Revisiting N fertilisation rates in low-rainfall grain cropping regions of Australia: A risk analysis

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Abstract

Mallee farmers minimize downside risk in dry seasons by applying low rates of nitrogen (N) fertiliser to their cereal crops. The opportunity to respond to and capitalize on the better years is further limited as most inputs are applied upfront at sowing. We used an economic-risk decision model to identify a range of tactical N fertilisation options that increase net returns, while minimising risk for farmers with different risk attitudes. Importantly, we concluded that when accounting for long-term risks affecting farmers, the use of higher N rates can play a risk-reducing role in a highly variable environment like the Mallee.

Keywords

Nitrogen, risk, variance, crop simulation, economic net returns, decision analysis, zone management, Monte Carlo, Mallee

1. Introduction

In the face of high climatic and spatial variability, low nutrient use efficiency, and intense market volatility, identifying the most profitable rate of nitrogen (N) fertiliser presents a challenge to dryland farmers. The situation is becoming even more pressing because fertiliser costs account for about 60% of all variable crop production costs in Australia (ABARE, 2010) and their costs have been growing faster than the prices obtained for grain prices (Kingwell and Pannell, 2005; Price, 2009; FAO, 2010).

Because N is such a significant investment, farmers seek to minimize the risk of a loss in poor seasons by applying standard low rates of N to their cereal crops. In doing so, their fertiliser management reflects recommendations for average seasons, and ignores the fact that N deficiency is one of the main causes of a gap between actual and potential yields, especially in the wetter seasons (Asseng et al., 2001; Sadras and Roget, 2004).

Part of the reason for the conservatism on the part of the farmer is the perception that excess N supply in dry seasons increases their exposure to risk, which is why N fertiliser is often considered to be a risk-increasing input in dryland agriculture (Russell, 1968; Just and Pope, 1979; Quiggin and Anderson, 1979; McDonald, 1989; Leathers and Quiggin, 1991; van Herwaarden et al., 1998; Sadras, 2002; Roosen and Hennessy, 2003; Broun, 2007; Lobell, 2007; Rajsic et al., 2009; Picazo-Tadeo and Wall, 2011). This issue is specific to risky dryland conditions, in contrast to other regions where the cost of over-applying N is clearly lower than the cost of under-fertilising (Rajsic and Weersink, 2008; Gandorfer et al., 2010).

In this context, it is timely to explore the significance of N management in dryland grain production under high risk and uncertainty, particularly since the variance in wheat revenue has more than doubled in every significant wheat-growing state in Australia over the last 15 years (Kingwell, 2011). So we ask the question: could those farmers in the low-rainfall Australian wheatbelt who adopt a low-input strategy in the attempt to minimize economic risk in fact be missing out on greater returns from more intense cropping in the more favourable seasons? In short, are dryland farmers under-fertilizing?

The issue of N management in agriculture has been widely studied in the context of managing risk, with one strategy of particular interest being the benefits of responding to seasonal conditions with extra N applied tactically in-season (Nordblom et al., 1985; McDonald, 1989; Kingwell et al., 1993; Angus, 2001; Broun, 2007; Lobell, 2007; Moeller et al., 2009; Oliver and Robertson, 2009). Most studies have used only a single or few

approaches in the risk analysis, and many have relied on limited data. In addition, only a few have accounted for seasonal or spatial variation as to trigger time- or site-specific management, or have included a full risk aversion analysis. In this study we aim, not only to overcome these limitations, but also to revisit the issue of N management in light of updated knowledge and information specific to the study region. In the process, we expect to address new concerns in the farming community that have arisen in recent times as a result of a shift in rainfall and market trends.

We use a range of tools, including crop growth modelling, Monte Carlo simulation, a profit function, financial theory techniques and stochastic efficiency analysis, to evaluate the combined impact of yield and price risk on long-term performance of N fertiliser strategies on different soil types, including those where rates are adjusted from year to year, according to the seasonal outlook, by applying extra N within the growing season. The results are then re-scaled according to the farmers' level of risk aversion. The main outcome for our case-study in the Mallee region in southern Australia is a response scale associated with adding N at the selected site, which is intended to help inform farmers in their fertiliser decisions. In particular, higher N input and tactical management, especially on sandier soil types, are proposed to be beneficial for farmers trying to cope with an increasingly risky environment.

2. Methods

2.1. Study area

The focus of this study is Karoonda in the Mallee, a low-rainfall region that lies south and east of the Murray River, across part of South Australia, Victoria and into New South Wales (Figure 1). The Mallee region comprises 7 million hectares of land, of which three quarters are allocated to dryland agriculture (Sadras et al., 2003). Mallee agricultural fields typically include sandy dunes and plains that have soils with a strong texture contrast between the surface (sand through to loam) and the subsoil (heavy clay). The northern part of the Mallee is dominated by limestone plains with low easterly-trending sand dunes with mean annual rainfall of 250 - 300 mm and mean annual evaporation of 2200 mm. The southern Mallee is dominated by sand plains with dunes and frequent outcrops of calcrete. Here, annual rainfall is around 300 - 350 mm and annual mean evaporation is 1975 mm (McLeod, 1989).

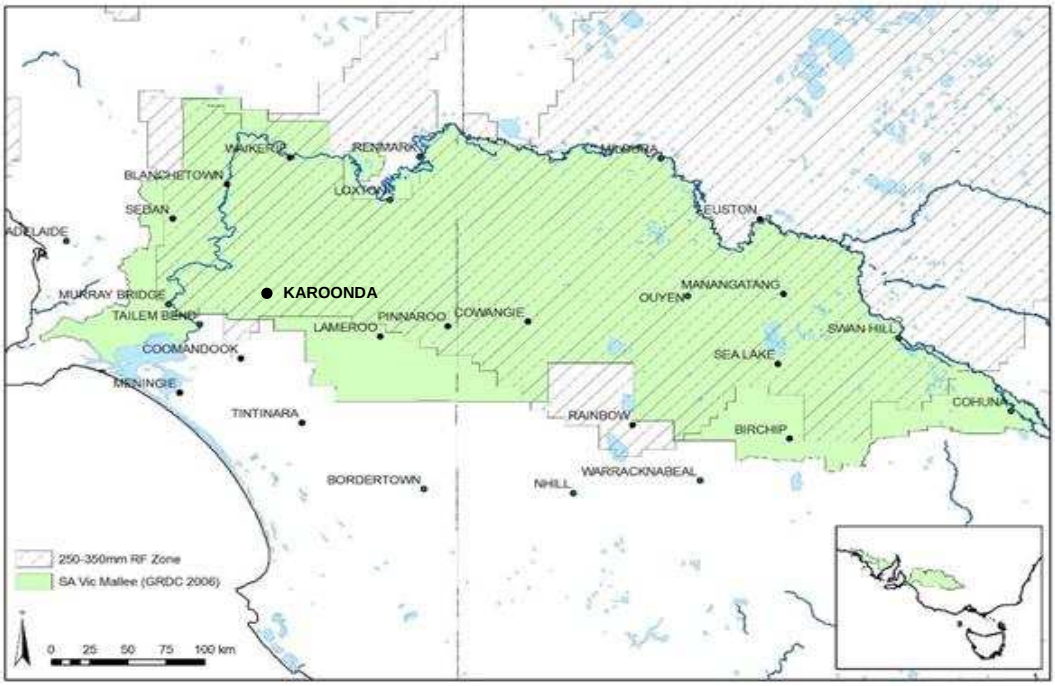

Figure 1. Map of the Mallee region (green shade).

The region has a Mediterranean-type climate (Aschmann, 1973; Boyce et al., 1991) and soils with low plant-available water content, resulting in winter cereal crops that are often exposed to varying degrees of moisture stress, including terminal drought (Sadras, 2002). Farming in the Mallee is considered risky (Makeham and Malcolm, 1988), and this is the reason why agricultural inputs, such as N fertiliser, have traditionally been kept at low levels (Sadras, 2002). Recent investigations suggest current rates in the region are in the order of 10-20 kg N ha^{-1} at sowing with some more intensive cropping farmers using up to extra 50 kg N ha^{-1} applied in-season (J. Braun, consultant 2011, pers. comm.). The use of variable-rate fertiliser on zones based on soil type is not yet standard practice (Robertson et al., 2012). For comparisons in this analysis, we assume an upfront application of 15 kg N ha^{-1} across all soil types as the current district practice.

2.2. Yield simulation and response curves

The Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003) was used to model water-limited yield potential and grain-yield N-response curves over the 1950-2010 growing seasons. The model was validated against wheat yield response to N application in 2009 and 2010 at the Karoonda site to ensure credibility of long-term simulations. The fit of

our validation run for Karoonda 2009-2011 actual vs. modelled yield is R2 = 0.84. To simulate yields, the APSIM wheat module was used in conjunction with the soil-water module (SOILWAT2), the soil-nitrogen module (SOIL N) and the surface-residue model (RESIDUE) (Probert et al., 1998, Oliver and Robertson, 2009). Daily climate data came from the township of Karoonda source in the SILO historical climate database. The wheat cultivar, Yitpi, was planted at 150 plants m^{-2} in every season, between 25th April and 14th July, following 10 mm of rainfall within a five-day period.

The model was parameterised for three representative soil types, based on soil and crop measurements within the field at a site near Karoonda in the Southern Mallee region of South Australia (Whitbread et al., 2008, 2009; Whitbread, 2010). Soils were grouped into three management zones: "dune", "slope" and "flat", each broadly consistent with a landscape position within the field, the main soil type and its corresponding subsoil constraints (Jones and Whitbread, 2010) (Table 1). Ten representative soil cores were taken for each soil type and the 'average' value of the analyses of these cores at depth intervals of 0-10, 10-20, 20-40, 40-60, 60-80 and 80-100 cm were used as the model soil parameter input values (Jones and Whitbread, 2010). These bulked soil samples were analysed for organic carbon, salinity, boron, chloride, total nitrogen and lower and upper limit of the crop.

Table 1. Typical Mallee soil management zones.

Zone	Location	Average % of typical farm	Main soil type	Level of subsoil constraints	Initial fertility status	Response to fertilisers
Dune	Hill-top	30	Sand	Low	Low	Good
Slope	Mid-slope	50	Sandy to clay loam	Medium	Medium	Average
Flat	Plain or swale	20	Medium-heavy clay	High	High	Poor

Annual yields were simulated for wheat on the three Mallee soils over 60 years from 1950 to 2010. The simulation treatments comprised 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}, as well as a tactical (i.e. a split approach) that tested all sowing N rates in combination with 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, soil N and rainfall rules were met. Tactical or split application of N was triggered by the simultaneous occurrence of threshold values of soil water (greater than crop lower limit), soil N (less than 100 kg N ha^{-1}), and rainfall (greater than 10 mm over 3 days) within GS31-40. Because crop yield potential is not known when the tactical N application treatment is triggered, there are some seasons where the crop yield potential is too low to warrant extra N addition but the GS31-40 conditions trigger N application, or GS31-40 conditions do not trigger N application but yield potential may be adequate to warrant extra N application. On average, in 21 seasons (35%) the tactical application of N was not triggered.

Simulated wheat crops were grown based on a starting mineral soil N of 18, 36 and 52 kg N ha^{-1} (0-110cm) for the dune, slope and flat zone, respectively, based on actual soil test values in the 2009-2011 growing seasons. Soil N and surface organic matter (1.5 t/ha) were reset on April 1 each year and soil water was reset each year on Jan 1 at crop lower limit to remove the effect of the previous crop and season on the following crop response to season and N treatment. A total of 192 scenarios were investigated for Karoonda.

The graphs in Figure 2 provide illustration of the scope of climate-induced yield variability that Mallee farmers are faced with, showing yield response to N in a very good season and in a very poor season. With yield differences of nearly 5.0 t ha^{-1} (higher with high tactical N applications) across the different soil types, there is potential zone N management in the Mallee.

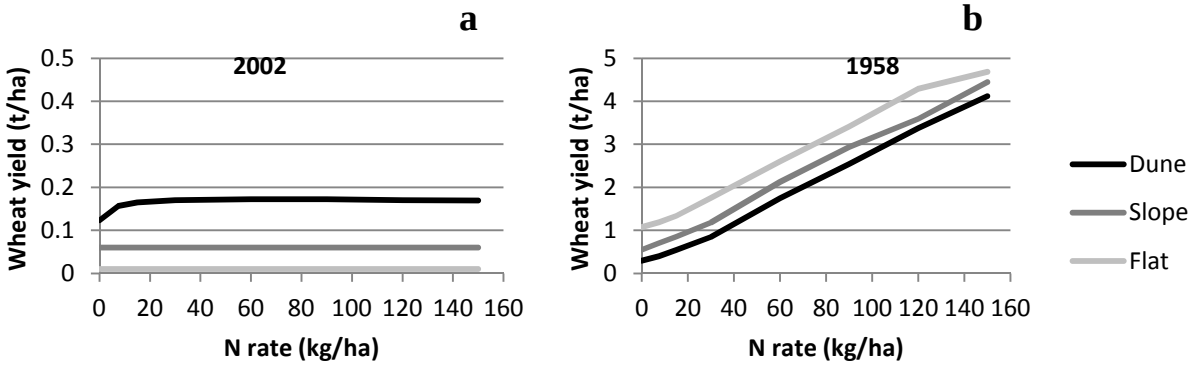

Figure 2. APSIM-simulated Karoonda wheat response curves for a range of upfront N rates across different management zones in a **a)** very poor season (2002) and in a **b)** very good season (1958) (note difference in y axis scale).

2.3. Data sets

In addition to the 60-year time-series wheat-yield data sets generated in APSIM, 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) and farm budget guides (Rural Solutions SA, 2009; 2010; 2011). 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. Real prices (in Australian dollars, A$) were used to capture long-term deflation over the 40 years from 1970 to 2010 (adjusted to 1998, using the consumer price index).

Correlation between wheat and N prices over that period was calculated, along with the means and variances of each price series (Table 2). 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 late 2000s.

Table 2. Mean, variance and correlation coefficients of wheat and nitrogen prices.

	Wheat	**Nitrogen**
Mean price (A$ t^{-1})	210	1030
Variance	0.16	0.22
Correlation coefficient	0.12	0.12

A coefficient of 0.12 reflects a relatively weak relationship between both prices because grain price depends primarily on the global grain supply and N price is affected by the cost of energy (Kingwell, 2000). Based on the correlated price distribution at Karoonda, 1000 random draws were generated using @RISK (Palisade Corporation, 2002). These price distributions were used in calculating economic net returns from growing wheat at a range of N fertiliser rates by two different methods, as shown later in Equation 2.

2.4. Crop yield variability

Climate, the key driver of yield variability, must be treated as stochastic (Quiggin and Anderson, 1979; Kingwell, 1994, 2011; Pannell et al., 2000). Climate-driven variability in crop yields, and thus variability in agricultural net returns over a given time frame can be quantified using a suitable framework identified in probability theory (Hardaker et al., 2004b; Hardaker and Lien, 2010).

Frequency distributions of wheat yields were generated for each of the N treatments. We then fitted probability density functions to the frequency distributions to characterize 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, Pearson5, 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. In comparisons of power, Stephens (1979) found A^2 to be one of the best empirical distribution function statistics for detecting most departures from normality, in other words, the one that best fits the distribution tail. We calculated the Anderson-Darling statistics, A^2, to measure the goodness of fit of each distribution using Equation 1.

$$A_n^2 = n\int_{-\infty}^{+\infty}\left[F_n(x)-\hat{F}(x)\right]^2\Psi(x)\hat{f}(x)dx \qquad \textbf{(1)}$$

Where,

n total number of data points (crop yield)

$$\Psi^2 = \frac{1}{\hat{F}(x)\left[1-\hat{F}(x)\right]}$$

$\hat{f}(x)$ the hypothesized density function

$\hat{F}(x)$ the hypothesized cumulative distribution function

$$F_n(x) = \frac{N_x}{n}$$

N_x the number of X_i's less than *x*.

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 net economic returns.

2.5. Net returns function

Crop yield risk and price of inputs/outputs or market risk are among some of the major risks faced by farmers (Hardaker et al., 2004b; Kingwell, 2000, 2011), particularly in marginal regions such as the Mallee (Makeham and Malcolm, 1988). To fully account for the effect of rainfall and soil variability, as well as of market volatility on economic net returns from dryland agriculture in the study area, we quantified variability in net revenue from sale of agricultural commodities produced per hectare less the fixed and variable cost incurred in its production.

We used a profit function to calculate economic net returns for wheat as shown in Equation 2, with the prices and costs (in Australian dollars, A$) obtained from a range of sources (ABARE, 2010; Rural Solutions SA, 2009, 2010, 2011).

$$\boldsymbol{NR_{nz}} = (\boldsymbol{Y_{nz}} \times \boldsymbol{P_w}) - ((\boldsymbol{R_{n1z}} + (\boldsymbol{R_{n2z}} * \boldsymbol{f})) \times \boldsymbol{P_n}) - (\boldsymbol{C_t} \times \boldsymbol{f}) - \boldsymbol{C_o} \quad \textbf{(2)}$$

Where,

NR_{nz}	net returns by total N rate *n* on management zone *z* (A$ ha^{-1})
Y_{nz}	crop yield by total N rate *n* on management zone *z* (kg ha^{-1})
P_w	price of ASW wheat grain (A$ kg^{-1})
R_{n1z}	rate of N applied at sowing on management zone *z* (kg N ha^{-1})
R_{n2z}	rate of N applied in-season on management zone *z* (kg N ha^{-1})
P_n	price of N (i.e. price of urea/0.46) (A$ kg-^{1} N)
C_t	operational cost of applying extra fertiliser in-season (A$ ha^{-1})
f	frequency of seasons with tactical N application in-season
C_o	other costs (A$ ha^{-1})

Other costs are calculated as follows:

$$\boldsymbol{C_o} = \boldsymbol{C_v} + \boldsymbol{C_f} + \boldsymbol{I_v} + \boldsymbol{D_m} \quad \textbf{(3)}$$

Where,

C_v	variable costs of growing wheat, including seed purchase and treatment, herbicides, fuel and oil, and fertilisers other than N
C_f	fixed costs of production apportioned on a A$/ha basis such as repairs and maintenance, labour, insurance and levies
I_v	interest on variable costs (8%)

D_m depreciation of machinery investment (10% of A$200 ha^{-1} in machinery investment)

To quantify variability in net returns for each scenario, we used @RISK to generate 1000 Monte Carlo simulations (Hardaker and Lien, 2010) of net returns using Equation 2 with random samples for the yield parameter Y_{nz} drawn from the modelled probability density functions for yields, as well as with random samples for the prices parameters based on the correlated distributions of these prices over the defined period. Frequency distributions were then developed for the average of net returns under all scenarios (see Equation 2). In the same way as for yield, we fitted probability density functions to them and selected the best using goodness of fit and Anderson-Darling test (see Equation 1).

2.6. Economic-risk measures

Farmers in the Mallee region are faced with the challenge of choosing from a range of N rates and timing of application with uncertain net returns in each season type. In a similar analysis comparing the benefits of four options for enterprise mix diversification, Kandulu et al. (2011) identified in the financial risk management literature four measures for assessing potential trade-offs between expected net returns and overall variability in net returns. Like them, we propose that variance or standard deviation used alone is an insufficient measure of risk to inform an N application decision, so we used a combination of eight main indicators to quantify the expected magnitude and variability of yield and net returns from each scenario. These are:

1. Mean of expected net returns, i.e. the magnitude of net returns;
2. Mode of expected net returns, i.e. the most frequent net return value in the distribution;
3. Standard deviation of net returns, *SD*, i.e. a measure of variance or dispersion from the mean;
4. Coefficient of variation, *CV*, i.e. a measure of dispersion of a probability distribution (*SD/mean*);
5. Probability of break-even, $P(NR_{i,d} \geq 0)$, i.e. the probability of returning a profit;
6. 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 risk of extreme financial loss associated with unfavourable events (Chavas and Holt, 1996);

7. Return on total fertiliser investment at risk (R_N), i.e. a measure of the investment in total N fertiliser made with the least certainty of return;
8. Return on tactical fertiliser investment at risk (R_{NT}), i.e. a measure of the value of extra tactical N fertiliser applied in-season;

Calculation of the return on total/tactical N fertiliser (R_N / R_{NT}) is shown in Equations 4 and 5:

$$R_N = \frac{NRnz - NR0nz}{Cnz} \quad (4)$$

$$R_{NT} = \frac{NRn2z - NR0n2z}{Cn2z} \quad (5)$$

Where,

NR_{nz} / NR_{n2z} net returns by total N rate *n* / tactical N rate *n2* on management zone *z* (A$ ha^{-1})

NR_{0nz} / NR_{0n2z} net returns by total zero N / tactical zero N on management zone *z* (A$ ha^{-1})

C_{nz} / C_{n2z} cost total N / tactical N on management zone *z* (A$ ha^{-1})

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 (Uryasev and Rockafellar, 2001; Rockafellar and Uryasev, 2002).

2.7. Farmers' preferences

Farmers with different degrees of risk aversion are likely to have different preferences for N strategies (Leathers and Quiggin, 1991; Kingwell, 1994; Pannell et al, 2000; Hardaker et al., 2004b). Therefore, assessment of nutrient management strategies is likely to be modified when attitude to risk is considered. This is because, when risk matters, an individual's objective shifts from maximizing expected profit to maximizing expected utility, or overall satisfaction (Arrow, 1971; Pratt, 1964; Lambert, 1990).

Fertilization preferences under risk were revealed in this study through a Stochastic Efficiency with Respect to a Function (SERF) analysis (Hardaker et al., 2004a). SERF ranks a set of risky alternatives (N fertilization application rates and methods in this case) in terms of Certainty Equivalence (CE) for a specified range of risk attitudes. The risk attitude range is typically measured by a risk aversion coefficient, measuring either absolute or relative risk aversion (Hardaker et al., 2004a), based on the magnitude and spread of the distribution of

net returns. In this study, a Constant Absolute Risk Aversion (CARA) coefficient, also known as Pratt's Measure of Risk Aversion (Arrow, 1971; Pratt, 1964) is used to represent the risk attitude of the farmer (Abdullahi et al., 2003; Hardaker et al., 2004a).

Constant aversion to risk implies a particular class of utility function, for example the negative exponential utility function (Anderson et al., 1977; Hardaker et al., 2004a, 2004b) shown in Equation 6:

$$\boldsymbol{U(W) = 1 - \epsilon^{-cW}} \quad \textbf{(6)}$$

Where,

W	wealth or income expressed as a wealth equivalent
c	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. 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).

3. Results

In this section, we present quantitative results on variability in both crop yield and economic net returns, assess the potential benefits of different N fertiliser management strategies, and consider how a set of preferred strategies might change according farmers' attitude to risk.

3.1. Yield variance analysis

A yield variance analysis is conducted here because yield variance was found to have a greater impact than price variance on variance in wheat revenue (Kingwell, 2011). Mean wheat yields ranged from 192 kg ha^{-1} in the dune zone with zero applications of N fertiliser to 2263 kg ha^{-1} in the flat zone with applications of 150 + 150 kg ha^{-1} of N (Tables 3 to 5). The most extreme individual yields recorded were crop failure (i.e. no harvestable yield) in the flat during the worst season type (2002) and above 5000 kg ha^{-1} in the slope in the best season type (1958). These yield values were accompanied by coefficients of variation of 0.25 and 6.99 of the mean yield, respectively (Tables 3 and 5).

Overall, some of the lowest coefficients of variation of the mean yield in each management zone were achieved with 15 kg ha^{-1} of N applied at sowing (CV of 0.23, 0.43 and 0.82 in the dune, slope and flat, respectively), indicating that farmers currently target lower yield variance. Coefficients of variation ranged between 0.23 and 0.7 on the dune, between 0.42 and 1.32 on the slope, and between 0.70 and 7.0 on the flat, confirming that yields are more stable in the sandy top-soils (hill-top and mid-slope) than the constrained swales or flats of the landscape (Tables 3 to 5).

Generally, application of higher N rates, both at sowing and in-season, contributed to higher yields in the sandy top-soils. Gains in crop yield arising from extra N inputs are often, but not always, accompanied by greater yield variance (reflected in larger standard variation and coefficients of variation), which may translate to higher economic risks, as discussed later.

The proportion of seasons that achieve wheat yields below 0.25, 0.5, 1.0 and 2.0 t ha^{-1}, and greater than 5.0 t ha^{-1}, was also calculated (Tables 3 to 5). In the dune and slope, very poor yields (Decile 1 and 2) were generated when no N was applied to the crop, while an upfront rate of at least 60 kg N ha^{-1} was required to achieve consistent yields between 1.0 and 2.0 t ha^{-1}. In the flat, applying most N rates greater than 15 kg ha^{-1} achieved yields of greater than 2.0 t ha^{-1} in 25% of seasons (in contrast with all yields less than 2.0 t ha^{-1} at district practice).

The yield variance analysis suggests that applying upfront N rates up to 90 kg N ha^{-1} in the dune, 60 kg N ha^{-1} in the slope and 30 kg N ha^{-1} in the flat, could be beneficial in terms of increasing yields, while managing yield variance. Because a rate of 60 kg N ha^{-1} in-season was the point at which the highest yield variance occurred in most cases, only economic results for scenarios with rates up to 60 kg N ha^{-1} applied tactically will be presented.

Table 3. Measures of yield variability for selected N rate scenarios (upfront N on left and extra in-season* N on right in first column) in the dune zone (current practice in bold font).

Kg N ha^{-1}		Mean (kg ha^{-1})	SD (kg ha^{-1})	CV	% years				
					< 0.25 t ha^{-1}	< 0.5 t ha^{-1}	< 1.0 t ha^{-1}	< 2.0 t ha^{-1}	> 5.0 t ha^{-1}
0	**+ 0**	192	48	0.25	92	100	100	100	0
	+ 15	368	182	0.50	40	67	100	100	0
	+ 30	382	195	0.51	40	67	100	100	0
	+ 60	390	201	0.52	38	65	100	100	0
	+ 90	394	203	0.52	38	65	100	100	0
	+ 150	398	206	0.52	38	65	100	100	0
15	**+ 0**	**405**	**92**	**0.23**	**7**	**85**	**100**	**100**	**0**
	+ 15	749	393	0.52	7	35	60	100	0
	+ 30	783	418	0.53	7	35	55	100	0
	+ 60	811	437	0.54	7	35	55	100	0
	+ 90	827	449	0.54	7	35	55	100	0
	+ 150	852	503	0.59	7	35	55	98	0
30	**+ 0**	727	199	0.27	5	12	95	100	0
	+ 15	1246	647	0.52	7	12	43	85	0
	+ 30	1300	697	0.54	7	12	42	83	0
	+ 60	1324	728	0.55	7	12	42	80	0
	+ 90	1329	735	0.55	7	12	42	78	0
	+ 150	1332	740	0.56	5	12	42	78	0
60	**+ 0**	1271	466	0.37	3	12	23	98	0
	+ 15	1797	1011	0.56	3	12	22	62	0
	+ 30	1871	1084	0.58	3	12	22	57	0
	+ 60	1913	1153	0.60	3	12	22	57	0
	+ 90	1923	1163	0.61	3	12	22	57	0
	+ 150	1928	1173	0.61	3	12	22	57	0
90	**+ 0**	1788	751	0.42	3	12	22	53	0
	+ 15	2056	1228	0.60	3	12	22	52	0
	+ 30	2125	1342	0.63	3	12	22	52	2
	+ 60	2147	1386	0.65	3	12	22	52	2
	+ 90	2156	1403	0.65	3	12	22	52	3
	+ 150	2158	1410	0.65	3	12	22	52	3
150	**+ 0**	2227	1229	0.55	3	12	22	52	0
	+ 15	2224	1472	0.66	3	12	22	52	3
	+ 30	2229	1489	0.67	3	12	22	52	3
	+ 60	2234	1500	0.67	3	12	22	52	3
	+ 90	2235	1510	0.68	3	12	22	52	3
	+ 150	2234	1513	0.68	3	12	22	52	3

* Tactical N applied only in the 39 seasons that meet the trigger conditions outlined in section 2.2.

Table 4. Measures of yield variability for selected N rate scenarios (upfront N on left and extra in-season* N on right in first column) in the slope zone (current practice in bold font).

Kg N ha^{-1}		Mean (kg ha^{-1})	SD (kg ha^{-1})	CV	% years				
					< 0.25 t ha^{-1}	< 0.5 t ha^{-1}	< 1.0 t ha^{-1}	< 2.0 t ha^{-1}	> 5.0 t ha^{-1}
0	**+ 0**	343	143	0.42	20	90	100	100	0
	+ 15	779	462	0.59	20	47	63	100	0
	+ 30	735	569	0.77	20	47	63	100	0
	+ 60	741	578	0.78	20	47	63	100	0
	+ 90	744	584	0.78	20	47	63	100	0
	+ 150	746	584	0.78	20	47	63	100	0
15	**+ 0**	**579**	**250**	**0.43**	**18**	**27**	**100**	**100**	**0**
	+ 15	1153	1087	0.94	18	27	57	78	0
	+ 30	1261	1378	1.08	18	27	57	75	0
	+ 60	1322	1647	1.24	18	27	57	70	0
	+ 90	1322	1603	1.20	18	27	58	70	0
	+ 150	1339	1780	1.32	18	27	58	70	0
30	**+ 0**	883	414	0.47	15	23	45	100	0
	+ 15	1319	1028	0.78	17	23	43	75	0
	+ 30	1389	1218	0.88	17	23	43	70	0
	+ 60	1465	1367	0.93	17	23	43	70	0
	+ 90	1477	1411	0.95	17	23	43	70	0
	+ 150	1485	1467	0.99	17	23	43	70	0
60	**+ 0**	1267	753	0.59	15	23	38	68	0
	+ 15	1618	1448	0.89	15	23	40	67	0
	+ 30	1629	1650	1.01	17	23	40	67	0
	+ 60	1662	1683	1.01	17	23	40	67	0
	+ 90	1664	1679	1.01	17	23	40	67	0
	+ 150	1667	1688	1.01	17	23	40	67	0
90	**+ 0**	1515	1147	0.76	15	23	38	65	0
	+ 15	1676	1694	1.01	15	23	40	65	0
	+ 30	1698	1714	1.01	17	23	40	65	2
	+ 60	1709	1731	1.01	17	23	40	65	2
	+ 90	1711	1731	1.01	17	23	40	65	2
	+ 150	1709	1727	1.01	17	23	40	65	2
150	**+ 0**	1725	1758	1.02	15	23	40	65	0
	+ 15	1743	1761	1.01	15	23	40	65	2
	+ 30	1744	1764	1.01	15	23	40	65	2
	+ 60	1743	1762	1.01	15	23	40	65	2
	+ 90	1742	1766	1.01	15	23	40	65	2
	+ 150	1740	1755	1.01	15	23	40	65	2

* Tactical N applied only in the 39 seasons that meet the trigger conditions outlined in section 2.2.

Table 5. Measures of yield variability for selected N rate scenarios (upfront N on left and extra in-season* N on right in first column) in the flat zone (current practice in bold font).

Kg N ha^{-1}		Mean (kg ha^{-1})	SD (kg ha^{-1})	CV	% years				
					< 0.25 t ha^{-1}	< 0.5 t ha^{-1}	< 1.0 t ha^{-1}	< 2.0 t ha^{-1}	> 5.0 t ha^{-1}
0	**+ 0**	660	461	0.70	27	42	68	100	0
	+ 15	935	814	0.87	27	42	57	83	0
	+ 30	1104	1741	1.58	27	42	57	75	0
	+ 60	1138	1866	1.64	27	42	57	77	0
	+ 90	1141	1849	1.61	27	42	57	77	0
	+ 150	1146	1923	1.67	27	42	57	77	0
15	**+ 0**	**857**	**699**	**0.82**	**27**	**38**	**53**	**100**	**0**
	+ 15	1246	1822	1.46	27	38	52	75	0
	+ 30	1431	3998	2.89	27	38	52	75	0
	+ 60	1482	3648	2.49	27	38	52	75	0
	+ 90	1554	5059	3.38	27	38	52	75	0
	+ 150	1477	3204	2.14	27	38	52	77	0
30	**+ 0**	981	876	0.89	27	38	53	88	0
	+ 15	1438	2524	1.72	25	38	53	75	0
	+ 30	1567	3553	2.23	27	38	53	73	0
	+ 60	1620	3595	2.13	27	38	53	73	0
	+ 90	1758	6470	3.77	27	38	53	73	0
	+ 150	2075	8205	4.77	27	38	53	73	0
60	**+ 0**	1316	1976	1.50	27	38	53	75	0
	+ 15	1714	4624	2.65	28	38	53	75	0
	+ 30	1760	4824	2.65	27	38	53	75	0
	+ 60	1755	4423	2.39	27	38	53	75	0
	+ 90	2220	7350	3.86	27	38	53	75	0
	+ 150	1784	4791	2.55	27	38	53	75	0
90	**+ 0**	1620	3848	2.34	27	38	53	73	0
	+ 15	1902	6902	3.58	27	38	53	73	0
	+ 30	1994	9202	4.80	27	38	53	73	0
	+ 60	1867	5483	2.77	27	38	53	73	0
	+ 90	2099	11442	5.71	27	38	53	73	0
	+ 150	1904	6655	3.36	27	38	53	75	0
150	**+ 0**	2107	10693	5.14	27	38	53	73	0
	+ 15	1969	6391	3.03	27	38	53	73	0
	+ 30	2049	8423	3.98	27	38	53	73	0
	+ 60	1930	5548	2.57	27	38	53	73	0
	+ 90	1825	4820	2.47	27	38	53	75	0
	+ 150	2263	14901	6.99	27	38	53	75	0

* Tactical N applied only in the 39 seasons that meet the trigger conditions outlined in section 2.2.

3.2. Economic-risk performance

The magnitude and variability of economic net returns across the full range of N management strategies for the three management zones at the Karoonda site were assessed against eight economic-risk indicators: mean and mode net returns; standard deviation and coefficient of variation of the mean net returns; $P(NR \geq 0)$; $CVaR_{0.1}$; and return on the total/tactical N fertiliser investment (see section 2.6 for detailed descriptions).

Overall, there was significant variation in mean net returns ranging from -A$122 ha^{-1} (0 + 150 kg N ha^{-1}, not shown here) to A$228 ha^{-1} (90 + 30 kg N ha^{-1}), both in the dune (Tables 6 to 8). The highest returns occurred with mid to high N rates (> 30 kg N ha^{-1}) applied upfront and/or tactically on all three zones, especially the dune (Table 6). The lowest returns resulted from zero N input in the dune, as well as very high in-season N applications (> 60 kg N ha^{-1}) with poor selection of initial inputs at sowing (either too low or too high) (Table 6). Very high rates of N applied in-season to the higher fertility mid-slopes and flats resulted in reductions in mean net return and an increase in the CV of the mean net return (Tables 7 and 8).

Table 6. Economic risk measures across a selection of N rates (upfront N on left and extra in-season* N on right in first column) in the dune zone (current practice in bold font).

Kg N ha^{-1}		Mean (A$ ha^{-1})	Mode (A$ ha^{-1})	SD (A$ ha^{-1})	CV	*P (NR ≥ 0) (%)*	*CVaR$_{0.1}$* (A$ ha^{-1})	*R$_N$* (ANR/AN)	*R$_{NT}$* (A$NR/$N$_T$)
	+ 0	-60	-59	12	0.21	0	-77		
	+ 7.5	-37	-72	38	1.02	16	-100	2.9	2.0
0	**+ 15**	-38	-50	41	1.09	19	-106	1.4	1.0
	+ 30	-45	-32	44	0.99	15	-118	0.5	0.3
	+ 60	-63	-78	44	0.70	8	-138	-0.1	0.0
	+ 0	-50	-53	16	0.32	1	-74	1.2	
	+ 7.5	-7	-29	60	8.01	43	-106	3.3	3.8
7.5	**+ 15**	-6	-11	64	11.36	45	-112	2.3	2.0
	+ 30	-11	18	68	6.16	42	-123	1.3	0.9
	+ 60	-29	-39	69	2.36	32	-145	0.4	0.2
	+ 0	**-30**	**-41**	**24**	**0.81**	**11**	**-68**	**1.9**	
	+ 7.5	27	-42	79	2.92	57	-78	3.7	5.1
15	**+ 15**	27	-61	87	3.21	54	-84	2.8	2.6
	+ 30	24	-91	93	3.84	53	-96	1.8	1.2
	+ 60	10	-96	98	9.92	47	-117	0.9	0.4
	+ 0	22	31	49	2.22	69	-67	2.6	
	+ 7.5	103	25	123	1.19	79	-78	4.2	7.2
30	**+ 15**	117	40	146	1.24	77	-84	3.8	4.2
	+ 30	118	123	157	1.33	76	-96	2.9	2.1
	+ 60	102	-33	159	1.57	70	-114	1.7	0.9
	+ 0	106	-2	109	1.02	82	-84	2.7	
	+ 7.5	185	182	203	1.10	82	-149	3.5	6.8
60	**+ 15**	200	162	222	1.11	82	-128	3.4	4.3
	+ 30	206	42	236	1.14	81	-139	2.9	2.3
	+ 60	198	78	260	1.31	77	-150	2.1	1.0
	+ 0	183	273	171	0.93	83	-125	2.6	
	+ 7.5	208	186	243	1.17	81	-195	2.7	2.2
90	**+ 15**	225	187	274	1.22	80	-167	2.6	1.8
	+ 30	228	57	290	1.27	79	-147	2.3	1.0
	+ 60	215	376	310	1.44	75	-199	1.8	0.3
	+ 0	178	210	230	1.30	73	-170	1.9	
	+ 7.5	212	107	277	1.30	78	-198	2.1	3.1
120	**+ 15**	220	53	308	1.40	76	-200	2.0	1.9
	+ 30	216	173	320	1.48	74	-209	1.8	0.8
	+ 60	198	53	322	1.63	71	-227	1.4	0.2
	+ 0	215	307	274	1.27	73	-196	1.8	
	+ 7.5	202	45	323	1.60	72	-222	1.6	-1.8
150	**+ 15**	198	-121	328	1.66	71	-222	1.5	-1.1
	+ 30	188	73	329	1.75	69	-235	1.3	-0.9
	+ 60	171	-32	330	1.94	66	-252	1.1	-0.8

* Tactical N applied only in the 39 seasons that meet the trigger conditions outlined in section 2.2.

Table 7. Economic risk measures across a selection of N rates (upfront N on left and extra in-season* N on right in first column) in the slope zone (current practice in bold font).

Kg N ha^{-1}		Mean (A$ ha^{-1})	Mode (A$ ha^{-1})	SD (A$ ha^{-1})	CV	*P (NR ≥ 0) (%)*	*CVaR$_{0.1}$* (A$ ha^{-1})	*R$_N$* (ANR/AN)	*R$_{NT}$* (A$NR/$N$_T$)
	+ 0	-28	-8	33	1.21	20	-87		
	+ 7.5	27	49	98	3.71	54	-95	7.1	4.9
0	**+ 15**	49	128	102	2.08	64	-103	5.0	3.4
	+ 30	29	-82	121	4.12	50	-110	1.8	1.3
	+ 60	11	-43	127	11.41	44	-132	0.6	0.4
	+ 0	-12	-2	44	3.77	41	-89	2.0	
	+ 7.5	58	2	130	2.22	64	-110	5.5	6.2
7.5	**+ 15**	84	70	130	1.56	68	-108	4.8	4.2
	+ 30	87	-83	244	2.80	59	-124	3.0	2.2
	+ 60	73	-32	270	3.69	52	-144	1.4	1.0
	+ 0	**7**	**55**	**57**	**8.46**	**57**	**-94**	**2.2**	
	+ 7.5	84	23	153	1.83	69	-121	4.8	6.9
15	**+ 15**	113	-38	242	2.14	67	-126	4.6	4.8
	+ 30	131	29	400	3.06	64	-131	3.3	2.7
	+ 60	117	-52	342	2.92	59	-151	1.9	1.3
	+ 0	55	133	92	1.69	72	-111	2.7	
	+ 7.5	114	166	188	1.64	71	-144	3.7	5.4
30	**+ 15**	134	88	234	1.75	69	-149	3.4	3.4
	+ 30	137	-23	263	1.93	65	-146	2.7	1.8
	+ 60	133	-45	300	2.25	60	-168	1.7	0.9
	+ 0	105	144	165	1.58	68	-143	2.1	
	+ 7.5	142	9	250	1.76	69	-188	2.4	3.2
60	**+ 15**	161	-43	306	1.91	67	-178	2.5	2.6
	+ 30	158	-181	363	2.30	56	-180	2.0	1.1
	+ 60	143	-102	367	2.63	55	-201	1.4	0.4
	+ 0	128	63	253	1.98	65	-198	1.7	
	+ 7.5	149	16	330	2.21	63	-205	1.8	2.1
90	**+ 15**	142	-159	358	2.52	55	-199	1.6	0.8
	+ 30	142	-187	371	2.61	53	-210	1.4	0.3
	+ 60	123	-142	376	3.05	51	-234	1.0	0.0

* Tactical N applied only in the 39 seasons that meet the trigger conditions outlined in section 2.2.

Table 8. Economic risk measures across a selection of N rates (upfront N on left and extra in-season* N on right in first column) in the flat zone (current practice in bold font).

Kg N ha^{-1}		Mean (A$ ha^{-1})	Mode (A$ ha^{-1})	SD (A$ ha^{-1})	CV	*P (NR ≥ 0) (%)*	*CVaR$_{0.1}$* (A$ ha^{-1})	*R$_N$* (ANR/AN)	*R$_{NT}$* (A$NR/$N$_T$)
	+ 0	38	-6	101	2.63	65	-133		
	+ 7.5	69	122	177	2.55	66	-235	3.8	2.6
0	**+ 15**	80	4	172	2.13	64	-151	2.8	1.9
	+ 30	104	-66	326	3.12	53	-132	2.2	1.5
	+ 60	93	-89	369	3.98	47	-153	0.9	0.6
	+ 0	55	86	133	2.39	67	-175	2.1	
	+ 7.5	79	38	193	2.45	67	-261	2.6	2.1
7.5	**+ 15**	95	-7	198	2.09	64	-163	2.4	1.8
	+ 30	134	-76	487	3.63	54	-140	2.4	1.7
	+ 60	122	-143	483	3.96	48	-160	1.2	0.8
	+ 0	**66**	**23**	**154**	**2.34**	**68**	**-200**	**1.7**	
	+ 7.5	95	-4	197	2.07	64	-165	2.4	2.7
15	**+ 15**	135	-83	437	3.24	56	-138	3.0	3.0
	+ 30	145	-128	498	3.44	53	-148	2.4	1.9
	+ 60	154	-82	845	5.50	50	-167	1.4	0.9
	+ 0	74	26	188	2.55	66	-260	1.2	
	+ 7.5	129	-95	387	2.99	54	-149	2.4	4.9
30	**+ 15**	177	-88	1018	5.74	52	-151	2.7	3.9
	+ 30	173	-92	738	4.26	50	-164	2.3	2.3
	+ 60	168	-139	808	4.79	45	-182	1.5	1.1
	+ 0	112	-77	379	3.38	51	-174	1.2	
	+ 7.5	157	-108	704	4.48	46	-182	1.8	4.2
60	**+ 15**	173	-131	767	4.44	45	-186	2.0	3.4
	+ 30	189	-155	1014	5.35	44	-195	1.7	1.8
	+ 60	210	-149	2168	10.34	42	-219	1.2	0.8

* Tactical N applied only in the 39 seasons that meet the trigger conditions outlined in section 2.2.

A clearer picture of the link between magnitude and variance of economic net returns emerges from Figure 3 showing the probability distribution functions for net returns for a range of selected scenarios across the three management zones. The graphs suggest that:

1. The dune generates the probability of highest returns within acceptable levels of risk when mid-high N rates are applied (e.g. 90 + 0 kg N ha^{-1}, Figure 3a);
2. High N input generates high returns and relatively high risk (e.g. 120 + 15 kg N ha^{-1} compared to the lower N scenarios in the three zones, Figure 3a to 3c);
3. It is generally lower risk to apply in-season N with low rather than high N rates (e.g. 60 + 30 kg N ha^{-1} versus 30 + 60 kg N ha^{-1} in the three zones, Figure 3a to 3c);

4. For the same total amount of N, split applications are more beneficial in terms of magnitude of net returns, but carry a higher risk (e.g. 60 + 30 kg N ha^{-1} compared to 90 + 0 kg N ha^{-1}, Figure 3a to 3c).

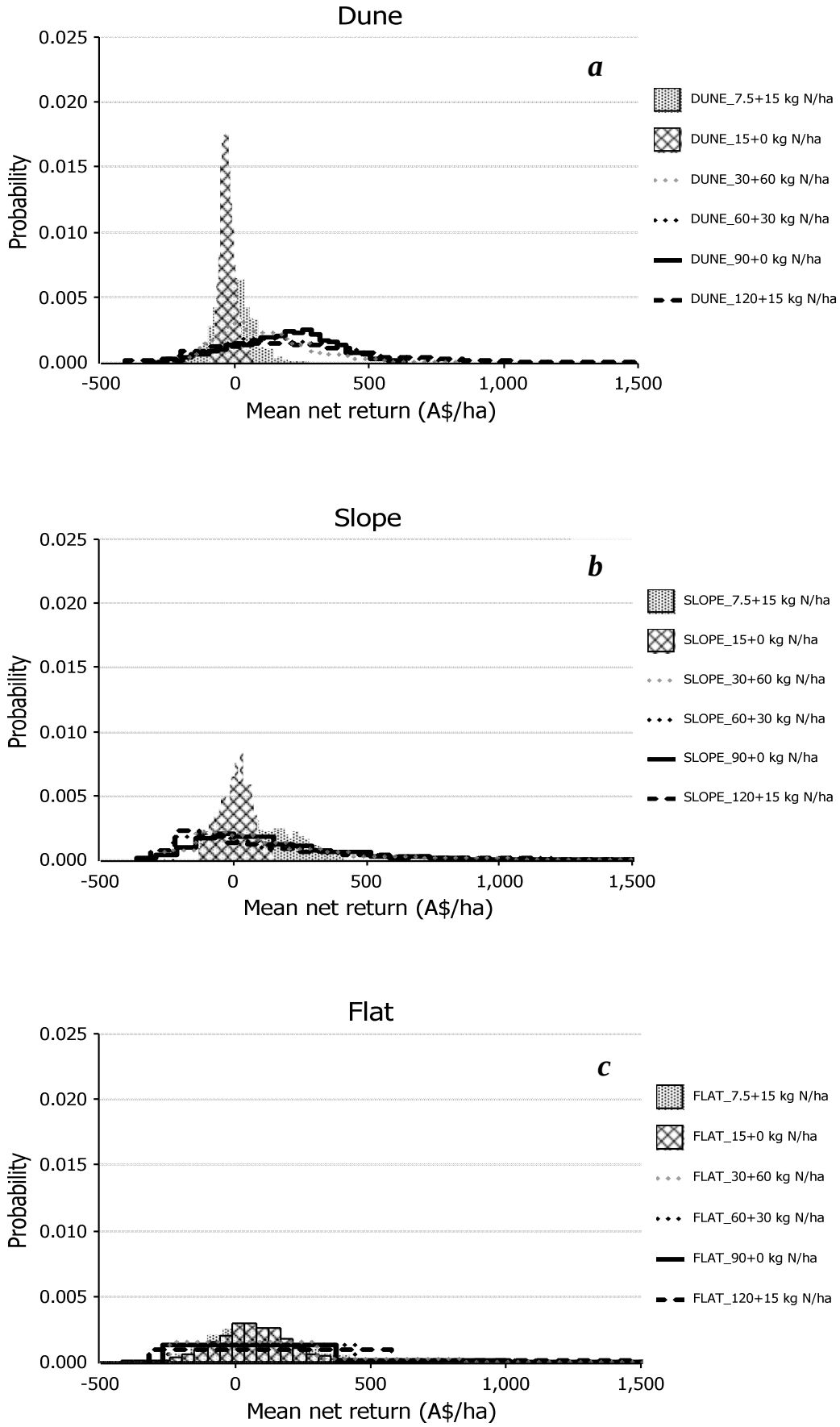

Figure 3. Comparison of magnitude and spread of probability density functions of economic net returns for a selection of N fertilization scenarios across the **a)** dune, **b)** slope and **c)** flat management zones.

The risk profile of each scenario was further defined by interpretation of the $P(NR \geq 0)$, $CVaR_{0.1,}$ R_N and R_{NT} (see section 2.6). In that regard, the probability of breaking even was relatively high (≥ 50%) where high mean net returns occurred and these were typically where mid-high N rates were applied upfront on all zones, especially the dune, and with all rates applied tactically after a sowing application of up to 60 kg N ha^{-1} on the dune and slope (lower rates in the flat). The probability of generating a profit was low (< 30%) in dune scenarios when low rates of N were applied at sowing and in flat scenarios where high rates of tactical N were used in-season (Tables 6 and 8).

Downside risk was assessed with $CVaR_{0.1}$ values up to around -A$400 ha^{-1} calculated for the slope and flat when high sowing N rates were combined with high N rates in-season (i.e. high downside risk). There were no positive $CVaR_{0.1}$ values for this management strategy, and the smallest negative values were calculated for low-mid sowing N rates applied to the dune and the slope zones. Overall, the highest $CVaR_{0.1}$ value of -A$67 ha^{-1} was calculated for 30 kg N ha^{-1} applied upfront to the dune, and this value decreased with increasing rates of N applied at sowing (i.e. higher risk of extreme financial loss associated with damaging events) (Table 6) .

Finally, the marginal value of the total and tactical N fertiliser was assessed with R_N and R_{NT} values. Considering both yield and price risk, the best value for money invested in total N fertiliser at the start of the season occurred in the slope when 15 kg of N was split between sowing and in-season at 7.5 + 7.5 kg N ha^{-1}, followed by the dune scenario of 30 kg N ha^{-1} at sowing + 7.5 kg N ha^{-1} in-season, with A$5.5 and A$4.2 net return for each dollar of N purchased, respectively (Tables 6 to 8). R_N was lowest (-A$0.4) in the unlikely scenario of 150 kg N ha^{-1} applied in-season after zero initial N inputs in the dune. The lowest value for R_{NT} (-A$1.8) was found to result from a small top-dressing application of 7.5 kg N ha^{-1} after upfront 150 kg N ha^{-1} in the dune. Interestingly, similar small tactical applications (7.5 or 15 kg N ha^{-1}) after mid-high N rates applied upfront in all zones offered the best value for the tactical N fertiliser when compared with other tactical scenarios.

In summary, we assume that the best scenarios overall in terms of economics and risk performance indicators (Table 9) meet all the following conditions:

- Mean NR ≥ Mean $NR_{15\ kgN/ha}$ in that zone
- CV≤ 3.0 and CV > $CV_{15\ kgN/ha}$ in that zone
- $P(NR≥0)$ > 50% and $P(NR≥0) > P(NR≥0)_{15\ kgN/ha}$ in that zone
- $CVaR_{0.1} \leq$ -A$150 ha^{-1} and $CVaR_{0.1} > CVaR_{0.1\ 15\ kgN/ha}$ in that zone
- $R_N \geq R_{N\ 15\ kgN/ha}$ and $R_N > 0$

- $R_{NT} \geq A\$1.0$ per dollar of N tactical

To assess the potential benefits from high and tactical N fertilization, we consider the decision to switch from the Mallee farming standard practice of applying 15 kg N ha^{-1} at sowing across all soil zones (with a negative mean net return of -A$30 ha^{-1} in the dune, a low net return of A$7 ha^{-1} in the slope, and a relatively higher net return of A$66 ha^{-1} in the flat) to all other scenarios considered in Table 9.

The standout strategies include mid to high N rates applied at sowing on both the dune and slope (Table 9). As expected, the best performing upfront rates are lower (15 to 60 kg N ha^{-1}) for the more fertile mid-slope zone and higher (30 to 90 kg N ha^{-1}) for the poorer dune soil. As for the flat, only two low N scenarios (15 + 7.5 kg N ha^{-1} and 7.5 + 15 kg N ha^{-1}) offer a benefit relative to the standard rate, despite the relatively high $CVaR_{0.1}$ values, with the former returning a slightly higher value on the tactical N invested (Tables 8 and 9). The results indicate that there is much scope to use more N within a field or paddock, especially in the dune and the slope zones, as well as potential for a small practice change in the flat zone. As mentioned earlier, clearly the least attractive scenarios (measured as a combination of economics and risk) result both from under-fertilizing with zero/low N inputs and from over-fertilizing with excessively high inputs (especially in-season).

Whilst a range of tactical N applications performed well across the dune and slope, typically those including an initial input of 30 to 90 kg N ha^{-1} in the dune and 15 to 60 kg N ha^{-1} in the slope, with a small in-season application of up to 30 kg N ha^{-1} in both zones, were the best (Table 9). For example, one of our best economic-risk scenarios included a tactical N application of 30 kg N ha^{-1} following 60 kg N ha^{-1} at sowing on the dune (Table 9). The decision to adopt this strategy on the dune would see mean net returns increase by A$236 ha^{-1}, while reducing the risk by increasing break-even probabilities by 70%, increasing $CVaR_{0.1}$ by A$71 ha^{-1} and increasing R_N by nearly A$1.0 per dollar of invested N fertiliser. In this case, the coefficient of variation would increase by a relatively small 0.33 in the dune, although more significant risk reductions were observed in the slope, relative to the current practice. The results further encourage a small in-season N application (Table 9).

Table 9. Best performing scenarios overall for each management zone according to pre-defined thresholds of the economic-risk measures (upfront N on left and extra in-season* N on right in first column).

	Kg N ha^{-1}		Mean (A$ ha^{-1})	CV	*P (NR ≥ 0) (%)*	*CVaR$_{0.1}$* (A$ ha^{-1})	R_N (ANR/AN)	R_{NT} (ANR/AN$_T$)
Dune	30	+ 7.5	103	1.19	79	-78	4.2	7.2
		+ 15	117	1.24	77	-84	3.8	4.2
		+ 30	118	1.33	76	-96	2.9	2.1
	60	+ 0	106	1.02	82	-84	2.7	
		+ 7.5	185	1.10	82	-149	3.5	6.8
		+ 15	200	1.11	82	-128	3.4	4.3
		+ 30	206	1.14	81	-139	2.9	2.3
		+ 60	198	1.31	77	-150	2.1	1.0
	90	+ 0	183	0.93	83	-125	2.6	
		+ 30	228	1.27	79	-147	2.3	1.0
Slope	7.5	+ 7.5	58	2.22	64	-110	5.5	6.2
		+ 15	84	1.56	68	-108	4.8	4.2
		+ 30	87	2.80	59	-124	3.0	2.2
	15	+ 7.5	84	1.83	69	-121	4.8	6.9
		+ 15	113	2.14	67	-126	4.6	4.8
	30	+ 0	55	1.69	72	-111	2.7	
		+ 7.5	114	1.64	71	-144	3.7	5.4
		+ 15	134	1.75	69	-149	3.4	3.4
		+ 30	137	1.93	65	-146	2.7	1.8
	60	+ 0	105	1.58	68	-143	2.1	
Fla1	7.5	+15	95	2.09	64	-163	2.4	1.8
	15	+7.5	95	2.07	64	-165	2.4	2.7

* Tactical N applied only in the 39 seasons that meet the trigger conditions outlined in section 2.2.

Despite the encouraging results from higher N rates, the decision to increase N inputs above the district practice of 15 kg N ha^{-1} in the Mallee is likely to depend on farmers' personal attitudes towards risk. Whilst one may opt for a high-return, high-risk scenario, another may prefer to 'play it safe' by choosing a management strategy with lower return and lower risk. Ultimately, the difference lies in whether the farmer is managing for the good, high-yielding years or simply targeting the average season. In the following section, we reassess some of the apparently best performing scenarios according to farmers' aversion to risk.

3.3. Impact of risk aversion

Our assessment of the N input strategies for a risk-neutral Mallee farmer (i.e. one that neither seeks nor avoids risk) over the 60 years revealed that the strategies of applying upfront rates of 30 to 90 kg N ha^{-1} on the dune, 15 to 60 kg N ha^{-1} on the slope, and 15 to 30 kg N ha^{-1} on the flat generated positive net returns in 80% of the years (Figure 4). When a tactical application of up to 30 kg N ha^{-1} followed these initial inputs, profits exceeding A$500 ha^{-1} were found in approximately 20%, 15% and 10% of the years, respectively. These split-rate strategies often surpassed their upfront equivalents with relative higher net returns, though with a slightly higher risk.

Assessing the utility to the farmer by the SERF method (see section 2.7), we defined a finite set of net return values (assumed as net wealth), *W*, in each cumulative density function (Figure 4), which were then converted to their utility via the exponential utility function presented in Equation 6, and the selected value of *c* (i.e. CARA). For a given utility function, the point at which the farmer or decision-maker becomes indifferent between the value of the strategy and its risky outcome gives the CE of a risky prospect (Hardaker et al., 2004a, 2004b). The risk measured is generally based on the magnitude and spread of the distribution of net returns.

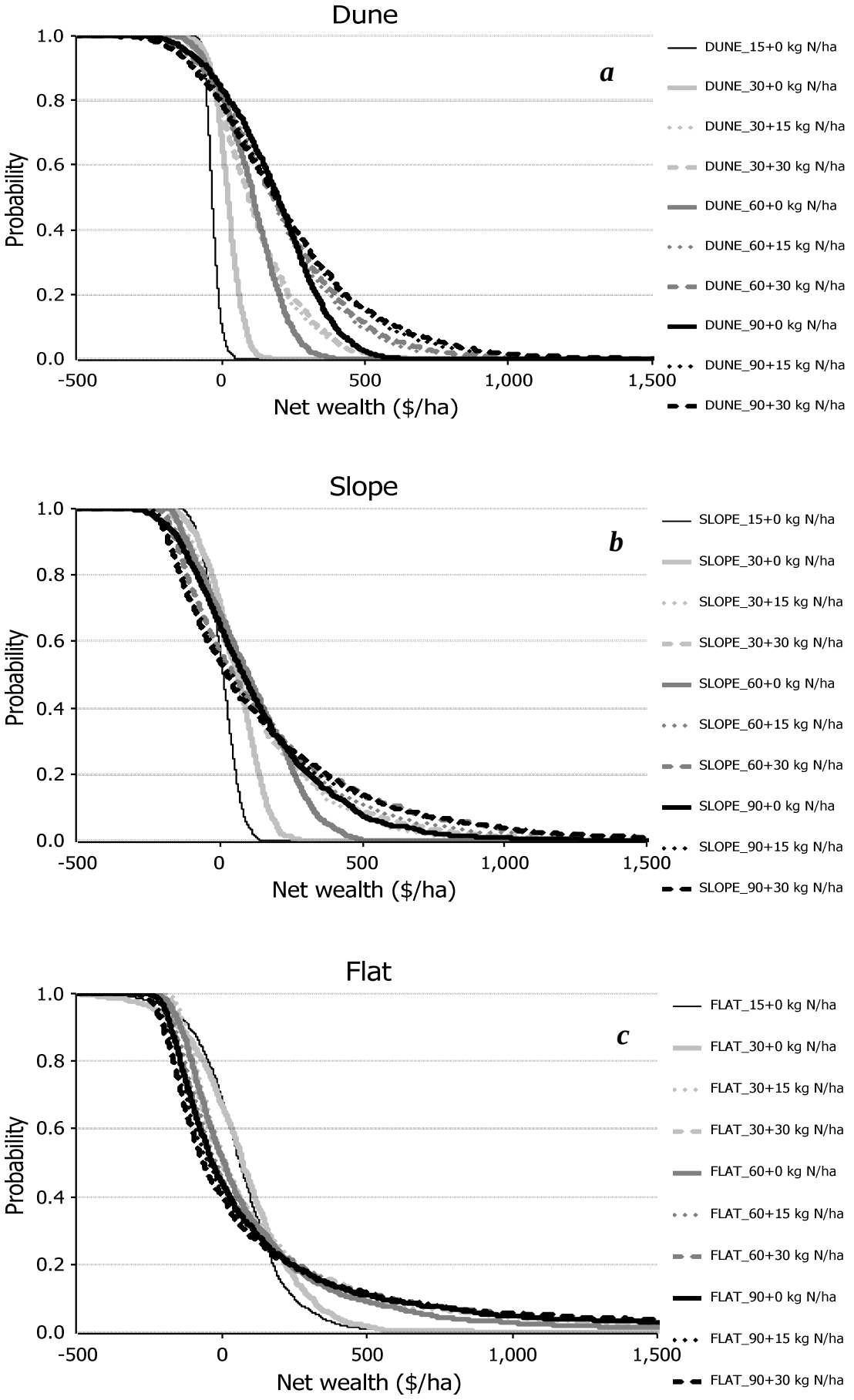

Figure 4. Cumulative density functions for a targeted selection of well-performing economic-risk scenarios, in the **a)** dune, **b)** slope and **c)** flat management zones.

A range of selected N application strategies for increasingly risk-averse farmers is depicted for the dune (Figure 5a) and the slope (Figure 5b), while no SERF analysis is included for the flat given the limited potential for higher N rates in this zone. Overall, CARA coefficients in this study ranged from 0.0 (risk-neutral) to 0.035 (very risk-averse). For each CARA coefficient level, the N strategy with the highest CE is considered the most attractive for those farmers. Generally, there is a shift from higher input strategies to lower input strategies with increasing risk aversion, which is consistent with the premise that most (risk-averse) farmers apply low inputs as they perceive N to be a risk-increasing input.

In addition, it is clear that the more risk-averse a farmer is, the more likely he or she is to favour fixed or upfront strategies (continuous lines) over tactical or split ones (dash lines) (Figure 5), especially in the slope, and despite the slightly lower returns. The results seem to show that relying on a late application of N can increase riskiness because of the chance that weather conditions may not allow application of the N within the window of opportunity. As mentioned earlier, in our APSIM-based analysis in-season applications are triggered by a range of soil and agronomic conditions which, while attempting to represent the season, do not guarantee that the in-season N is being applied to a crop with high yield potential.

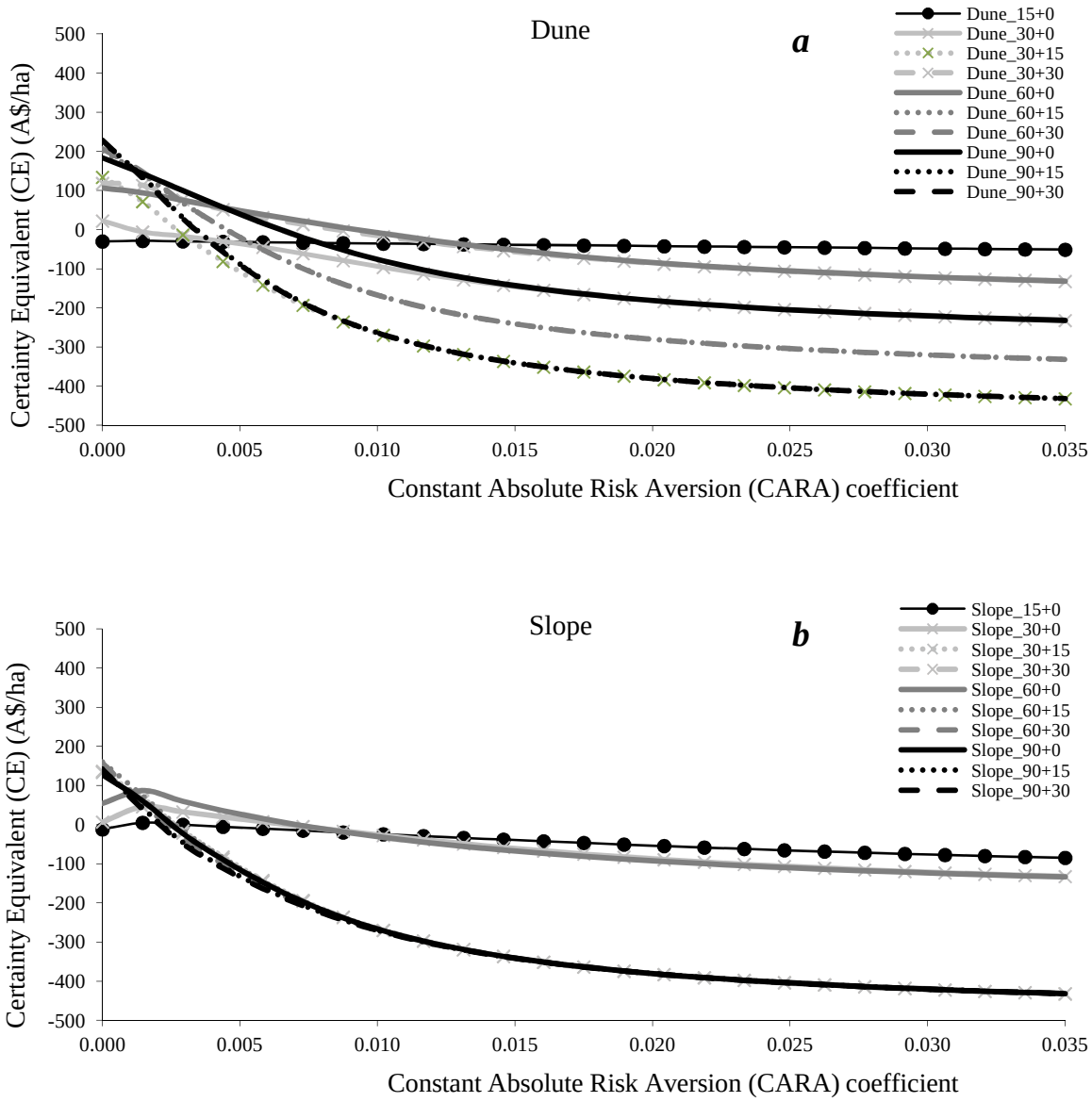

Figure 5. SERF results for a selection of well-performing economic-risk scenarios over the CARA range of 0.0 to 0.035, in the **a)** dune and **b)** slope.

The most attractive economic scenarios (90 + 30 kg N ha^{-1} on the dune and 60 + 30 kg N ha^{-1} on the slope) were outperformed by their upfront equivalents (90 and 60 kg N ha^{-1} on the dune, 60 and 30 kg N ha^{-1} on the slope) at risk aversion coefficients ranging from 0.001 to 0.005 (close to risk-neutral) (Figure 5), meaning that more risk-averse farmers, such as most in the dryland regions of Australia, are not likely to adopt them, but will consider upfront fertilisation or lower tactical applications instead. More interestingly, the overall favourite strategies using lower or split N rates, including 60 kg N ha^{-1} and 30 + 30 kg N ha^{-1} on the dune, and 30 and 60 kg N ha^{-1} on the slope, were slightly outperformed by a single low upfront application of 15 kg N ha^{-1} at relatively high risk-aversion coefficients of 0.015 and

0.010 in the dune and slope, respectively (Figure 5). Therefore, our results suggest that the average Mallee farmer is likely to sit around the 0.015 level (at least between 0.010 and 0.015) on the CARA scale, based on the average current N fertilization practice in the region.

In summary, applying more than a total of 90 kg N ha^{-1} on the dune and over 60 kg N ha^{-1} in the slope is considered by farmers as a very risky strategy, despite the potential very high returns, because these strategies are preferred above any other only at the near-neutral CARA coefficient levels (close to the zero mark), and are almost the only presented options that assume negative CE values at relatively low levels of risk aversion (up to 0.01). These are also the strategies presented with the highest average change in CE (greater than A$500 compared to lower than A$100 in some scenarios with lower N rates) as a result of an increase in farmers' risk aversion from 0.0 to 0.035.

So we conclude that, when taking into account the farmer's attitude to risk, strategies that include an application of 15 to 60 kg N ha^{-1} at sowing on both the dune and the slope (as well as a split application of 30 + 30 kg N ha^{-1} on the dune) are the most likely to be adopted by farmers (assuming a range of risk preferences, even if all considered risk-averse). As expected, typically risk-averse farmers prefer consistent returns and are thus willing to take a somewhat lower, but less variable, expected payoff (Kingwell, 2011).

4. Discussion

The results confirm our hypothesis that dryland farmers, who, currently and persistently, adopt a low N input strategy in an attempt to minimize economic downside risk, are missing out on the returns available from more intense cropping in the good years on most of their farm. In other words, when both yield and price risks are factored in over a long time-frame, it becomes evident that farmers are better off if they reduce the probability of under-fertilizing in the dry seasons (hence making a loss), while increasing the probability of sufficiently fertilizing when the season develops well (by providing enough N upfront or 'playing the season' in some cases). Further support for this strategy comes from the possibility that left-over N from potential over-application in the poor years (assuming that is not lost or transformed) may be taken up by the crop in the following season, and the possibility that having extra N in the plant may improve grain quality, and thus its market price, although neither has been accounted for in the analysis.

In comparison with the current practice of adding about 15 kg N ha^{-1}, the use of higher upfront rates up to 90 kg N ha^{-1} is an attractive strategy across all zones but the flat, in terms of both long-term economics and risk. Moreover, several of the tactical N fertilization

scenarios can significantly increase farmers' mean net returns while in some cases also reducing income variance, although the full potential of tactical fertilization is likely to be realised when other factors such as grain quality, crop rotation and whole-farm farm budget are factored in the analysis. Overall, these findings are consistent with previous studies that demonstrate the benefits of tactical N management (Nordblom et al., 1985; McDonald, 1989; Kingwell et al., 1993; Angus, 2001; Broun, 2007; Lobell, 2007; Moeller et al., 2009; Oliver and Robertson, 2009), and provide supporting evidence for the proponents of higher input strategies designed to extract higher returns from marginal dry environments (Babcock, 1992; Asseng et al., 2001; Sadras, 2002; Good, 2004; Sadras and Roget, 2003; Spiertz, 2010). Our results also add weight to the case for profitable zone management.

There are several plausible explanations as to why farmers in low-rainfall environments may be applying what appear to be sub-optimal rates of N. The main reason seems to be that farmers seek to minimise the risk of a costly yield shortfall (and thus reduced profit) arising from over-fertilization with N in poor seasons. In seeking to manage for average seasons, conservative application strategies are being recommended, and these may result, at least partly, from a lack of substantial datasets to support the use of high N rates in dryland regions (Broun, 2007). Importantly, the decision to apply a lower N rate may also be directly linked to the financial health of the farm business at the start of the year when most inputs are purchased, and to the ability to borrow money or cover short-term losses (Pannell et al., 2000; Hardaker et al, 2004b). The additional expenditure on a range of other inputs that would be required to achieve the anticipated crop yields may influence the decision (Broun, 2007), as may a recent history of consecutive poor seasons, as seen in the Mallee from 2005 to 2009. Finally, farmers' concern for the environment and sustainability of their farm may also impact on the rate of N they choose to apply, as an average of 30% of applied N is lost from dryland cereal cropping in Australia (McDonald, 1989; Angus, 2001; Chen et al., 2008).

The results produced here must be interpreted with caution, because it is widely accepted that variance of APSIM yield potentials is generally lower than the variance of actual crop yields since the model cannot accurately capture all phenomena, including unpredictable damage by weather, pests, diseases and weeds, or occasional crop failures caused by 'haying off' (crop damage caused by a combination of water deficit and excess N) in extremely dry seasons (van Herwaarden et al., 1998). Similarly, the model has been fixed to have the same starting N conditions for every season in a given soil type, which may in fact vary considerably with prior management. The effect of higher intensity of cropping on increasing initial soil test N values, as well as grain protein, could be captured in a follow-up analysis that tests a range of N starting values for each soil type. If Mallee farmers are able to establish the relevance of

this analysis to their own farm and soil conditions by, for example, defining the proportion of a certain soil type on their farm, and relating the analysis to the initial N fertility on their given management unit, then these results could usefully inform individual farmers' decisions.

5. Conclusion

Our economic-risk analysis suggests that, in terms of maximising average returns, farmers in a low-rainfall cropping region such as the Mallee are under-fertilizing with N on up to 80% of their farm (dune and slope soils). When accounting for long-term yield and price risks, the use of higher rates of N on the most common soils (applied at sowing and in combination with a subsequent tactical application) can be a risk-reducing strategy in a highly variable dryland environment. Our conclusion challenges the widely held belief that N fertiliser is a risk-increasing input in low-rainfall regions because it increases the farmers' exposure to risk in very dry seasons. Whilst this may be true, we argue that a more complete risk assessment, like the one conducted in this study, reveals that improved economic returns in a marginal region, like the Mallee, arise from reducing the probability of under-fertilizing in the good seasons. To do that, the less risk-averse farmers will need to increase their N rates, and apply tactical in-season N when conditions are favourable. The more risk-averse farmers may prefer a more convenient upfront (and less profitable) approach, while still increasing their rates of N on the sandier soils of their farm. The study further supports the argument that variable fertiliser rates based on soil-specific management can both increase average returns and reduce risk.

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