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A modelling investigation into the economic and environmental values of 'perfect' climate forecasts for wheat production under contrasting rainfall conditions

Qiang Yu,[a,b]* Enli Wang[a] and Chris J. Smith[a]
[a] *CSIRO Land and Water/APSRU, GPO Box 1666, ACT 2601, Canberra, Australia*
[b] *Institute of Geographical Sciences and Natural Resources Research, Beijing 100101, China*

ABSTRACT: With increased investment in improving climate forecasting techniques, it is essential to find ways of quantifying the maximum benefit of climate forecasts for a given industry. This paper describes an approach to quantify the value of 'perfect' climate forecasts to direct nitrogen management in a wheat-cropping system at two Australian locations with contrasting annual rainfall. For annual wheat-cropping systems, and compared with the N management based on optimal N rate derived from long-term climatic conditions, N management based on 'perfect' climate forecasts can lead to an average benefit of $65.2/ha/year at Walbundrie (annual rainfall 560.0 mm) and $66.5/ha/year at Wanbi (annual rainfall 314.5 mm). Generally, the economic benefit is highest in extreme (wet and dry) years and lowest in normal years. At the high rainfall site Walbundrie, where average N-application rate is high, the maximum yearly benefit was from significant saving through reduction in N application in driest years. At the low rainfall site Wanbi, where average N rates are low, the highest benefit was from both yield increases in the wettest years and saving of management and fertilizer cost in the driest years. Such optimized nitrogen management has little impact on excess drainage, but it can have significant impact on reduction of excess nitrogen, especially in high rainfall areas. An excess N reduction of 1314 kg N/ha at Wanbi and 1538 kg N/ha at Walbundrie can be achieved in 114 years. The significant reduction in N excess at Walbundrie may have profound environmental implications. Copyright © 2007 Royal Meteorological Society

KEY WORDS climate variability; wheat yield; nitrogen management; Australia; APSIM

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1. Introduction

Climate variability has been recognized as one of the major drivers causing instability and increased risk in agricultural production and the consequent degradation of farming land in Australia. The highly variable frequency and magnitude of rainfall events lead to mismatches of water supply to crop water demand and crop yield instability. Such mismatches also allow water to pass beyond the crop root zone, thereby causing increased groundwater recharge, rising tables of saline groundwater, and land and river salinization. Therefore, managing climate variability has been one of the major focuses of research for solutions to reduce production risk and negative environmental impact. Many studies have focused on improvement of on-farm management to increase production profit (Carberry *et al.*, 2000; Hammer, 2000; Asseng *et al.*, 2001b; Lythgoe *et al.*, 2004). Increased efforts have also been directed to look at the potential of mitigating the detrimental environmental impact of farming systems (Keating and McCown, 2001; Asseng *et al.*, 2001a, 2001b; van Ittersum *et al.*, 2003). While historical climate records can provide valuable data sets for risk analysis associated with climate variability, improved seasonal climate forecasts have been considered to offer added value, especially for tactical decision-making.

In many regions of Australia, large rainfall variability and low mean-annual rainfall often limit management options such as crop choice, rotation type, fertilizer application and fallow management, etc., for dryland agricultural production. The value of climate forecasts may vary considerably among regions and may be dependent on the climate itself. As many of the farming systems have been adapted towards a high economic return, assessment of climate forecasts to influence management practices under current systems often indicates some increased economic value but little environmental value (Asseng *et al.*, 2001b; Lythgoe *et al.*, 2004). To increase the environmental value (or to reduce the negative environmental impact) of farming systems often requires changes to the current system (Stirzaker *et al.*, 2000), which are associated with trade-offs in the economic return (Keating *et al.*, 2002). In this regards, the value of the climate forecasts needs to be assessed in terms of how it can contribute to minimize the trade-offs and maximize the environmental value (e.g. reduce drainage).

* Correspondence to: Qiang Yu, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, No. 11A, Datun Road, Beijing 100101, China. E-mail: yuq@igsnrr.ac.cn

For any type of climate forecast, its value in influencing management practices depends on its actual skill in predicting certain climate variables (e.g. rainfall) or other integrated variables of the system (e.g. crop yield) with an appropriate lead time. The value of any forecast is also limited by the maximum difference between outcomes obtained using no forecasts and 'perfect' forecasts. By 'perfect' forecasts, we assume we know what is going to happen in the coming season at any time. The present forecasting skill is imperfect, and the knowledge to modify actions ahead of likely impacts is a limitation of applying climate predictions to improve agricultural systems (Hammer *et al*., 2001). So far, increasing efforts have been made on how to increase the value of the currently available forecasts, compared to no forecasts, by adjusting management practices and improving the climate-forecasting skill. Both of them require significant investment. One question that needs to be answered is how much more value we can get through further improving the climate forecast skill.

The objective of this paper is to quantify the value gap between no forecasts and 'perfect' forecasts in south-eastern Australia in terms of influencing nitrogen management practices in dryland agriculture. Nitrogen management was chosen as an example because nitrogen fertilization is a significant cost in the farming systems and management decision-making is closely related to weather. The potential of nitrogen application to increase crop yield is greatly dependent on rainfall, and a varying application rate can significantly alter economic benefit. In fact, it is the only management option that has significant impact on the performance of farming systems and that can be modified at the time when the ENSO-based climate forecasts are available for most years in south-east Australia (May–July). Previous studies on N management responding to ENSO-based climate forecasts appear to be inconsistent. Some indicated that coupling N-management decision with southern oscillation index (SOI)-based forecasts increased benefits and reduced risk (Hammer *et al*., 1996; Asseng *et al*., 2001b; Lythgoe *et al*., 2004). Conversely, others found such an approach may have limited value due to inappropriate skill quantification (Robinson and Butler, 2002) or due to the flatness of response of economic return to nitrogen input around the optimal nitrogen rate (Hyaman and Turpin, 1998; Hayman, 2003). In terms of water balance, although some studies show that improved N management could significantly improve crop water use (Angus *et al*., 2001), many indicated that such changes have limited impact on drainage (Asseng *et al*., 2001b; Stirzaker *et al*., 2000; Lythgoe *et al*., 2004).

In this paper, we focus on two selected sites with contrasting annual rainfall to study the value of 'perfect' climate forecasts to direct N management for a continuous wheat-cropping system, compared to no forecast. We (1) use a modelling approach and historical climate data (1889–2004) to quantify the response of crop yield, gross margin, risk and drainage to a range of nitrogen application rates, (2) estimate the optimal N rates for different climatic years and for long-term average climatic conditions and (3) compare the value of N management based on 'perfect' climate knowledge with that based on the long-term average optimal N rates in terms of economic return and drainage reduction.

2. Materials and methods

2.1. Site specification and climate data

Two study sites were selected. One is located in the high-rainfall zone at Walbundrie in southern New South Wales and the other one is in the low-rainfall zone in Mallee at Wanbi in South Australia (Figure 1). Historical climate data from 1889 to 2004 were obtained from the SILO patched database (www.bom.gov.au/SILO). At Walbundrie (Station No 074 115, 35.69°S, 146.72°E), annual rainfall ranges from 199.7 to 1030.2 mm with a mean of 560.0 mm (1889–2004). Rainfall distribution within a year and from year to year has been highly variable. On average, spring, summer, autumn and winter rainfall accounts for 27, 20, 23 and 30% of the annual rainfall respectively. At Wanbi (Station No. 025 034, 34.78°S, 140.27°E) annual rainfall ranges from 136.0 to 570.1 mm with a mean of 314.5 mm (1889–2004). On average, the spring, summer, autumn and winter rainfall accounts for 27.8, 17.5, 21.8, and 32.8% of the annual rainfall respectively. Long-term monthly average rainfall, temperature and variability in annual rainfall (1889–2004) for Walbundrie and Wanbi are illustrated in Figure 2.

At Walbundrie, a duplex soil with contrasting texture between the A (upper) and B (lower) horizons (a soil horizon is a layer of soil, approximately parallel to the land surface, with morphological properties different from layers below and/or above it) was used for the simulation study. It has a plant available water content (PAWC) of 183.0 mm in the plant root zone (0–1.5 m for wheat). At Wanbi, a sandy loam soil was used with a PAWC of 190.1 mm. Figure 3 shows profiles of water content at a lower limit (15 bar suction), drained upper limit and saturation.

2.2. APSIM model and simulation scenarios

The agricultural production systems simulator (APSIM) (3.2) (Keating *et al*., 2003a) was used to simulate a continuous wheat-cropping system, i.e. planting wheat every year followed by a summer fallow period after harvest. The APSIM modules include wheat, soilwat2, soiln2, residue2 and manager. The model has been widely used in Australia (Keating *et al*., 2003b), and applied in different crop-growing zones worldwide (Asseng *et al*., 2000, 2001b). Model validation for simulation of crop growth and water use was also done in areas close to both study sites (Verburg and Bond, 2003; Luo, 2003). The same crop parameters were used in both sites, and soil parameters were site-specific.

In the simulation, wheat cultivar Janz was sown every year in a sowing window when cumulative rainfall

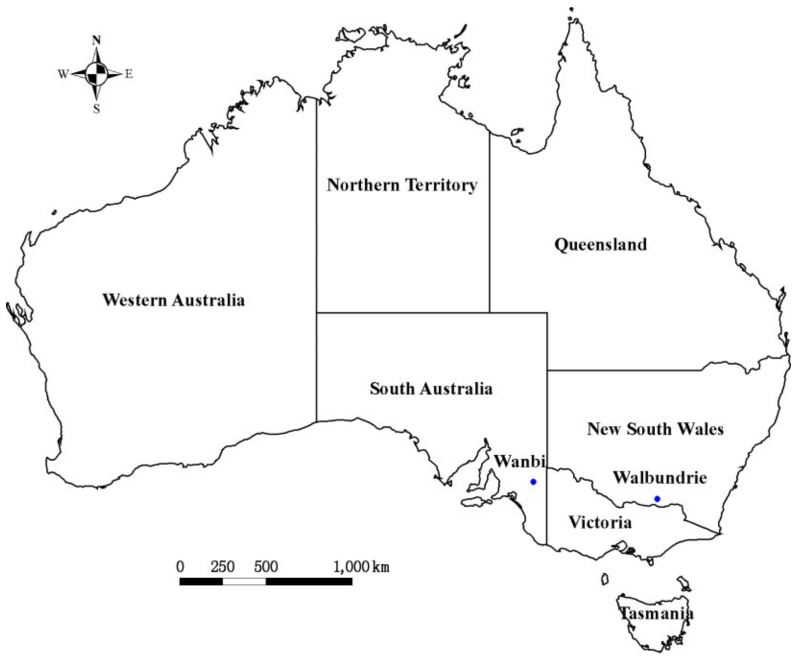

Figure 1. The locations of the two study sites (Walbundrie and Wanbi) in South and south-east Australia. This figure is available in colour online at www.interscience.wiley.com/ijoc

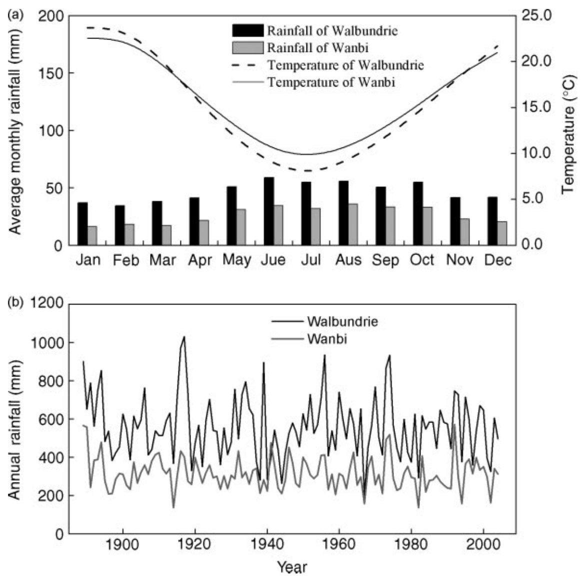

Figure 2. Long-term monthly average temperature and rainfall (a), and annual rainfall (b) for Walbundrie and Wanbi (1891–2004).

in 10 consecutive days was greater than 25 mm or when the end of the sowing window was reached. The sowing window was from 1 May to 30 June. Wheat was sown to a depth of 4 cm with a plant density of 100 plants/m^2. At maturity, wheat grain was harvested and each year the wheat stubble was burnt at the end of March. Simulation outputs include above-ground biomass, grain yield, evapotranspiration (ET) and drainage. Drainage within and outside the wheat-growing season was separately reported.

For all simulations, the initial nitrogen condition was set at 30.0 kg mineral N per hectare for both Walbundrie and Wanbi in the 0–1.5 m soil profile. Soil nitrogen was reset to the initial soil N level each year at sowing. Soil moisture was simulated continuously from year to year to allow for the carry-over effect to be simulated.

For each site, 31 nitrogen intervals from 0 to 300 kg N/ha every year with an increment of 10 kg N/ha were simulated to study the response of crop yield, gross margin and drainage to N rates. This was referred to as the fixed N rates scenario. Nitrogen was applied twice in each growing season: the first application on sowing day and the second application at wheat booting stage. The base fertilizer at sowing was kept at 25.0 kg N/ha, and the second fertilization varied with different nitrogen level. When the total fertilizer input was below 30.0 kg/ha, half was applied each time. All together, 62 simulation runs were conducted (2 sites × 31 N levels).

For the purpose of determining the optimal N rate each year, as described below, a procedure was developed to sample the optimal N rate in the range of 0–300 kg N/ha as affected by the starting soil moisture at sowing time of wheat and rainfall in the coming wheat season. This was done by running the model with 31 nitrogen rates each year from the wheat-sowing date and with the soil moisture level left by the previous wheat/fallow season as a result of the optimal N management in the previous season. This procedure allows the impact of the residual soil moisture from the previous season to be accounted for.

2.3. Determination of optimal nitrogen application rates

Optimal N rate can be defined for crop yield, drainage or maximum gross margin. Here, the optimal N rate refers to the nitrogen application rate at which maximum gross margin can be obtained. Under this definition, optimal N rate is influenced by prices of N fertilizers

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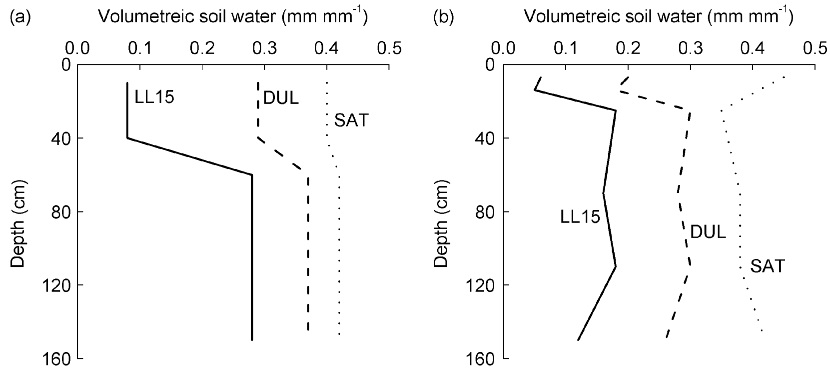

Figure 3. Soil water content at lower limit of 15 bar suction (LL15), drained upper limit (DUL) and saturation (SAT) for the soils at Walbundrie (a) and Wanbi (b).

and wheat grain yield. Gross margin is calculated as the difference between benefit (i.e. yield × price) and total cost. In addition to the cost of nitrogen fertilizers, total cost also includes a cost related to fertilizer application and an annual non-fertilization management cost. The fertilizer price is based on the cost of urea, and its management is in terms of pure N rate. For simplicity, a fixed price for both wheat grain and N fertilizer was used. Average wheat grain price was set at 208.0AUS$/t, urea price at 436.0AUS$/t based on ABARE data (ABARE, 2004). Wheat price change with protein content was not considered. The cost related to fertilization application and the annual non-fertilization cost were assumed to be 10 AUS$/ha and 150 AUS$/ha respectively (Ringrose–Voase *et al.*, 2003).

Optimal rate of nitrogen application depends on crop nitrogen demand in different climatic years. Inter-annual and seasonal variability of climate, especially rainfall, leads to variations in crop growth and crop nitrogen demand from year to year. Therefore, two types of optimal N rates are defined here: N_{opta}, optimal N rate based on long-term average climate condition, N_{optm}, optimal N rate for each climatic year (i.e. perfect knowledge).

For each site, crop yield and drainage were simulated for each year and each N level. Gross margin was calculated on the basis of the simulated grain yield, grain price and total cost. The average gross margin over the 114 years for each N level was then calculated. N_{opta} is the N rate that leads to the maximum average gross margin for all years (Figure 4). The optimal N rate for each year (N_{optm}) was derived using the procedure described previously to account for the impact of stored soil moisture at sowing on N rate.

To analyse the nitrogen response of crop yield, water use, drainage and gross margin in different climatic years, climatic year types were classified using K-means cluster analysis in the SPSS package (SPSS 11.5) based on simulated crop yield, rainfall amount within and outside the wheat growing season and simulated drainage within and outside the wheat growing season. At Wanbi, deep drainage happens only in very few years with low amount, therefore, it is not taken as an element in clustering for year types. Rainfall is the determining

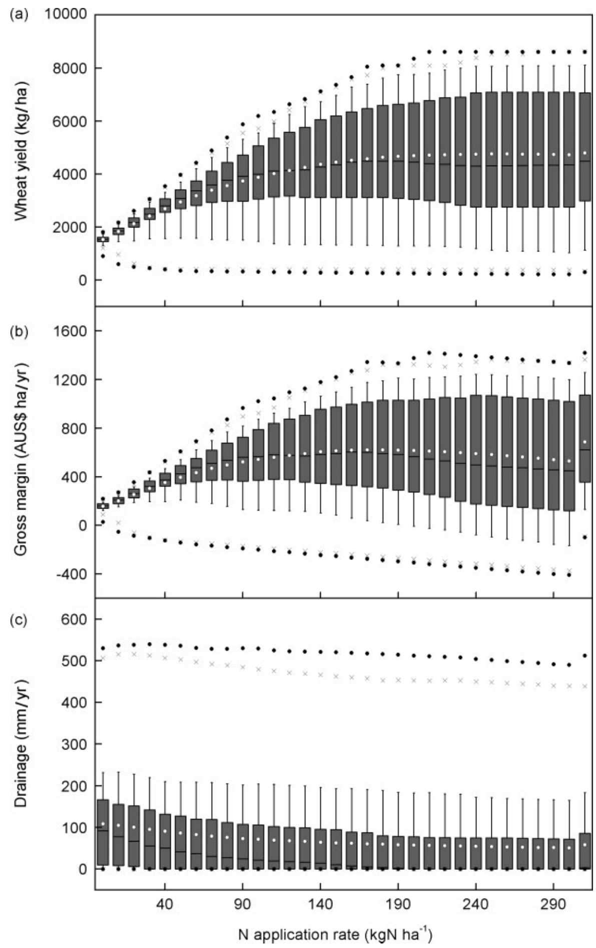

Figure 4. Simulated responses of wheat grain yield (a), gross margin (b) and annual drainage (c) to nitrogen application rates at Walbundrie (1891–2004). The box plots show the 10, 25, 50, 75 and 90 percentiles. The crosses show the 1 and 99 percentiles. Black dots represent maximum and minimum values and grey dots the mean.

factor on crop yield and drainage. Six year types were considered enough to distinguish characteristics of the composition of rainfall, yield and drainage, in which high, moderate and low values of each factor were clustered. Tables I and II show the average values for each year type. Clustering was done separately for each site, which means that the critical value of rainfall to separate each type is different for the same year types for the two sites. For example, the high-rainfall type in Wanbi is similar to that of moderate rainfall in Walbundrie. The nitrogen responses were then analysed (Figures 5 and 6).

2.4. Value of historical climate knowledge and perfect climate forecast to direct N application

For options with no forecast, but with historical climate knowledge, the long-term average optimal N rate (N_{opta}) was applied each year to conduct another simulation scenario to simulate crop yield, gross margin, ET and drainage. The difference in outputs between this scenario and any known current management practice would represent the value of historical climate knowledge.

'Perfect' climate forecasting is assumed to be a situation where, at any time, we know exactly what is going to happen within the forthcoming season. In this way, the optimal N rate for each year (N_{optm}) would be the rate to apply to each year. The simulated crop yield, ET, drainage and gross margin represent the outcomes with N management in response to 'perfect' climate forecast.

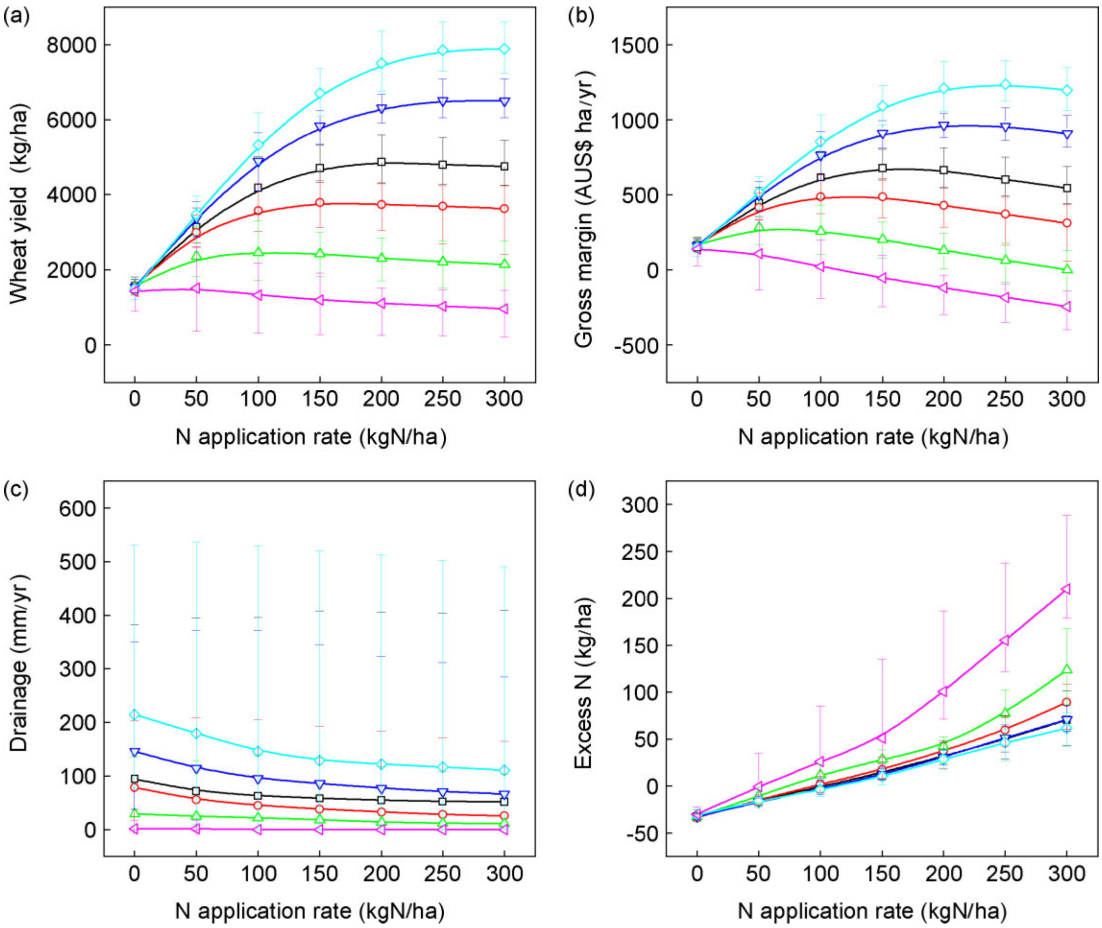

Figure 5. Changes in simulated wheat grain yield (a), gross margin (b), drainage (c) and excess N (d) in response to N rate for six climate year types at Walbundrie, New South Wales. The year types from high to low grain yield are H(rainfall) – H(yield) – H(drainage) (cyan lines), H–H–M (blue lines), M–M–M (black lines), M–M–L (red lines), M–L–L (green lines), L–L–L (magenta lines), in which H, M and L refer to high, moderate and low values. This figure is available in colour online at www.interscience.wiley.com/ijoc

Table I. Six year types clustered based on rainfall, crop yield and drainage at Walbundrie (1891–2004) (R – rainfall; Y–wheat yield; D – drainage; H: high; M: moderate; L: low).

Type (R–Y–D)	Rain in growing season (mm)	Rain out of growing season (mm)	Drainage in growing season (mm)	Drainage out of growing season (mm)	Wheat yield (kg/ha)	Number of years
H-H-H	460.8	248.6	84.3	37.9	7906.6	28
H-H-M	396.5	246.7	53.2	24.1	6503.0	15
M-M-M	373.5	196.5	43.6	12.8	4916.5	16
M-M-L	296.7	218.7	23.3	9.5	3675.8	27
M-L-L	222.5	193.1	7.0	8.3	2238.4	17
L-L-L	163.2	181.6	0.0	0.0	942.2	11

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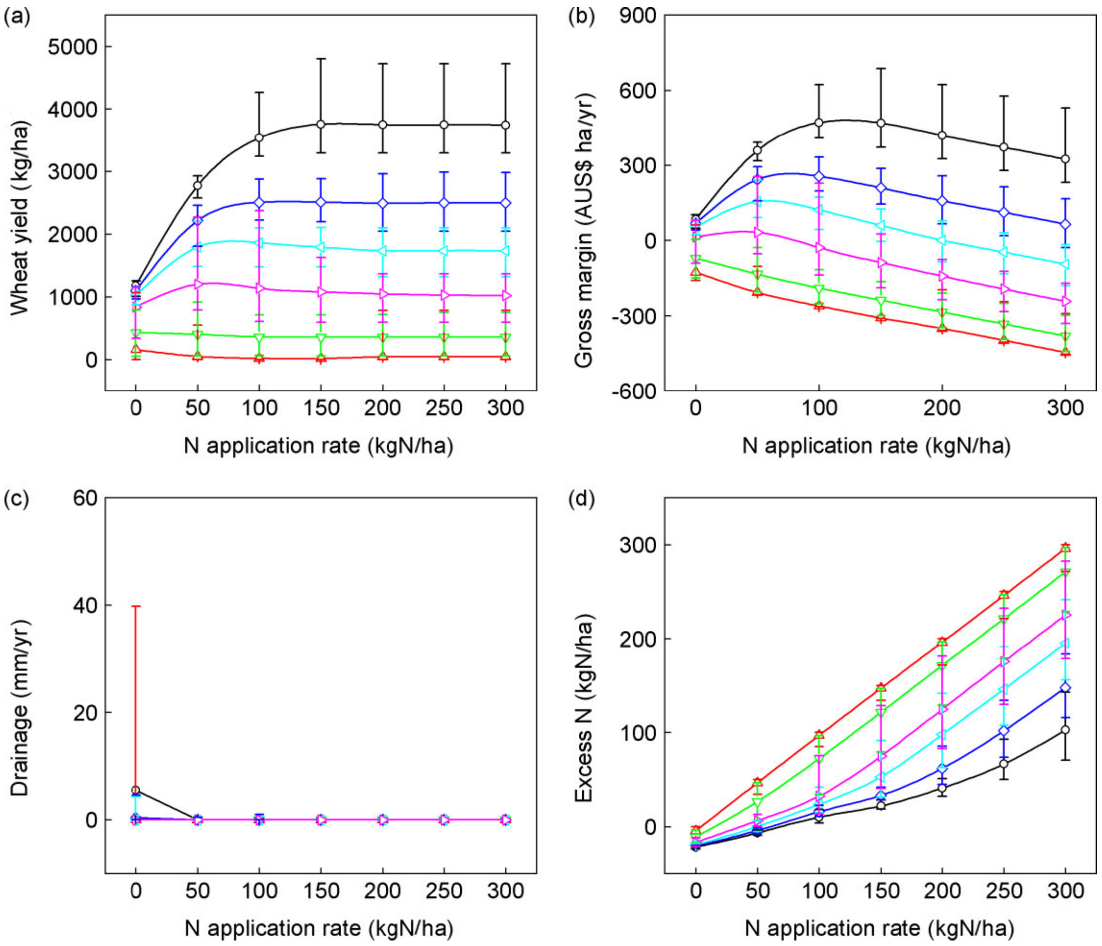

Figure 6. Changes in simulated wheat grain yield (a), gross margin (b), drainage (c) and excess N (d) in response to N rate for six climate year types at Wanbi, South Australia. The year types from high to low grain yield (a) are H(rainfall) – H(yield) (black lines), H–M (blue lines), M–M (cyan lines), M–L (magenta lines), L–M (green lines), L–L (red lines), in which H, M and L refer to high, moderate and low values. This figure is available in colour online at www.interscience.wiley.com/ijoc

Table II. Six year types clustered based on rainfall and simulated wheat yield at Wanbi (1891–2004) (R – rainfall; Y – wheat yield; H: high; M: moderate; L: low).

Type (R–Y)	Rain in growing season (mm)	Rain out of growing season (mm)	Yield (kg/ha)	Number of years
H-H	289.4	151.4	3783.8	8
M-H	235.1	117.9	2516.8	11
M-M	234.6	147.7	1808.6	13
L-M	200.3	114.2	1083.7	19
L-L	167.0	109.2	350.7	36
Crop fail	142.3	121.3	0.0	27

The difference in gross margin between the above two scenarios (using N_{opta} and N_{optm}) is considered as the value of 'perfect' climate forecasts compared to no forecasts but with historical climate knowledge. This was done for all years and each of the five climatic year types at both sites. Tables III and IV show the average values.

3. Results

3.1. Response of simulated wheat yield, gross margin, drainage and N excess to N rates

At each nitrogen level, the simulated wheat yield, gross margin and drainage vary considerably from year to year. The inter-annual variability of wheat yield and gross margin increases significantly with nitrogen input (Figure 4(a) and (b)), while the variability of drainage decreases (Figure 4(c)). This implies that the climate risk or the value of climate forecasts, in terms of economic return (grain yield and gross margin) increases with N input level, but the risk in terms of excess drainage decreases. However, excess N application can not only lead to unnecessary cost but can also result in increased N leaching in the environment. The assessment of the value of improved management based on climate forecasts needs to take all these aspects into consideration.

Figures 5 and 6 further show the N responses of wheat yield and gross margin. Owing to the contrasting climate at the two study sites, the productivity (grain yield or gross margin) and environmental impact (drainage, N excess) of the same continuous wheat-cropping system are different. The extent to which N management can

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Table III. Average optimal N rates and benefit of N management based on perfect climate forecast in six types of climatic years compared to that with fixed N rate of 180 kg N/ha/year at Walbundrie.

Year type (R-Y-D)	Average optimal N rates (kg/ha)	N saving (kg/ha/yr)	Value of N saving (AUS$/ha/yr)	Yield increase (kg/ha)	Value of yield increase (AUS$/ha/yr)	Drainage decrease (mm)	Benefits (AUS$/ha/yr)	Number of years
H-H-H	231.1	−51.1	−48.4	624.5	129.9	2.0	81.5	28
H-H-M	212.0	−32.0	−30.3	342.6	71.3	2.8	40.9	15
M-M-M	170.0	10	9.5	65.6	13.6	−0.8	23.1	16
M-M-L	117.8	62.2	59.0	−72.5	−15.1	2.3	43.9	27
M-L – L	64.7	115.3	109.3	−111.4	−23.2	0.6	86.1	17
L-L – L	25.5	154.5	146.4	−52.0	−10.8	0.0	156.7	11
Years with negative income	155.0	25.0	23.7	−160.1	−33.3	0.0	−9.6	2
Years with positive income	148.4	31.6	30.0	174.7	36.3	0.0	66.6	112
All years	148.5	31.5	29.9	168.9	35.1	1.4	65.2	114

Table IV. Average optimal N rates and benefits of N management based on perfect climate forecast in six types of climatic years compared to that with fixed N rate of 40 kg/ha/year at Wanbi.

Year type (R-Y)	Average optimal N rates (kg/ha)	N saving (kg/ha)	Value of N saving (AUS$/ha/yr)	Yield increase (kg/ha)	Value of yield increase (AUS$/ha/yr)	Benefits (AUS$/ha/yr)	Number of years
H-H	123.8	−83.8	−79.4	1235.1	256.9	177.5	8
M-H	86.4	−46.4	−44.0	440.3	91.6	47.6	11
M-M	54.6	−14.6	−13.8	65.3	13.6	−0.3	13
L-M	35.8	4.2	4.0	−107.8	−22.4	−18.4	19
L-L	10.3	29.7	28.1	−63.1	−13.1	20.3	36
Crop fail	0.0	40.0	37.9	−64.7	−13.5	194.8	27
Years with negative income	38.0	2.0	1.9	−175.4	−36.5	−34.6	25
Years with positive income	30.9	9.1	8.6	156.1	32.5	94.9	89
All years	32.5	7.5	7.1	83.4	17.3	66.5	114

influence different aspects of the system performance is also different. At Walbundrie, grain yield ranges from 0 to >8 t/ha (Figure 5(a)) and in the best years the gross margin can reach $1,420/ha (Figure 5(b)); at Wanbi, due to the lower rainfall, wheat yield has a range of 0–<5 t/ha, and the highest gross margin in best years is only close to $700/ha (Figure 6(a) and (b)). At both sites, in wet years, higher N rate is needed (>200 kg N/ha at Walbundrie and 150 kg N/ha at Wanbi) to achieve the potential crop yield (Figures 5(a) and 6(a)), while in dry years crop growth is limited mainly by water supply (rainfall), and increased N application leads to crop hay-off (reduced crop yield due to excess water use in early stages leading to dry soil towards the end) (Figures 5(a) and 6(a)), unnecessary cost and low gross margin (Figures 5(b) and 6(b)). In each group of climatic years, there is a limit for drainage reduction through N management, and, in wet years, drainage can be high, especially in a high-rainfall area like Walbundrie (Figures 5(c) and 6(c)). While increased N application reduces N deficit of the crop in wet years, it leads to increased N excess in dry years (Figures 5(d) and 6(d)).

3.2. Optimal N application rates

Under average long-term conditions from 1889 to 2004, the optimal N rate (N_{opta}) estimated from the fixed N simulation scenarios is around 180 kg N/ha for Walbundrie (Figure 4(a) or (b)) and 40 kg N/ha for Wanbi (figure not shown) respectively. Above this N rate, there is little change in crop yield and drainage with increasing N input, but a decrease in gross margin due to high cost associated with N applications. In different climatic years, this optimal N rate can range from 0 to 250 kg N/ha at Walbundrie (Figure 5(b)) and 0 to 150 kg N/ha at Wanbi (Figure 6(b)).

The optimal N rate for each year (N_{optm}) at both sites is significantly correlated with available water for the growing season, i.e. rainfall in the growing season plus the stored soil moisture at sowing (Figures 7(b) and 8(b)), due to the strong dependency of crop growth and yield

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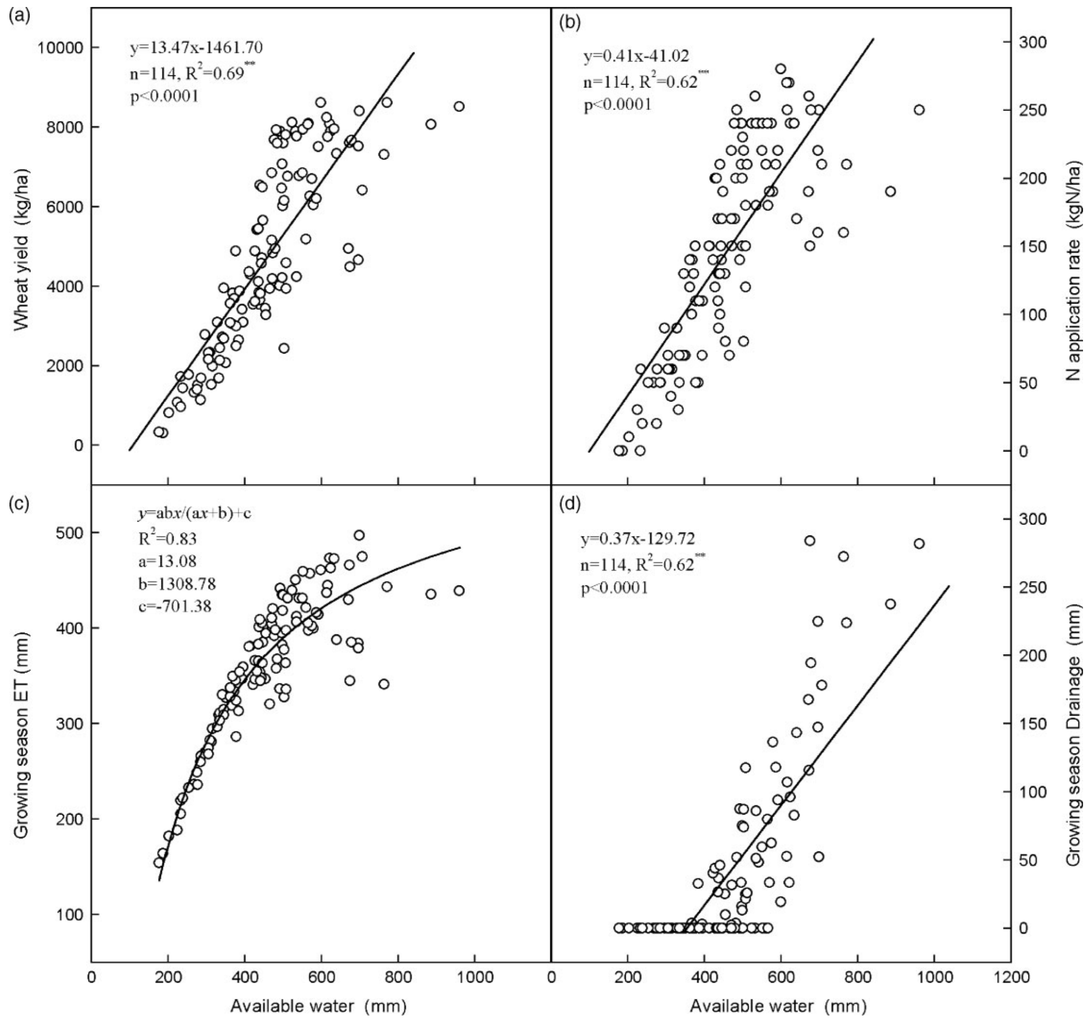

Figure 7. Effect of available water (rainfall plus store soil moisture at sowing) on wheat grain yield (a), optimal N rate (b), ET (c) and drainage (d) during the growing season simulated based on 'perfect' climate forecasts at Walbundrie.

on available water (Figures 7(a) and 8(a)). It ranges from 0 to 280 kg N/ha at Walbundrie (Figure 7(b)) and 0 to 170 kg N/ha at Wanbi (Figure 8(b)). The mean of N_{optm} is 148.5 kg/ha for Walbundrie and 32.5 kg/ha for Wanbi. At Walbundrie, there are 68 years out of the 114 years when N_{optm} is lower than the optimal N rate derived from the fixed N scenarios (180.0 kg/ha), which highlights the difference in optimal N rate determination between using fixed N intervals and the procedure developed in this paper. Despite the contrasting rainfall conditions between Walbundrie and Wanbi, the relationships between available water and simulated grain yield, optimal N rate and growing season ET are similar (Figures 7 and 8), where the responses at Wanbi roughly corresponds to that at Walbundrie in drier years. At both sites, for each 100 mm increase in available water up to a total of 760 mm, grain yield would increase by 1300∼1500 kg/ha, which requires an increase in N application of 40 kg N/ha (Figures 7 and 8). Optimal N management based on perfect climate knowledge would lead to a crop wheat yield range of 300–8600 kg/ha at Walbundrie (Figure 7(a)) and 0–5000 kg/ha at Wanbi (Figure 8(a)).

3.3. Values of N management based on 'perfect' climate forecasts

The added value of N management based on 'perfect' climate forecasts is given in Tables III and IV. It is also shown in Figure 9 (also see Figure 4, where the rightmost box plot in Figure 4(a), (b) and (c) represents the simulation results using the N_{optm} determined for each year for Walbundrie). Compared to N management using the fixed N rate of 180 kg N/ha/year, N management based on 'perfect' climate forecasts would only increase crop yield in high-yielding years (Tables III, IV and Figure 9(a)). Such management would lead to the biggest increase in gross margins in extremely wet and dry years and the least benefits in medium years (Tables III and IV and Figure 9(b)). It has little impact on drainage (Figure 9(c)). On average for all the years, 'perfect' forecasts–based N management leads to an average gross margin increase of AUS \$65.2/ha at Walbundrie and of AUS \$66.5/ha at Wanbi compared to N management using N_{opta} every year (Tables III and IV).

Tables III and IV show the average of optimal N rate and benefit for each year type obtained from N management based on 'perfect' climate forecasts at Walbundrie

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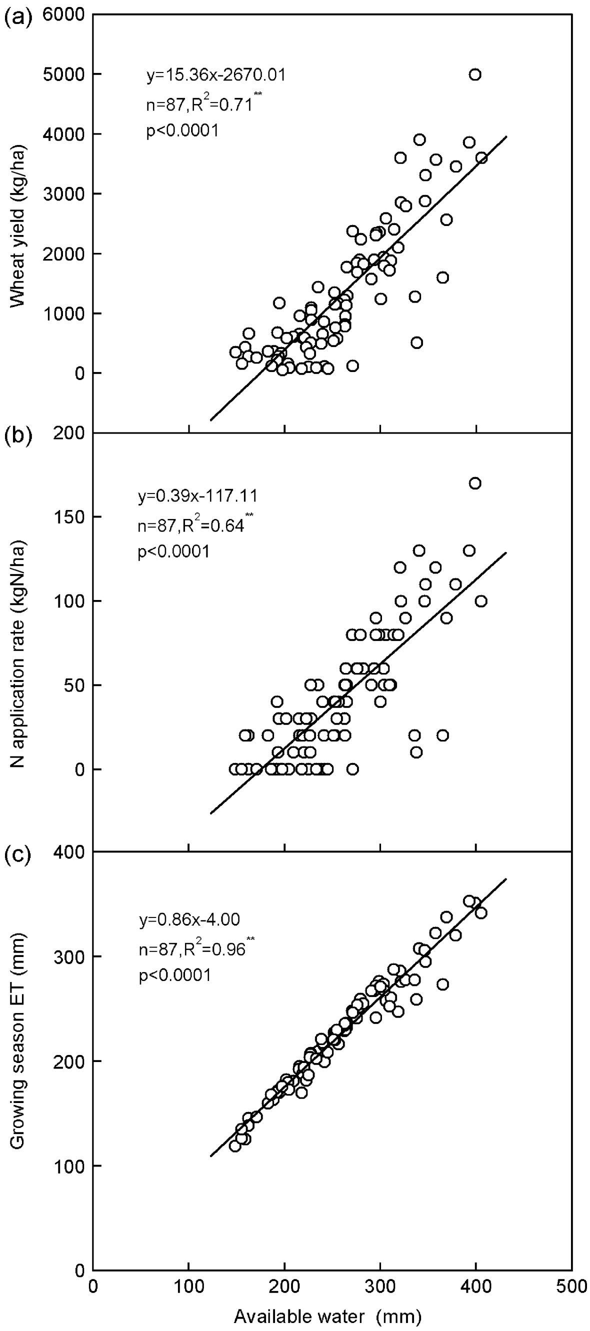

Figure 8. Effect of available water (rainfall plus store soil moisture at sowing) on wheat grain yield (a), optimal N rate (b), ET (c) during the growing season simulated based on ‘perfect’ climate forecasts at Wanbi.

and Wanbi respectively. They also show the N saving for the six climatic year types, which was roughly calculated as the difference between N application rate under ‘perfect’ forecasts and the optimal N rate estimated for long-term average climatic conditions (historical climate knowledge). In wet years, the benefits are mainly from crop yield increase. In dry years, saving from reduced N application becomes the major part of the benefits. Out of 114 years simulation results, ‘perfect’ forecasts–based N management leads to benefits from crop yield increase in 43 years at Walbundrie and 26 years at Wanbi. At Walbundrie, the benefit came from both nitrogen saving and yield increase in 20 years, and from nitrogen saving only in the other 49 years. At Wanbi, in 45 years, benefits were derived from cost saving by reducing N application. Interestingly, N management based on ‘perfect’ forecasts also leads to negative benefit in 2 years at Walbundrie (Table III) and 25 years at Wanbi (Table IV). At Wanbi, this ranges from −0.8 to −18.4AUS$ ha/yr. This happens because the optimal N management in the previous year resulted in increased water consumption and left less soil water, leading to worse crop growth in the coming year compared to that under N management based on long-term climatology.

In general, climate forecasting has much higher value in extreme (wet or dry) years than in normal years based on the simulation results (Tables III and IV and Figure 9). In high rainfall areas like Walbundrie, optimal N rates based on long-term average climate conditions (N_{opta}) are usually high; large part of the benefits of ‘perfect’ climate forecasts–based N management is from extremely dry years by significant amount of saving through reduction in N application (Table III). In low rainfall areas such as Wanbi, N_{opta} is lower and the benefits from extremely wet years by significant increase in crop yield through increase in N application becomes more important (Table IV). In all areas, the benefit of climate forecasts is lowest in normal years when the N_{opta} is close to N_{optm}. At Wanbi, the benefit is even negative in climatic years with moderate rainfall, compared with N-management-based climatology.

In terms of the environmental impact of N management based on ‘perfect’ climate forecasts, we look at its impact on drainage and excess N application. While N management based on ‘perfect’ climate forecasts has little impact on drainage, it has the potential to significantly reduce the N excess in agricultural systems, especially in high-rainfall areas. On the basis of the N-saving values in Tables III and IV, such N management would have saved, on average, 7.5 kg N/ha/year at Wanbi and 31.5 kg N/ha/year at Walbundrie. Excess N application exceeding crop demand can lead to nitrate leaching into groundwater and emission of greenhouse gases into the atmosphere. This study shows that the environmental value of climate forecasts in terms of excess N reduction increases with an area’s rainfall and crop productivity.

4. Discussion and conclusion

With increased investment in improving climate forecasting techniques, it is essential to understand the maximum potential benefit of improved climate forecasts, which is the benefit derived from optimized management responding to climate forecasts of ‘perfect’ skill (‘perfect’ forecast) under currently available management options. This benefit represents the maximum value we can expect from improved climate forecasts, although this figure could potentially change with new management practices as they become available. This paper develops an approach

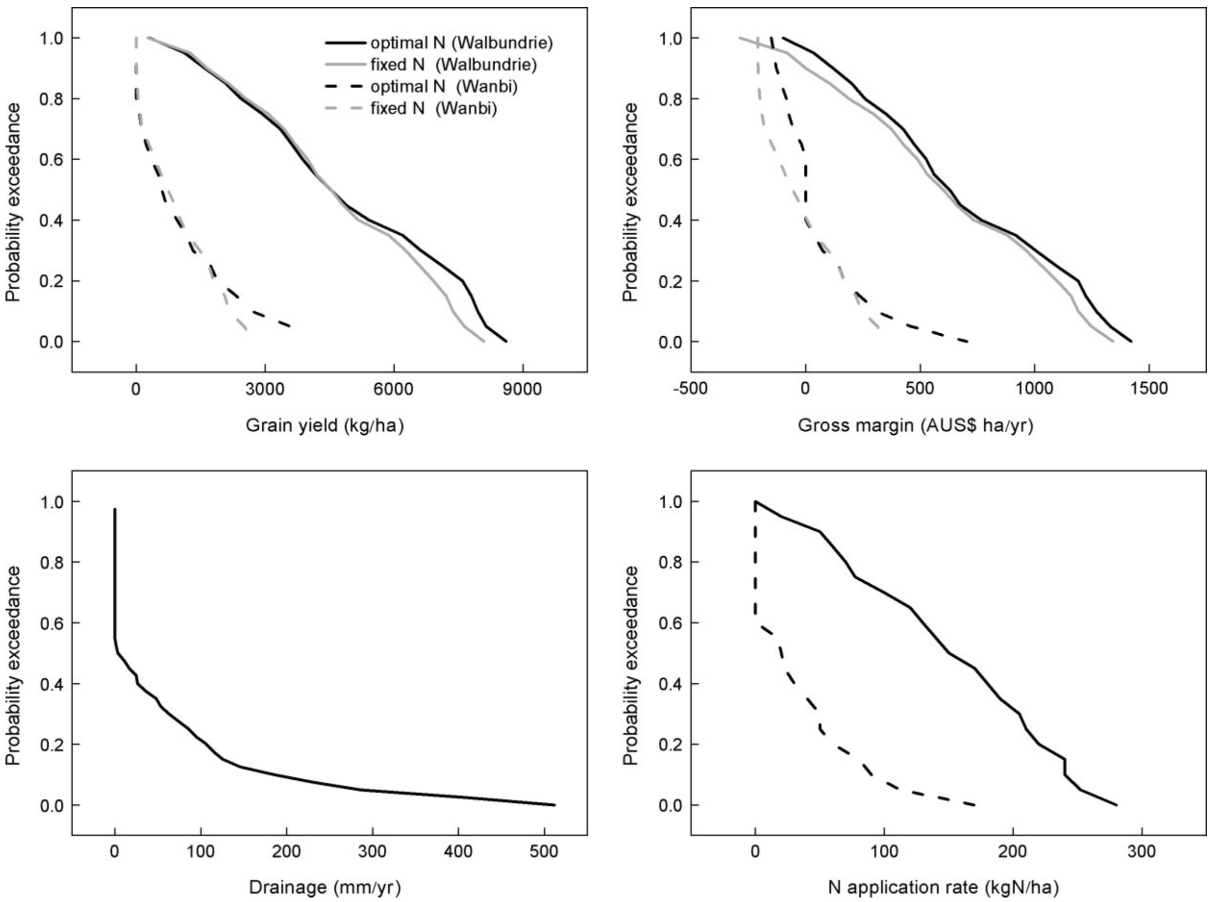

Figure 9. Comparison of probability distribution of yield, gross margin, drainage and fertilizer use between N management based on 'perfect' forecasts (optimal N) and at fixed long-term average N rate of 180 kg N/ha/year (fixed N) for Walbundrie and 40 kg N/ha/year for Wanbi.

to quantify the value of 'perfect' climate forecasts based on systems modelling and nitrogen management in dryland farming as an example. The results provide some reference values on the benefit of climate forecasting research in southern Australia.

For annual wheat cropping, compared to the N management based on optimal N rate derived from long-term climatic conditions, N management based on perfect climate forecast can bring an average benefit of $65.2/ha at Walbundrie (annual rainfall 560.0 mm) and $66.5/ha at Wanbi (annual rainfall 314.5 mm). Such economic benefits are sensitive to prices of nitrogen fertilizers and wheat grain prices, and the presented results are derived using a fixed grain price of $208/t and a fixed urea price of $436/t. The economic benefit is highest in extreme years and lowest in normal years. At the high rainfall site Walbundrie, where average N application rate is high, the maximum yearly benefit was from significant saving through reduction in N application in the driest years. At the low rainfall site Wanbi, where average N rates are low, the benefits in both high and low rainfall year types were higher than those in the high rainfall site. This means the site with low rainfall may benefit from significant yield increase in high rainfall years, and management cost reduction in dry years (Tables III and IV). The optimized N management based on 'perfect' climate forecasts has little impact on excess drainage, but it can have an impact on reduction of excess N applications, especially in high-rainfall areas. It could lead to a reduction of excess N of 11.5 kg N/ha/yr at Wanbi and 13.5 kg N/ha/yr at Walbundrie. This corresponds to a reduction of excess N application of 1538 kg N/ha in 114 years in Walbundrie. The significant reduction in N excess at Walbundrie may have profound environmental implications such as N leaching into the groundwater, greenhouse gas emission and ecological quality.

It should be emphasized that the value of 'perfect' climate forecasts presented here represents the maximum possible value under the assumed conditions. The results of this study were obtained under several assumptions to simplify the system studied, which include fixed grain and fertilizer prices, predefined times and rates of N application, a single soil type for each site and a simplified cropping system – a continuous wheat-fallow system for both sites. Furthermore, the benefit was quantified only for improved N management. In the real world, the cropping systems are more complicated. Available management options may include the choice of spatial and temporal arrangement of crops and other vegetation, irrigation, fertilization and better spatial matching of the plant system to land suitability. Even for N application, the farmers can adopt multiple N applications depending on soil moisture, weather and crop stages to improve N efficiency. Such N management may lead to better

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outcomes than management based on historical climatology. The prices of wheat grain and N fertilizer also change from time to time and prices of wheat grain also depend on grain protein content (ABARE, 2004), which was ignored in this study. The fertilizer rate can have a significant impact on grain protein content, leading to changes in price or income. Although some changes to the assumptions will decrease or increase the forecast value, the principles developed in this study will apply to alternative systems and other management options. Furthermore, the grain price can be considered as a function of grain N content, which can be based on average prices over the last decade. For optimizing N-management-based 'perfect' climate forecasts, the changes in the economic benefit with climate/rainfall regions and the environmental value found in this study should be representative for regions in South and South-east Australia.

This paper is an attempt to quantify the value of 'perfect' climate forecasts in terms of directing N management in a simplified dryland farming system. Under the assumption of 'perfect' knowledge about the coming season, production risk could be avoided, i.e. if a loss is estimated for the coming season, no crop will be planted. For the two study sites, the production risk (calculated as percentage of years of making a loss) is 1.8% for Walbundrie (at 180 kg N/ha) and 21.9% for Wanbi (at 40 kg N/ha) respectively under N management based on historical climatology. Current climate forecasts are imperfect, and always probabilistic (McIntosh *et al.*, 2005). Adaptive strategies using probabilistic forecasts are more complex because the risk of decision under false forecasts or low probability of climatic events should be evaluated, and then a decision could be made on the basis of the trade-off between benefit under correct forecasts and losses under wrong forecasts. Another factor is the financial stability of a farm to endure losses due to 'bad' decisions based on inaccurate forecasts.

Previous studies show that, in some regions, 70–80% of farm profit was made in just 30% of good years (Egan and Hammer, 1996). This study shows that the use of skillful climate forecasts can improve farm profit, not only through increased profit in good years but also through significant reduction in production/fertilizer costs. Several studies indicate that improved N management based on seasonal climate forecasts has little environmental value in terms of drainage reduction in Australia (Asseng *et al.*, 2001b; Stirzaker *et al.*, 2000; Lythgoe *et al.*, 2004). This study has similar results on drainage, but indicates that environmental value of climate forecast in terms of N excess reduction can be significant.

The value of climate forecasts seems to be closely related to both the type and the variability of climate for a given region. Climate forecasts may have higher integrated values in higher value systems in more variable climate. Furthermore, crop productivity is also influenced by the interactions between climate and soil. For a given climatic region, especially in semi-arid areas, variability of productivity is determined by the efficiency of the soils and the landscape to absorb, store and make the limited supply of water available to plants. With no other constraints, the water-holding capacity of the soil is the most important factor influencing crop production and field water balance. Sandy soils have lower water holding capacity, which may induce fast and high drainage, resulting in lower productivity and optimal N rates than loam soils. In the current study, although two representative soil types are used, they have similar water-holding capacity. Therefore, the impact of soil difference on the results is considered small. Further study is needed to evaluate the impact of soil–climate interactions on the value of climate forecasts. In any case, investment in climate forecast research may need to be spatially specific. A forecast may have high value in one region for one industry, and may have lesser or greatly reduced value in another region. Field experiments may provide data to quantify the responses of a system component to climate and soil factors; but experimental data is usually limited to several years, not capturing the impact of long-term climate variability. Climate variability is best quantified by using long-term historical climate records, and its impact on agricultural systems is best analysed by using agricultural systems modelling.

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