt of Australia, yield-and profit-maximising N rates are often quite similar, but can differ substantially from N rates influenced by risk and risk-aversion. Potential yields using N rates selected using risk-return criteria were often similar to yield potential when using N rates commonly used by farmers at the case-study sites. With the exception of the high rainfall site, not considering risk led to much higher N rates and potential yields. The study demonstrates the importance of risk and risk-aversion in determining farmer preferred N rates and thereby N-limited yield potential. The role of risk and risk-aversion needs to be considered when evaluating strategies for managing yield gaps and profit-maximisation on dryland farms.

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Appendix: Supplementary material

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References
