

Assessing the spatial impact of climate on wheat productivity and the potential value of climate forecasts at a regional level

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Abstract Quantification of the spatial impact of climate on crop productivity and the potential value of seasonal climate forecasts can effectively assist the strategic planning of crop layout and help to understand to what extent climate risk can be managed through responsive management strategies at a regional level. A simulation study was carried out to assess the climate impact on the performance of a dryland wheat-fallow system and the potential value of seasonal climate forecasts in nitrogen management in the Murray-Darling Basin (MDB) of Australia. Daily climate data (1889–2002) from 57 stations were used with the agricultural systems simulator (APSIM) to simulate wheat productivity and nitrogen requirement as affected by climate. On a good soil, simulated grain yield ranged from <2 t/ha in west inland to >7 t/ha in the east border regions. Optimal nitrogen rates ranged from <60 kgN/ha/yr to >200 kgN/ha/yr. Simulated gross margin was in the range of -\$20/ha to \$700/ha, increasing eastwards. Wheat yield was closely related to rainfall in the growing season and the stored soil moisture at sowing time. The impact of stored soil moisture increased from southwest to northeast. Simulated annual deep drainage ranged from zero in western inland to >200 mm in the east. Nitrogen management, optimised based on ‘perfect’ knowledge of daily weather in the coming season, could add value of \$26~\$79/ha compared to management optimised based on historical climate, with the maximum occurring in central to western part of MDB. It would also reduce the nitrogen application by 5~25 kgN/ha in the main cropping areas. Comparison of simulation results with the current land use mapping in

MDB revealed that the western boundary of the current cropping zone approximated the isolines of 160 mm of growing season rainfall, 2.5t/ha of wheat grain yield, and \$150/ha of gross margin in QLD and NSW. In VIC and SA, the 160-mm isohyets corresponded relatively lower simulated yield due to less stored soil water. Impacts of other factors like soil types were also discussed.

1 Introduction

Climate sets the limit to the productivity of crops. Spatial and temporal variation of climate directly affect the economic and environmental performances of agricultural systems in a region. Quantification of the spatial impact of climate on crop productivity can effectively assist the strategic planning of crop layout at a regional level. Assessment of the potential value of seasonal climate forecasts spatially helps to understand to what extent climate risk can be managed and whether responsive management strategies can be developed. In semi-arid areas like the Murray-Darling Basin (MDB) of Australia, the variability of climate (especially rainfall) is the major determinant of the variation in crop yield and economic return (Anderson 1987; Egan and Hammer 1996). Wheat is the most important crop in the MDB. A better understanding of how regional wheat productivity is influenced by the spatial variation of climate and how much value seasonal forecasts can potentially add to management practices can contribute to future planning and development of cropping and management strategies. However, the complex interactions between agricultural systems performance, climate, soil, and management practices make it difficult to assess the impact of individual factors. Agricultural systems’ modelling provides a useful means to evaluate the impact

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of the climate by assuming all other factors at a reasonable constant level. This paper aims to assess, via agricultural system modelling, the potential value of wheat production and seasonal climate forecasts as determined by spatial climate variations at regional level in MDB.

The Murray-Darling Basin covers an area of more than 1 million km², equivalent to 14% of the country's total area. The basin drains roughly 3/4 of New South Wales (NSW) (including all area of the ACT), half of Victoria (VIC), a portion of southern Queensland (QLD), and a small part of eastern South Australia (SA) (Fig. 1). It is the most significant agricultural area in Australia, has 42% of the nation's farmland and produces about 40% of the nation's food crops (Murray-Darling Basin Initiative, <http://www2.mdbc.gov.au/>).

The climate in most parts of the MDB is generally characterised as semi-arid climate with hot and dry summer and mild winter. Rainfall variability is high in most areas. Figure 2 shows the current land-use types in MDB. Apart from the native forests and shrublands, the major agricultural land use types changes approximately with the annual rainfall (Fig. 3a) from east side to the inland west regions. They range from high input grazing systems in the high rainfall area in the east, to a cropping/sheep belt in the middle and rangeland systems in the west (Stirzaker et al. 2000). Dryland cropping has been practiced in most cropping areas, which is characterised by opportunity summer/winter cropping in the northern part to winter cropping in the southern part. Irrigation agriculture only accounts for less than 1.5% of the total area, though its value can be as high as 50% of the total profit generated from agricultural land use (National Land & Water

Resources Audit 2002). Wheat is one of the major crops grown in the cropping zone of MDB (Fig. 2) and its grain yield is strongly influenced by inter-annual climate (especially rainfall) variations.

Studies have been carried out in MDB to quantify the impact of climate variability on agricultural systems performance. Some of them have focused on improvement of on-farm management to increase production profit (Carberry et al. 2000; Hammer 2000; Hammer et al. 2001; Lythgoe et al. 2004). Increased efforts have also been directed to look at the potential of mitigating the detrimental environmental impact of farming systems (Walker et al. 1999; Keating and McCown, 2001; Keating et al. 2002; Ringrose-Voase et al. 2003), e.g., excess deep drainage passing the crop root zone, which is a major cause for dryland and river salinity. Many studies have involved the application of climate forecasting in agriculture management and quantification of the value of climate forecasts (e.g., Hammer et al. 1996; Meinke and Stone 1997; Hammer 2000; Hammer et al. 2001; McIntosh et al. 2005; McIntosh et al. 2007). Most of these studies were carried out at specific sites of the current cropping zone. Potgieter et al. (2002) studied the spatial and temporal patterns in Australian wheat yield and their relationship with ENSO, but they used a model trained on actual shire wheat yield. Hill et al. (2004) investigated the implications of seasonal climate forecasts on world wheat trade in a broad national/global scale including countries of the US, Canada and Australia, but did not depict the impact of climate variability in individual regions. A region-wide perspective is lacking on how the potential value of a cropping system is determined by spatial variations of climate, and to what

Fig. 1 The study region, Murray-Darling Basin of Australia, and the sites where historical climate data were used

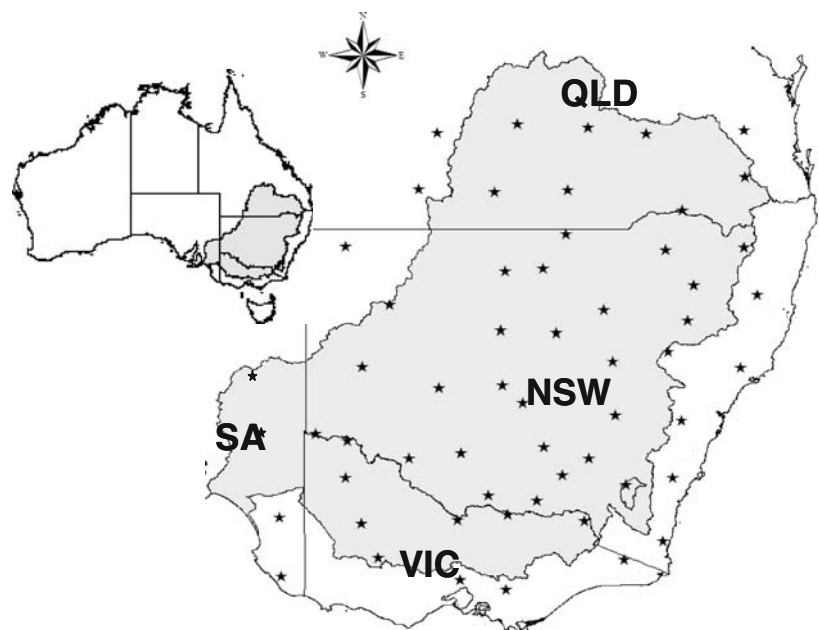
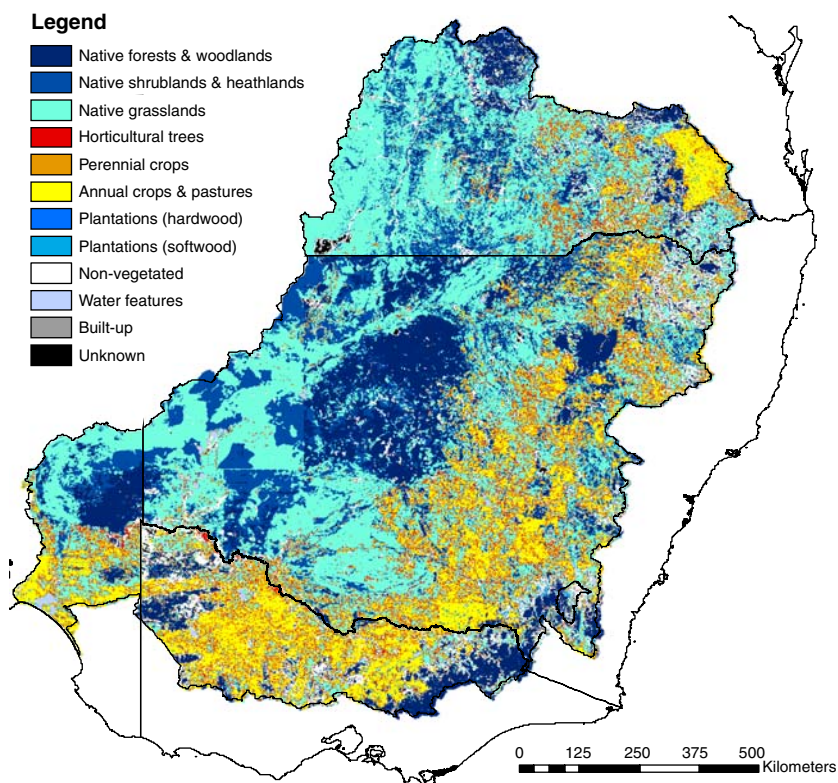


Fig. 2 Current land uses in the Murray-Darling Basin of Australia. Source: Bureau of Rural Sciences, Integrated Vegetation Cover (2003), Version 1



extent the temporal variation of climate can be managed, i.e., the potential value of climate forecasting across the MDB. Such information is essential in understanding the potential value of natural resources (climate, soil, etc.) and would provide insights into possible shifts in cropping regimes under a changing climate.

A regional approach to studying agricultural systems performance as affected by climate has clear advantages. From a climate science point of view, seasonal climate forecasts are essentially made on a regional rather than a point basis. From an industry perspective, and especially for companies providing inputs such as fertiliser or responsible for grain storage and transport, a regional focus is useful. From a policy process in terms of exceptional circumstances, drought support, regional development and vulnerability to climate change the regional perspective is important. In terms of deep drainage and other NRM issues, a regional focus provides insights that are not captured by a point source.

This paper presents a simulation study using a simplified wheat-fallow system and 114 years of historical climate data from 57 climate stations across the MDB to investigate how climate sets limit to the performance of the wheat cropping system. We will quantify: (1) the spatial distribution of rainfall in wheat growing season and its variability across MDB, (2) wheat yield level under optimal nitrogen management, its water use efficiency and economic value as affected by spatial variation of climate, (3) nitrogen input level required to support the potential production level, (4)

impact of climate variability on systems performance and potential value of seasonal climate forecasting for nitrogen management in wheat production.

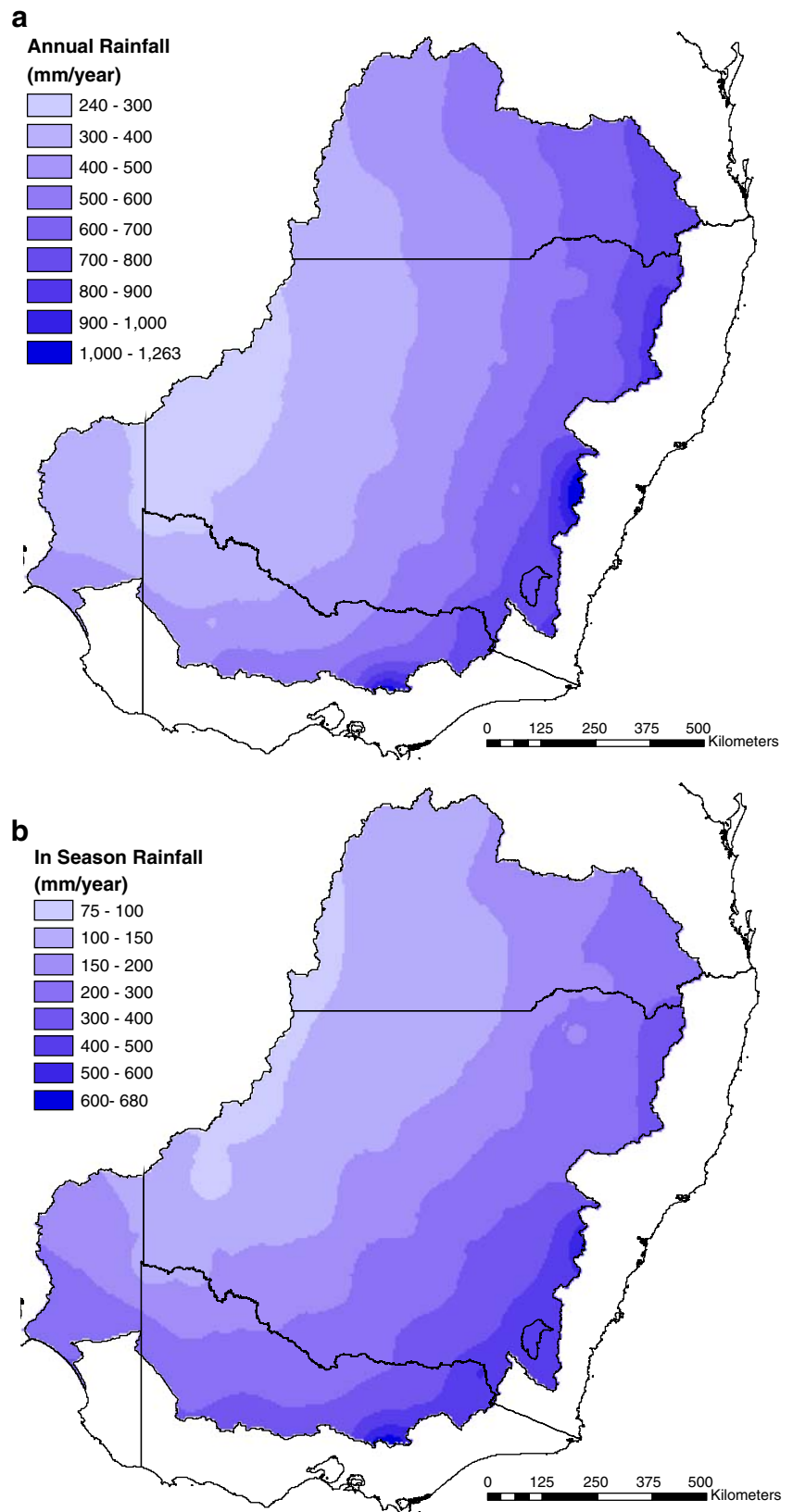
2 Material and methods

2.1 Study region, climate, soil and the simulated wheat-fallow system

The study region, Murray-Darling Basin of Australia and the sites where historical climate were used is shown in Fig. 1. All together, 57 sites roughly uniformly distributed across the region were selected. A total of 52 sites are CLIMARC stations, which have daily weather records dating back to 1889. For the remaining five stations, daily climate data are available since 1957, and the pre-1957 daily data were interpolated from daily observations using anomaly interpolation method for CLIMARC data (Rayner et al. 2004). All the daily weather data from 1889 to 2002 were obtained from the SILO patched database (<http://www.bom.gov.au/SILO>). Some sites are outside the MDB and selection of those outside sites was to capture the spatial variation of climate at the edges of MDB. Simulations were also done for those sites for the purpose of smooth interpolation in GIS.

Across the study region, temperature increases from the southeast to the northwest. The ranges of average annual

Fig. 3 Spatial distributions of annual rainfall (a) and rainfall in the simulated wheat growing season (b) in the Murray-Darling Basin, Australia (1891–2002)



minimum and maximum temperatures are 3~15°C and 15~30°C, respectively. Mean annual rainfall ranges from about 1,000 mm in the footslopes of the Great Dividing Range in the east to less than 300 mm in the west plains (Keating et al. 2002, and also see Fig. 3a). From north to south, rainfall pattern changes from more summer-dominant rainfall in Queensland and northern NSW, to uniformly distributed rainfall area in central NSW, and then to more winter-dominant rainfall regions in southern NSW, Victoria and South Australia.

A simplified dryland wheat-fallow system, i.e., growing a wheat crop every year with a short fallow period between wheat harvest and the sowing time next year, was simulated for all the selected sites to study the impact of climate on wheat productivity. This includes the current cropping zone and areas currently covered with native or improved grasses (rangelands and grazing areas) (Fig. 2). In reality, wheat is only grown in the current annual cropping zone; there is no wheat in the western inland area. However, the objective of this paper is to study the climate-determined productivity, and including the whole area enables the analysis of boundary conditions of current cropping areas. Therefore, simulations at all sites were performed and simulation results were then interpolated in ArcInfo to produce regional maps.

The major soils in MDB include red, brown, grey earths with texture ranging from fine sandy loam, to clays and coarse sands. The soil-related problems relate to nutrient status, sub-soil constrains, water availability for plant growth, and availability of herbage plants under semi-arid conditions. In most dryland farming areas, climate conditions (mainly rainfall) limit the potential productivity of the land. Local variation in 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 (Butler et al. 1983). There are significant interactions between climate factors, soil hydraulic parameters, and the economic and environmental performance of farming systems in this region.

For simplicity, one soil type, a red earth soil, was used for all the simulations at all sites (because the main focus here is to sample the impact of climate across the region). The soil is a well-drained soil and can hold 233 mm of plant available water (plant available water holding capacity – PAWC) up to 1.5 m (the assumed rooting depth of wheat crop in this study). The use of one soil type eliminates the impact of soil variation and soil interactions with climate on the systems performance. This may lead to over- or underestimation of systems performance in areas where a worse or better soil exists. Such impact of soils will be analysed in a separate study.

2.2 The agricultural systems model APSIM and its parameterisation

The agricultural production systems simulator APSIM (Keating et al. 2003) version 5.2 was used for the simulation from 1889 to 2002. Key APSIM modules used include –wheat, soilwat2, soiln2, residue2, and manager. APSIM has been tested in Australia under a wide range of conditions (see Keating et al. 2003). Validation results of the APSIM-Wheat module can be found in Wang et al. (2003). Performance of APSIM to simulate wheat systems in terms of crop yield, field water and nitrogen balance at some of the selected sites or in areas close to the study sites can be found in Verburg and Bond (2003), Lilley et al. (2003, 2004). These studies concluded in general that APSIM model is able to simulate wheat growth and yield formation, to reproduce closely water balance measurements, reasonably simulate nitrogen balance and their observed sensitivity to management changes.

A medium variety wheat cultivar Janz, with the default cultivar parameters in APSIM, was used in this study. It was assumed that the wheat crop was sown every year in a sowing window between 1 May till the end of June when cumulative rainfall in ten consecutive days was greater than 25 mm or when the end of the sowing window was reached. Each year, wheat grain was harvested at maturity and the crop stubble was removed at the end of March. Growing season rainfall was calculated each year as the rainfall total from the simulated sowing to harvest dates. Soil moisture stored in the 0~1.5-m soil profile was also calculated at sowing time and harvest time.

2.3 Simulation scenarios with varying nitrogen application rates

The first set of simulation scenarios (S1) was designed to explore the response of wheat crop yield, gross margin, drainage, and nitrogen leaching to historical climate variations across the MDB region as well as nitrogen input levels. Simulations were run for each site continuously for 114 years from 1889 to 2002 with nitrogen application rate ranging from 0 to 300 kgN/ha at an interval of 10 kgN/ha, i.e., 31 simulations in total. At wheat sowing time each year, mineral nitrogen content in the soil profile was reset to 30 kgN/ha. N fertilisation was split into two applications: if the N level was less than 50 kgN/ha, all the nitrogen was applied at sowing, otherwise, the rest was applied at stem elongation stage as top-dressing. Soil water content was simulated continuously to allow its carry-over effect on the performance of the wheat-fallow system. For all the simulations, the simulation results from the first two

years (1889–1890) were discarded to avoid the impact of the uncertain initial conditions.

For each site, the optimal nitrogen application rate based on the 112 years of simulations (1891–2002) was calculated as the N application rate that resulted in the maximum average gross margin over the 112 years (Fig. 4a). Under the average optimal nitrogen application rate, the corresponding wheat grain yield (Fig. 4b), water use efficiency (Fig. 7), gross margin (Fig. 8a), the production cost ratio expressed as the total cost as a percentage of the gross margin plus cost (Fig. 8b), annual deep drainage (Fig. 9a) and nitrate leaching (Fig. 9b) were simulated.

For all the simulations, gross margin (GM) was calculated based on Hayman (2003) as

$$GM = Y \times P_Y - (N \times P_N + C_H + C_S + C_O) \quad (\$/ha)$$

where Y is wheat grain yield (t/ha), P_Y is wheat grain price (\$/t), N is the nitrogen application rate (kgN/ha), P_N is nitrogen price (= \$1.0/kgN), C_H is harvest cost, C_S is the cost of seed ($C_S = \$100/ha$) and C_O other cost (estimated $C_O = \$10/ha$).

Grain price was dependent on grain protein content (G_{PN}):

$$P_Y = 140 + 0.5(G_{PN} - 10)/0.1 \quad (\$/ha)$$

Price of wheat grain at 10% protein was assumed to be \$140/t and a sliding scale of \$0.5 used for each 0.1% grain protein above and below 10%.

Wheat protein content was calculated from grain nitrogen concentration (G_{NC} , kgN/kg grain) as:

$$G_{PN} = G_{NC} \times 100 \times 5.7 \quad (\%)$$

Harvest cost was dependent on grain yield level:

$$C_H = 25 + 13(Y - 2.5) \quad (\%)$$

It was assumed that harvest cost was \$25/ha for grain yield up to 2.5t/ha and increased by \$1.3/ha for each additional 0.1t of grain yield.

The second set of simulation scenarios (S2) was designed to study the value of ‘perfect’ future climate knowledge (assuming we know the daily weather in the coming season) in assisting nitrogen management, i.e., to benchmark the value of seasonal climate forecasts. Due to the inter-annual variation of the climate, the level of nitrogen application in a given cropping season will affect the crop growth, water use and the amount of water left in the soil at the season end, which again will affect the

optimal level of nitrogen application in the next season. Therefore, the nitrogen application rate needs to be optimised for each year first. The optimal nitrogen rate each year has to be used to run the model for the current year; the residual soil water and the weather of the coming season has to be used to optimise the nitrogen rate for the next season. This was done by running the model each year 31 times (with N rates of 0–300 kgN/ha) up to the next sowing time, choosing the simulation with the maximum gross margin, and using the residual water from this simulation as the start soil moisture to run the model 31 times for the next season. This process was repeated from 1889 to 2002. The selected N rate each year represents the optimal N application rate optimised with perfect knowledge of daily weather of the coming season, plus the knowledge of starting soil moisture. The simulated gross margin, crop yield, drainage and N leaching represent the performance of the wheat-fallow system under the best nitrogen management strategy.

The potential economic value of future climate forecasts in wheat nitrogen management was calculated as the added value of N management based on ‘perfect’ climate forecasts as compared to the value of using the long term average optimal N rate every year, i.e., the difference in gross margins obtained from scenarios S2 and S1 (Fig. 11a). Effects of N management based on ‘perfect’ climate forecasts on reduction of annual drainage (not shown due to the insignificant differences) and access nitrogen application (Fig. 11b) was considered as the environmental value here.

To quantify the inter-annual variation of climate variables and simulated yield, gross margin and drainage etc., variability was calculated as the coefficient of variation, i.e., standard deviation over the mean of the climate variables or simulated outputs over the 112-year period.

2.4 Production of regional maps from the point simulations

The mean values or coefficients of variations calculated for the 112-year simulations at all the sites were interpolated with the software package ESRI® ArcMap™9.1 using the inverse distance weighting method. In Fig. 5, the areas that can not be used for cropping (e.g., native forests, shrublands, plantations, etc.) were excluded from the maps. The scattering of the non-cropping areas makes the simulated spatial trends of climate impact less visible. Therefore, in all the other maps, those areas are not excluded; those maps need to be combined with Fig. 2 to recognise the areas that can not be cropped.

Fig. 4 Spatial distribution of simulated optimal nitrogen application rate (a) and grain yield (b) of dryland wheat crop in the Murray-Darling Basin, Australia (1891–2002). 30 kgN/ha of available soil nitrogen at sowing time was assumed

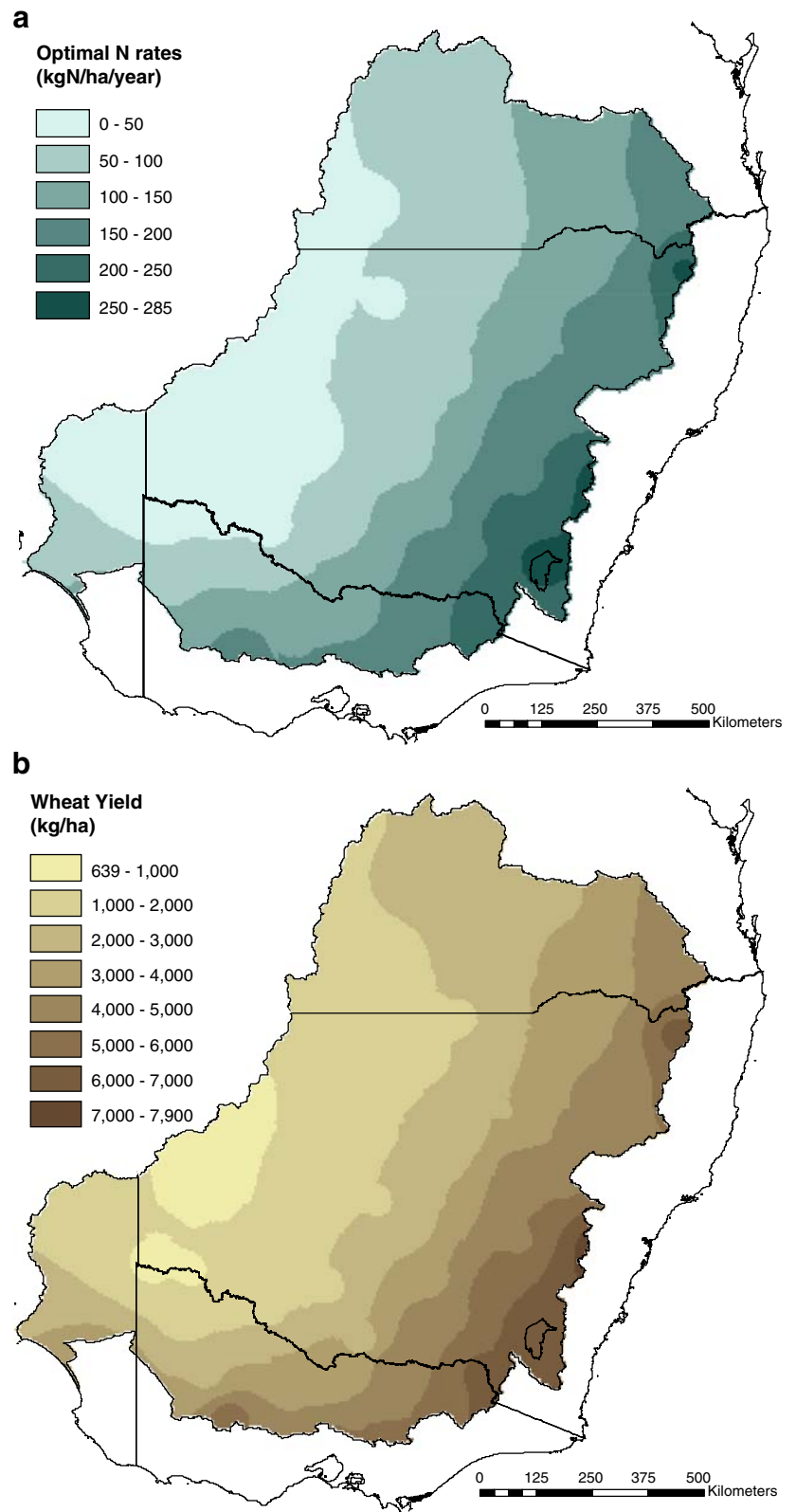


Fig. 5 Spatial distribution of simulated optimal nitrogen application rate (**a**) and grain yield (**b**) of dryland wheat crop in the Murray-Darling Basin, Australia (1891–2002) with the non-crop areas excluded. 30 kgN/ha of available soil nitrogen at sowing time was assumed

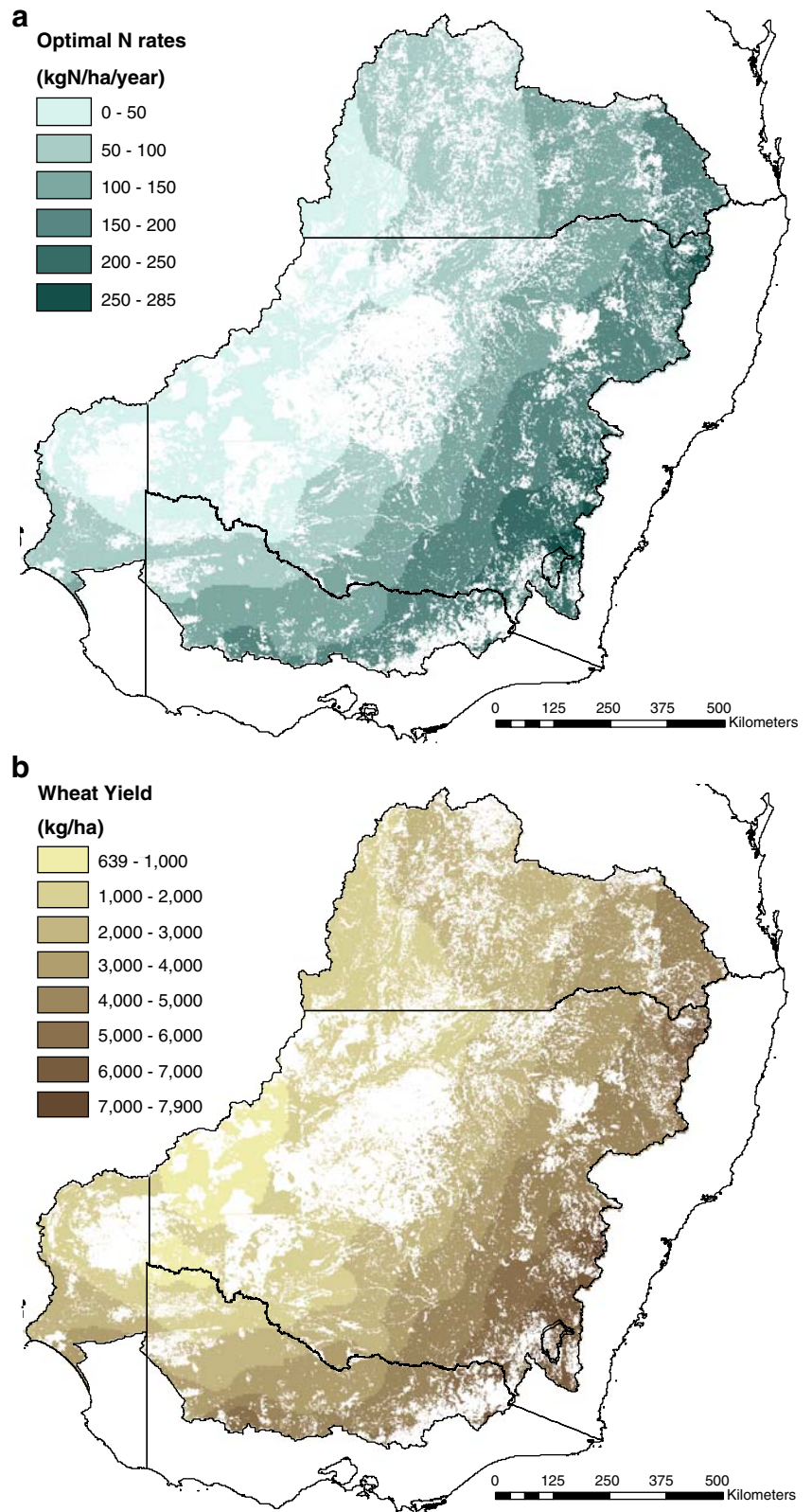
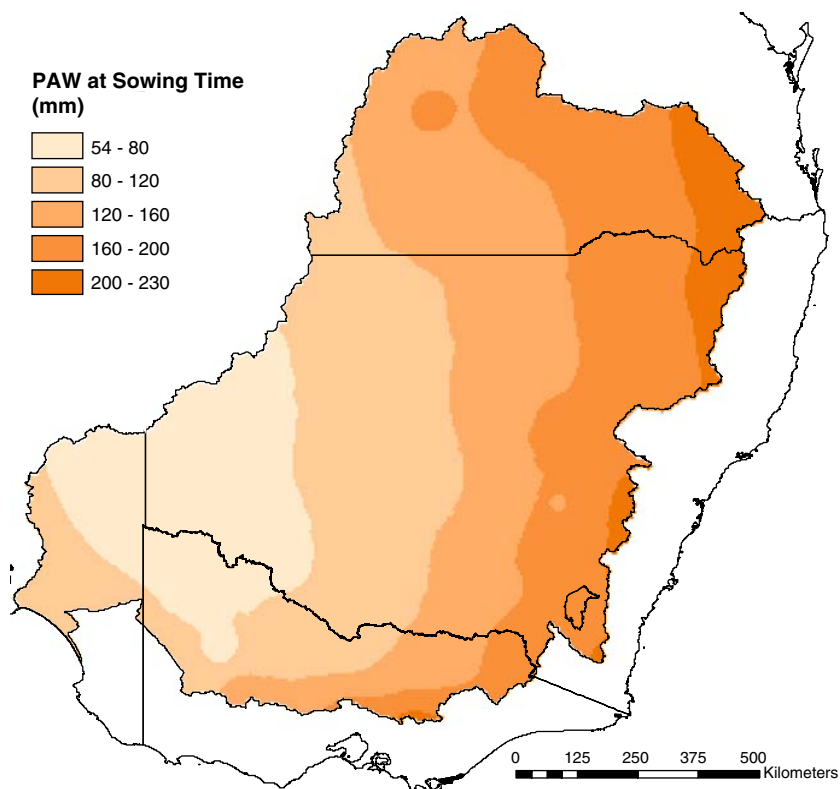


Fig. 6 Spatial distribution of simulated stored soil moisture (plant available water content) at wheat sowing time in the Murray-Darling Basin, Australia (1891–2002)



3 Results and discussion

3.1 Rainfall in wheat growing season

Spatial distribution of rainfall in wheat growing season is shown in Fig. 3b. Slightly different from the spatial distribution of annual rainfall, which decreased from east to the west (Fig. 3a), the growing season rainfall decreased from around 600 mm in southeast to less than 100 mm in northwest. This reflects the rainfall pattern change from the northern to southern part of the MDB. Winter rainfall fraction increased from around 40% in the north to 70% in the south. This, together with the east-to-west decreasing trend of annual rainfall, led to increased growing season rainfall from northwest to southeast.

3.2 Average optimal nitrogen application rate

Under the MDB climate and based on the soil type, grain price and other costs assumed in this study, the simulated long-term average optimal nitrogen application rates are shown in Fig. 4a. Optimal N rate ranged from zero in the inland dry area to >200 kgN/ha in the southeast areas. The simulated optimal N rate represents the extra nitrogen

requirement by dryland wheat crop each year in order to gain the maximum gross margin. This was based on the assumption of 30 kgN/ha available in the red earth soil at start of the season. Changing soil type, or changes in soil organic pools and the available soil nitrogen at start of the season will lead to changes in the simulated optimal N rates.

The reset of soil nitrogen at wheat sowing time each year to 30 kgN/ha was to eliminate the impact of variation in soil nitrogen mineralisation during the fallow period on wheat growth. Under this assumption, wheat season started with the same soil nitrogen condition each year. Only the impact of mineralisation during the growing season was captured. In reality, nitrogen mineralisation in the fallow period will affect wheat growth. If soil organic carbon content is sufficient, a year when there is plenty of water in the profile is often a year when there is more nitrogen mineralisation (Hayman and Alston 1999). For such situations, resetting soil nitrogen to the same level each year may result in overestimation of the optimal nitrogen rates as well as the value of climate forecasts described later.

The areas in the MDB where no crops can be grown include areas covered by native forests and woodlands, native shrublands and heathlands, plantations, and land used for other purposes like built-ups and water areas (see

Fig. 7 Average of simulated water use efficiency (a) and transpiration efficiency (b) of wheat crop (kg grain/ha produced per mm water used for evapotranspiration or transpiration) in the Murray-Darling Basin, Australia (1891–2002)

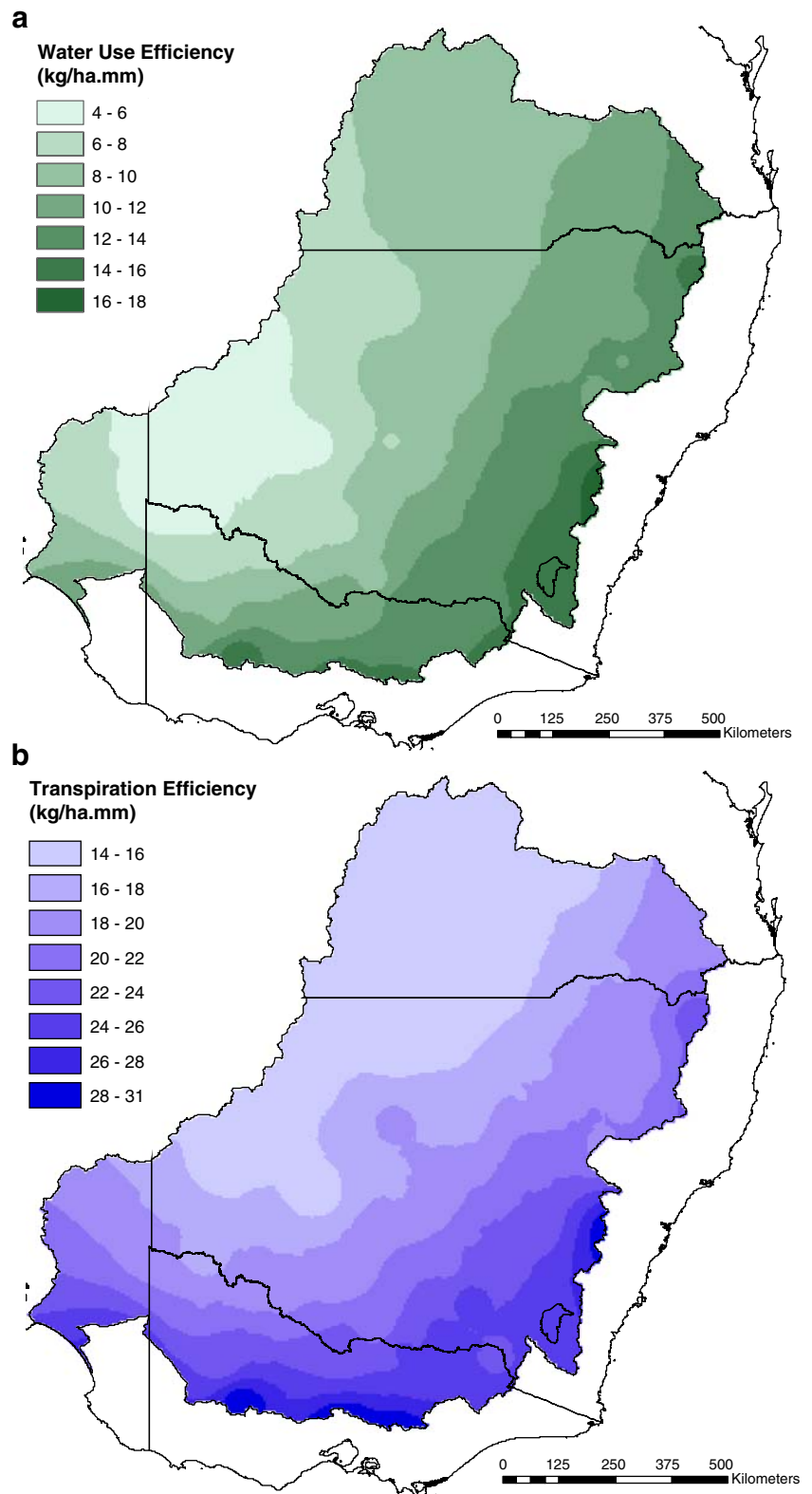


Fig. 8 Spatial distribution of simulated gross margin (a) and cost ratios (b) of growing dryland wheat in the Murray-Darling Basin, Australia (1891–2002)

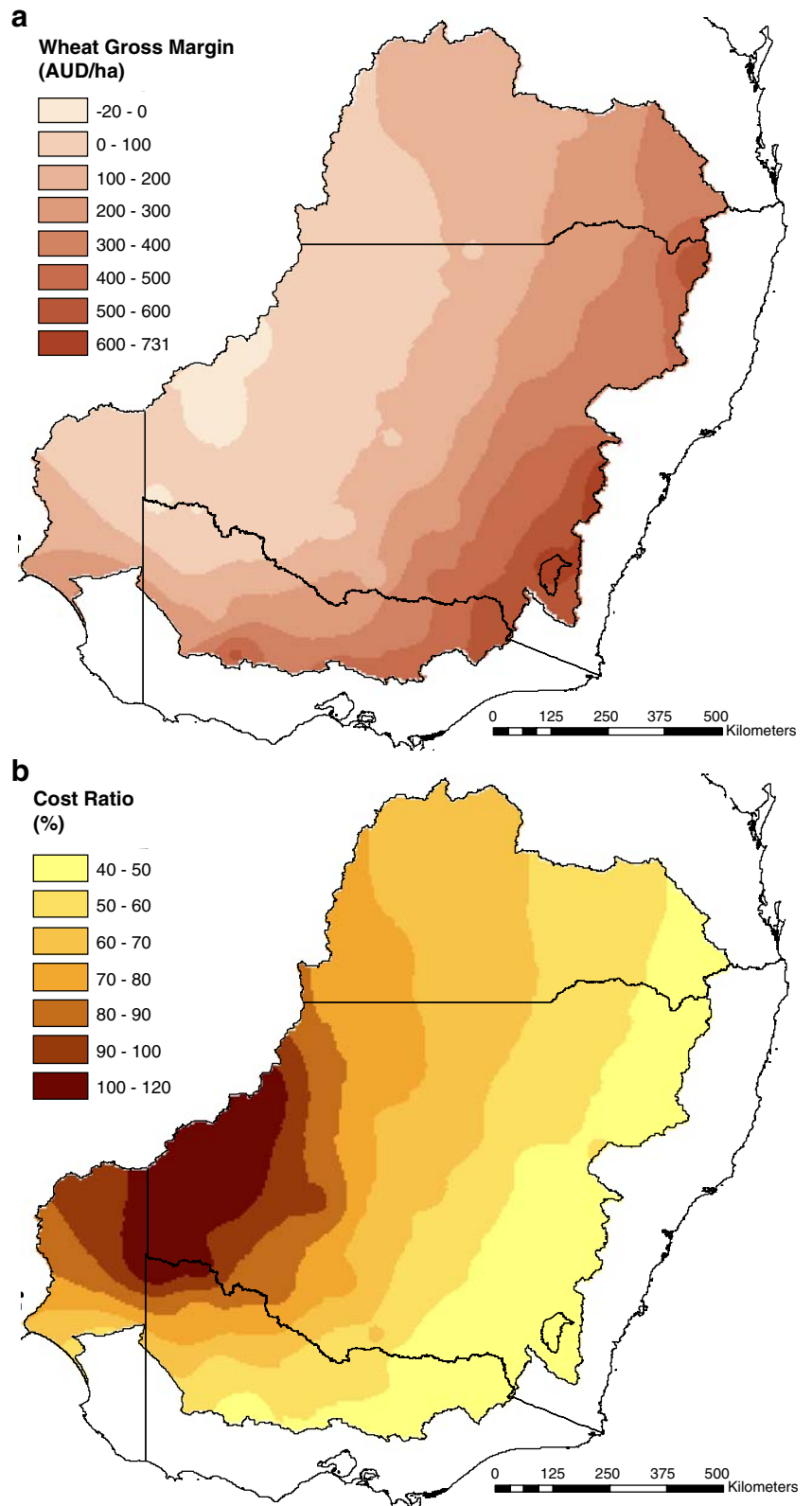


Fig. 9 Spatial distribution of simulated annual deep drainage (a) and nitrate leaching (b) of a dryland wheat-fallow system in the Murray-Darling Basin, Australia (1891–2002)

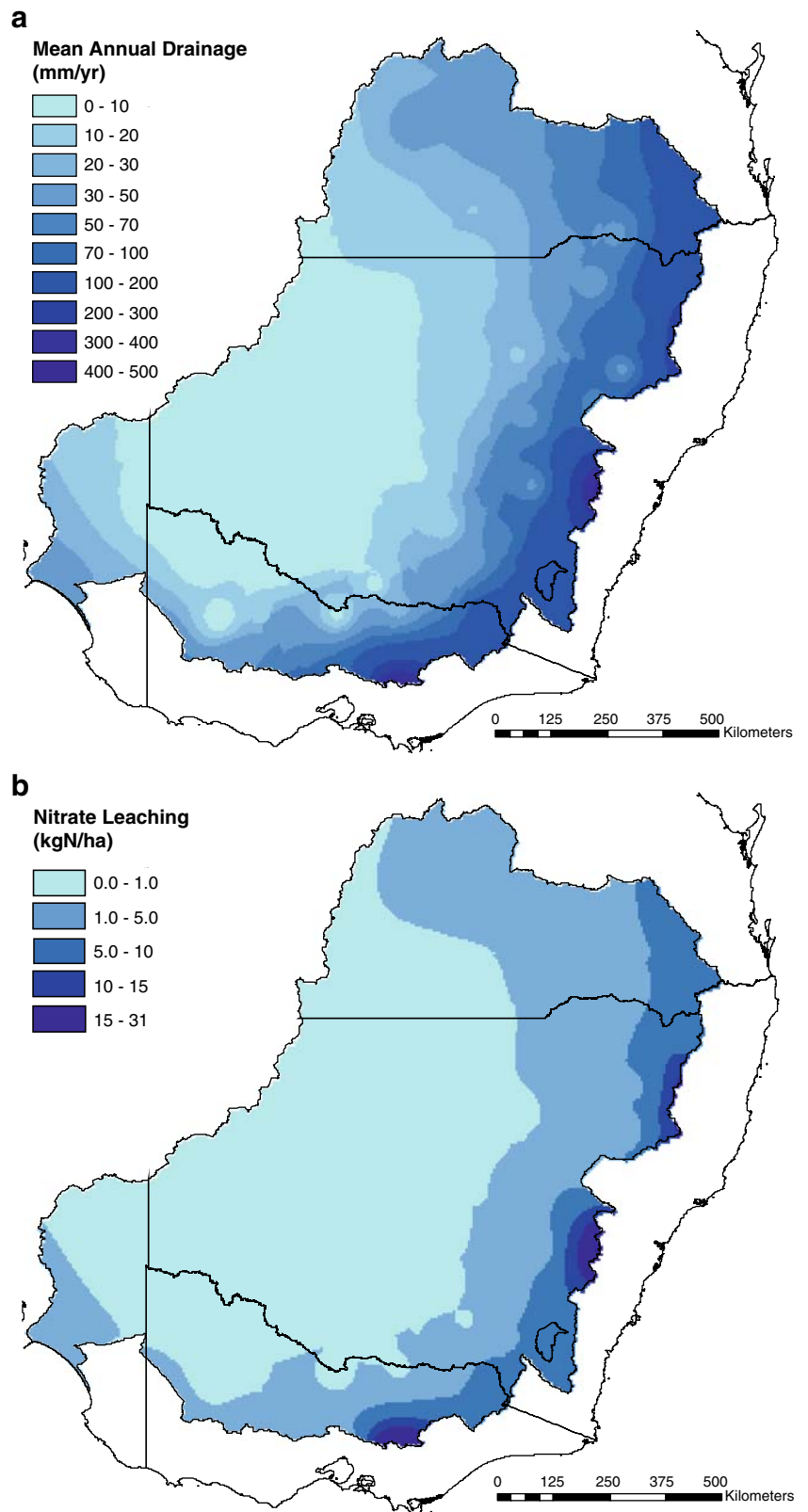


Fig. 10 Spatial distribution of simulated variability of rainfall in wheat growing season (a) and of wheat yield (b) in the Murray-Darling Basin, Australia (1891–2002)

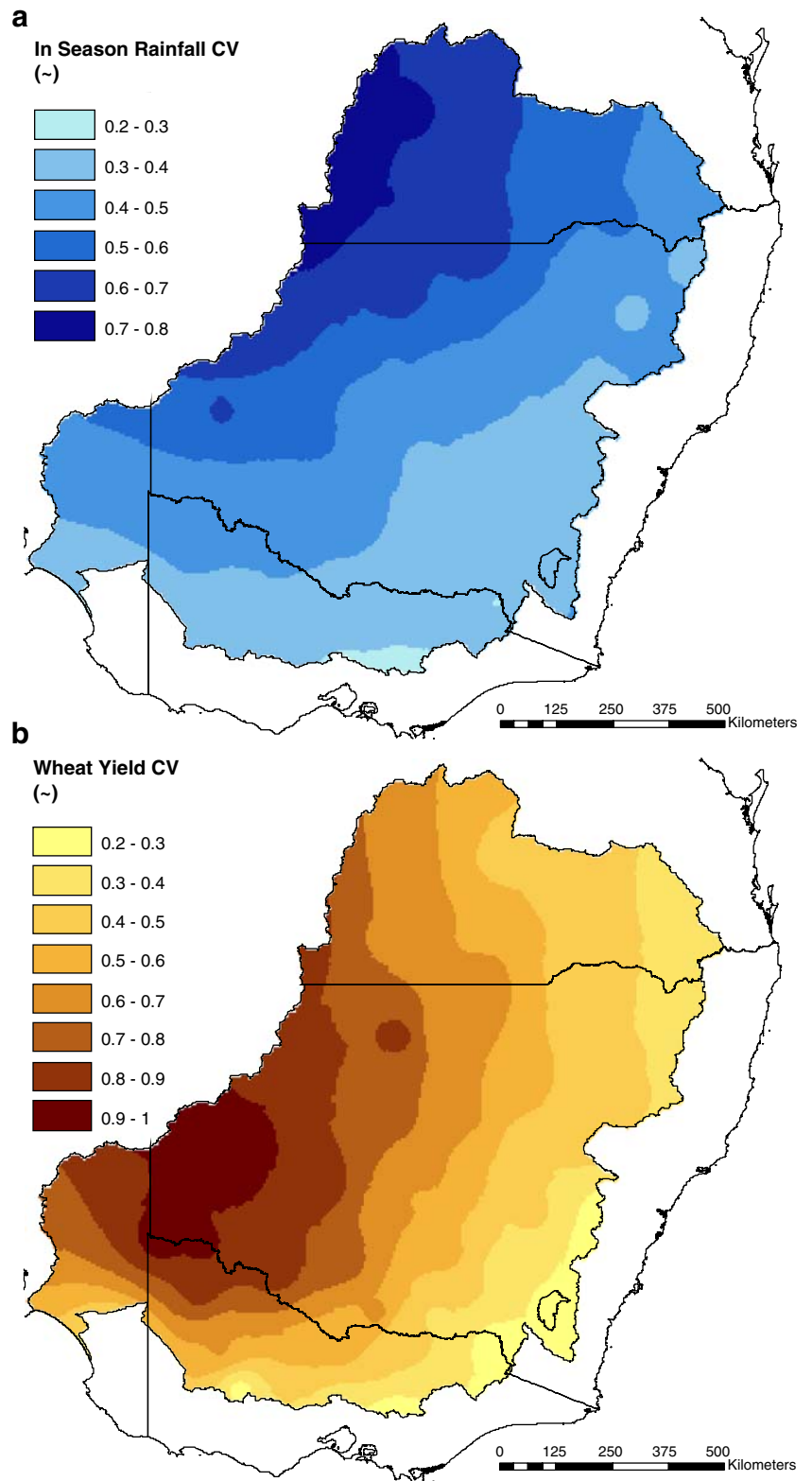


Fig. 11 Spatial distribution of simulated potential value of ‘perfect climate forecasts’ to influence nitrogen management in a wheat-fallow system (**a**), and simulated difference in N applications between N management based on historical climatology and perfect climate forecasts (**b**) in the Murray-Darling Basin, Australia (1891–2002)

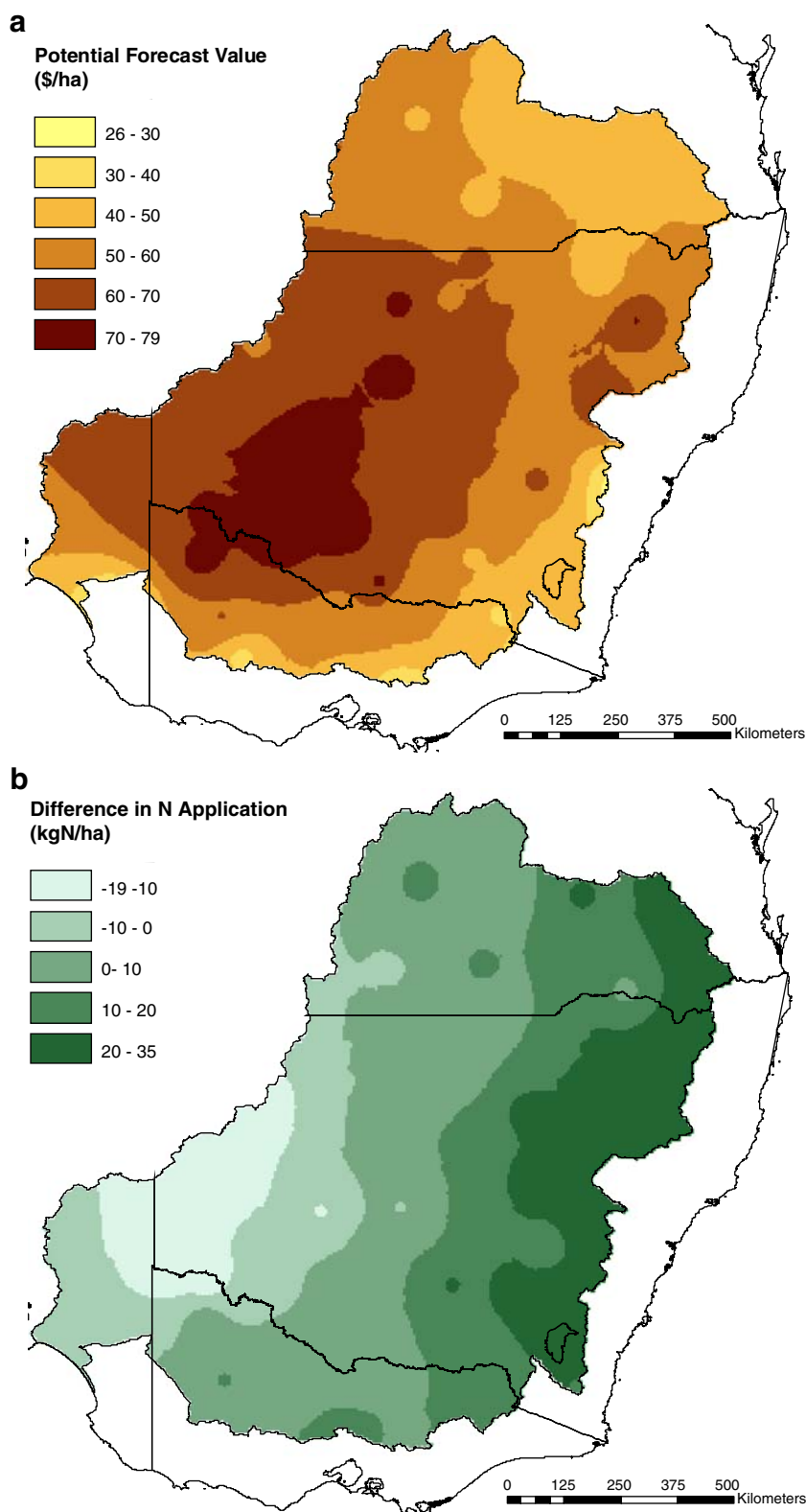


Fig. 2). If all these land areas are excluded, Fig. 4 becomes Fig. 5. The scattering of the non-crop land areas in MDB makes the southeast to northwest trends in wheat yield and optimal N rate less distinguishable. In order to show the

simulated trends clearly, those non-crop areas are no more overlaid on the maps in Figs. 6, 7, 8, 9, 10, 11. In that way, Figs. 2 and 5 have to be used as reference maps for areas that are and are not to be cropped.

3.3 Simulated wheat grain yield under optimal nitrogen application rates

Under the MDB climate, and the average optimal nitrogen application rates (Figs. 4a and 5a), dryland wheat grain yield was predicted to range from around 7t/ha at the footslopes of the Great Dividing Range in the east to less than 2t/ha in large part of the inland areas of MDB (Figs. 4b and 5b). Spatial distribution of the simulated wheat grain yield did not exactly follow that of the growing season rainfall; rather, it was similar to the distribution of annual rainfall (Fig. 3a).

In the northern part of the MDB, more rain falls in the summer period outside of the wheat growing season. Wheat grain yield is not only dependent on rainfall in the growing season, but also the stored soil moisture at sowing, which is left from the previous summer season. Figure 6 shows the simulated annual average value of stored soil moisture at wheat sowing time. It increased from around 50 mm in the southwest to around 200 mm in the northeast part of the MDB. The high values of stored soil moisture at sowing time in northeast MDB were due to more summer rainfall in that area and the assumed summer fallow. The combined impact of stored soil moisture (Fig. 6) and growing season rainfall (Fig. 3b) resulted in the grain yield distribution (Figs. 4b and 5b).

The simulated wheat yield was much higher than the average shire wheat yield simulated by Potgieter et al. (2002) whose values were roughly half of the simulated yield here. This can be explained by the conditions based on which the wheat yield was estimated. In this study, wheat yield was simulated as the grain yield at each selected site on a very good soil and management across the region, while in Potgieter et al. (2002) wheat yield was estimated as shire average yield under actual soil and management conditions.

3.4 Water use efficiency of wheat crop across the MDB

Figure 7 shows the simulated mean water use efficiency (WUE) and transpiration efficiency (TE) of wheat crop across the MDB, calculated as kilograms of grain produced per millimeter evapotranspiration and transpiration, respectively. WUE ranged from less than 6 kg/ha.mm in the inland to a maximum around 16 kg/ha.mm at the east border of MDB (Fig. 7a). For most of the current cropping zone (Fig. 2), WUE ranged from 8–14 kg/ha.mm. TE ranged from 14–16 kg/ha.mm in the northwest to more than 26 kg/ha.mm in the southeast part of MDB. Both WUE and TE decreased with the dryness (vapour pressure deficit, VPD) of the air during the growing season (data not shown). More stored soil moisture at sowing in northeast MDB (Fig. 6) led to higher fraction of water used by the

crop, leading to a slightly different spatial distribution of WUE than TE.

The WUE and TE values in Fig. 7 were the mean values of 112 years (1891–2002) calculated based on the assumptions that wheat crop was sown in the red earth soil, under average optimal nitrogen supply and no pest and disease conditions. Therefore, the spatial variation in WUE and TE shown were driven by climate variations. The range of WUE values simulated in this study (4–18 kg/ha.mm) is consistent with the water use efficiency values calculated by Sadras and Angus (2006) for SE Australia using data from experimental plots and growers' fields (0–24 kg/ha.mm with the majority within the range of 2–18 kg/ha.mm). The range of TE values simulated (18–26 kg/ha.mm in the current wheat belt) is consistent with the calculated values of Angus and van Herwaarden (2001) and Sadras and Angus (2006) (22 kg/ha.mm as the maximum attainable WUE). The slighter higher TE values simulated in this study may be partly due to the assumption of optimal conditions.

The increase of both WUE and TE spatially from northwest to southeast MDB implies that benchmarking of water use efficiency for yield gap analysis needs to take into consideration the spatial impact of climate on WUE and TE. Analysis of Roderiguez and Sadras (2007), based on empirical data and modelling along a south-north transect, showed that TE increased southwards in the east MDB at a rate of 2.6% per degree latitude and the increase was also due to the increase in fraction of diffuse radiation, in addition to VPD. By accounting for the influence of rainfall patterns, they further showed that latitudinal trends in WUE were a complex result of southward increasing TE and soil evaporation, and season-dependent trends in wheat harvest index (Sadras and Rodriguez, 2007). Our results in Fig. 7 give more complete pictures on the spatial change of WUE and TE over the whole MDB region. Under long-term average climatic conditions, attainable TE in southeast MDB may reach 24–26 kg/ha.mm, but in major part of the northern MDB and the inland parts, the attainable TE was predicted to be well below 18–20 kg/ha.mm (Fig. 7b). Inter-annual variations in TE were also significant due to temporal climate variability. Around the Wagga Wagga region, the predicted TE in the past 112 years ranged from 10 to 35 kg/ha.mm (data not shown).

3.5 Gross margin and cost ratio of wheat production

Under the average optimal nitrogen application rates, the mean simulated gross margin of dryland wheat ranged from around \$600/ha in the east to -\$20/ha in the inland areas of MDB (Fig. 8a). For large part of the inland areas currently covered with native grass, the simulated wheat gross margin was less than \$100/ha. From east to west, both the

growing season rainfall (Fig. 3b) and the stored soil moisture at sowing time (Fig. 6) were decreasing, leading to decreasing wheat yield (Fig. 4b). Although the production cost decreased as well (data not shown), the cost as percentage [i.e., $\text{cost}/(\text{gross_margin}+\text{cost})$] increased towards inland (Fig. 8b), leading to decreasing gross margin (Fig. 8a).

In the gross margin calculations, costs associated with weed, disease and pest control were not considered. In reality these costs need to be included. In low rainfall areas, costs of weed control and fungicides, etc., are lower, so the growing cost is less. Furthermore, the larger farms in the western part of the region are able to gain considerable economies of scale, which is not studied in this paper.

3.6 Deep drainage and nitrate leaching

Excess drainage passing the crop root zone has been recognised as the major cause of the rising of saline groundwater table and dryland salinity in MDB. Under the red earth soil and the average optimal nitrogen application rates (Fig. 4a), the simulated mean annual deep drainage of the wheat-fallow system ranged from above 200 mm/year in the east to zero in the inland area (Fig. 9a). Spatial pattern of drainage was similar to that of annual rainfall and the stored soil moisture at sowing, implying that both the rainfall amount and rainfall distribution influence drainage. The higher stored soil moisture and drainage simulated in the northern part of the MDB was a result of summer rainfall. In that area, summer cropping is also practiced, where the summer crops use most of the summer rainfall and lead to less soil moisture left and less deep drainage compared to the wheat-fallow system simulated in this study. Therefore, a more thorough assessment on drainage under current cropping systems should include summer cropping in the northern part of the MDB.

The nitrogen leaching spatial pattern followed approximately that of drainage, ranging from >15 kgN/ha at the east edge to zero in the inland area (Fig. 9b). >5 kgN/ha N leaching was only simulated in areas with drainage of more than 100 mm/year. Again, in the northern part of the MDB, summer cropping also needs to be considered for more accurate assessment of nitrogen leaching.

3.7 Spatial distribution of the temporal variability of wheat growing season rainfall and wheat grain yield

The variability of growing season rainfall increased from around 0.3 in southeast to above 0.7 in the northwest MDB (Fig. 10a). Within the current annual cropping regions (see Fig. 2), variability of growing season rainfall increased from 0.3~0.5 in SA, VIC and south NSW to 0.4~0.6 in north NSW and QLD. The decreasing winter rainfall from

south to north and from east to west resulted in the increased variability.

The variability of simulated wheat yield increased westwards in QLD and NSW, northwest-wards in VIC, and roughly northwards in SA (Fig. 10b). The increasing stored soil moisture at wheat sowing time from southwest to northeast of MDB (Fig. 6) contributed to decreased variability of wheat grain yield in QLD and NSW, compared to that of growing season rainfall. In the high rainfall areas along the east border of MDB, the variability of wheat yield was about 20~40% of the average wheat yield, while in more inland areas, it was nearly equal to the average wheat yield. The greater inter-annual variations in grain yield in the inland areas of MDB imply that management of climate variability may have higher value towards inland dryer areas.

3.8 Potential value of seasonal climate forecasts

The potential value of ‘perfect’ climate forecasts, i.e., with perfect knowledge of the daily weather in the coming season, was calculated as the difference in gross margin between the simulation scenarios S2 and S1 (at average optimal N rates). This difference represents the maximum economic value that can be obtained when a seasonal forecast is used to assist nitrogen application in the wheat-fallow system with the crop variety and soil type assumed in this study.

The economic value of ‘perfect’ climate forecast ranged from \$26/ha to above \$70/ha if the whole of the MDB was considered (Fig. 11a), with the maximum value occurring in northwest Victoria and in central to southwest New South Wales. From the centre of MDB towards the coastal directions, the potential value of seasonal forecasts was predicted to decrease. This was due partly to the decreased variability and increased reliability of growing season rainfall. The value of climate forecasts also tended to decrease towards more inland directions and northwards. The decrease towards inland was due to the reduced rainfall amount, which consequently reduced the value of wheat production. The decrease northwards was due to the increased impact of stored soil moisture before sowing and reduced reliance on growing season rainfall.

Potential value of climate forecasts tended to increase with the variability of wheat yield initially and to flatten when wheat yield variability approaches 1.0 (Fig. 12). This implies that a skilful seasonal forecast may have the highest value where the inter-annual variability of crop yield is highest. This is consistent with the observation that production systems on very marginal land where the rainfall variability is high are the hardest to manage without knowledge of the coming season.

Apart from the increased gross margin, N management based on perfect forecasts reduced nitrogen applications

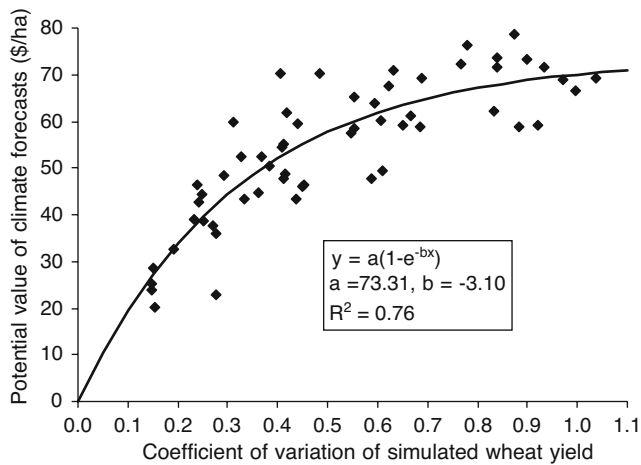


Fig. 12 Relationship between coefficient of variation of simulated wheat yield and the potential value of seasonal climate forecasts in MDB. The *solid line* is a regression line using exponential rising curve with parameter shown

(positive values) in higher rainfall regions and increased nitrogen applications (negative values) in low rainfall regions (Fig. 11b). Excluding the dry inland areas where wheat is not currently grown, ‘perfect’ forecast-based nitrogen management generally reduced nitrogen amount applied. The reduction ranged from zero in the middle of the basin to 20–35 kgN/ha/year in the east part of the MDB.

‘Perfect’ climate forecasts-based N management had a insignificant impact on drainage compared with N management based on historical climatology (data not shown). On average, it only led to $\pm 2\sim 4$ mm/year difference in deep drainage.

3.9 Comparison to current cropping areas and interpretation of the results

In MDB, land currently used for annual cropping is mainly restricted in a narrow band from northeast to the southwest of the MDB (Fig. 2). The dry inland part is mainly dominated by rangelands or native grasslands, native shrublands and forest woodland, while some of the wet-east border section, especially the southeast border of MDB, is covered with native forests and high-value grazing grasslands. In reality, no wheat crop is grown in those areas. However, this should not form a constraint for the assessment of the climate-determined potential crop yield in the whole MDB region. Because crops can not be grown in areas covered with protected native forests, shrubland, plantations, water bodies, and built-up areas, those areas were excluded in Fig. 5, but not in others in order to show the climate impact trends. The simulation results crossing to the non-cropped dry areas facilitate analysis of cropping region boundaries, while the results crossing to the wetter

non-cropped areas indicate potential for cropping. The result maps generated provide not only the impact of climate on wheat-fallow system in the currently cropped areas, but also indicate the potential of wheat yield in the areas currently not cropped with annual crops, e.g., in the areas currently covered with grassland.

Comparison of simulation results and the current land use mapping in MDB (Fig. 2) revealed that the western boundary of the current cropping zone approximated the isolines of 150–160 mm of wheat growing season rainfall (Fig. 3b), 2.5t/ha of simulated potential wheat grain yield (Fig. 4b), and \$150/ha of gross margin (Fig. 8a) in QLD and NSW. In VIC and SA, relatively lower crop yield and gross margins were simulated in current cropping zones south to the 160-mm isohyets of wheat growing season rainfall (Figs. 2, 4b, and 8a) due to the low stored soil moisture at wheat sowing time (Fig. 6).

This simulation study focused mainly on the impact of climate on the performance of a dryland wheat-fallow system in the Murray-Darling Basin of Australia. One wheat variety with defined sowing rules and one soil type were used to construct the simulation scenarios. The main objective was to assess the spatial variation in climate as it impacted on wheat yield, gross margin, water balance, and the potential value of climate risk management practices based on seasonal climate forecasting. The simulated trends of various variables studied reflected purely the impact of climate, and were not moderated by other factors like soil variations. The maps constructed can help understand the economic value of the agro-climatic resources in the MDB region. This value was quantified by translating the climate variable into crop yield and gross margins of a wheat-fallow system using crop modelling. Such an approach can be easily extended to assessment of the impact of future climate change on agricultural production in the whole MDB. Information generated can provide insights into the development of innovative management practices and exploration of new industry development outside the current cropping regions.

Due to the assumptions used in the study, it may be more appropriate to treat the results in a spatially relative sense, rather than absolute values. Although the APSIM model has been validated at various sites in the MDB, the validation has certainly not been stretched in a so wide region across the whole MDB. Although the model was able to simulate the response of the wheat-fallow system to climatic conditions in normal range, it might not be able to capture the impact of extreme conditions like damage of frost and high temperature during wheat flowering time. Under such conditions, the wheat yield and value of climatic resources would have been over-estimated. Nonetheless, a physiologically and physically based model was the best tool we could use to interpolate and extrapolate

data spatially to assess the impact of regional climate. Such analysis was essential in regional natural resource management. Climate should be viewed as a resource, rather than purely an environment, because it can be valued in terms of determining cropping systems types and setting the production potential.

3.10 Impacts of soil variations

The use of one soil type with a relatively high plant available water holding capacity (PAWC) of 233 mm up to 1.5 m depth across the whole MDB was to eliminate the impact of soils so that the impact of climate could be studied. The soil used represents a very good soil in the study region. The simulated yields provided near upper-limit reference values across the whole MDB, reflecting the relative impact of spatial climate variation. Soils can have a significant impact on the climate-determined potential wheat yield, though this is not the focus of this paper. Soils with different PAWC differ in their ability to store rainfall to supply water to crop roots, leading to different crop water use and crop yield under the same climate. Furthermore, the value of climate forecasts is likely to be overestimated without nitrogen adjustment for stored soil water in simulation scenario S1 (Hayman and Turpin 1998).

Inclusion of soil types into the assessment of crop productivity and value of climate forecasts at a regional level would require a significant amount of further work to tease out the complex climate–soil interactions. A preliminary modelling analysis showed that simulated wheat yield increased almost linearly with PAWC of soils in wet regions, but changed little with PAWC in dry areas. Figure 13 gives an example, showing the relative change of simulated wheat yield with PAWC of soils at Wagga Wagga site. The slope of the regression line in Fig. 13 will change with climate (rainfall) regions (data not shown). Due to the big spatial variations in soils even within a small area, a grid-based approach with high spatial resolution has to be taken. It would be impractical to run a detailed point model like APSIM at such high resolution grid level across a big region like MDB. A preferred approach would be to generate summary models (response surfaces, like the linear response shown in Fig. 13) using the point model and the range of soils found in different climatic regions. Those summary models could then be used at grid level to scale the simulated results obtained from using one good soil type like the ones presented here. Two companion papers of ours will follow: one aims to address the impact of soils on crop yield and value of seasonal climate forecasts across different climatic zones in MDB and the other tries to demonstrate the summary approach for estimating the impact of climate-soil combination on crop yield.

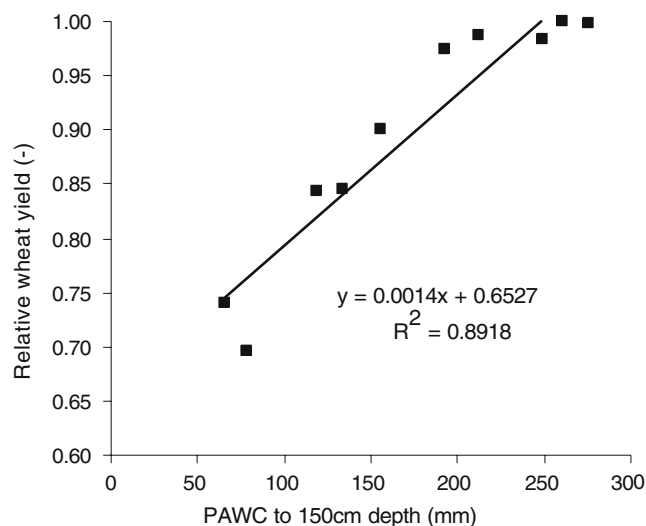


Fig. 13 Relationship between simulated relative wheat yield and the plant available water holding capacity (PAWC) to 1.5 m depth of the soil profile at Wagga Wagga, NSW, Australia

4 Conclusions

The results of this study showed clearly that both temporal and spatial variation of climate could lead to significant variations in the economic and environmental performance of a given production system. In order to better capture the productivity potential, understanding the interactions in the soil–plant–climate systems is essential for the development of sustainable management strategies. Spatially explicit land use systems synchronised with climate variations leads not only to high productivity but also to better environmental performance.

In the MDB the average wheat growing season rainfall decreased from more than 600 mm in the southeast corner to less than 100 mm in northwest inland region (1891–2002). The declining rainfall and increased dryness led to decreased crop nitrogen demand, and also declining water use efficiency of wheat crops. On a 112-year basis and on a soil with 233 mm of plant available water holding capacity, the spatial variation of climate in MDB could lead to a variation in wheat yield range of 1~7t/ha and gross margin range of -\$20~\$700/ha increasing from west inland to east MDB border areas. Temporal variability of wheat yield increased from 0.2 in east MDB to 1.0 in the west inland area, due to decline of growing season rainfall combined with reduced stored soil moisture at sowing time. Fully capturing the temporal variation of climate (perfect forecasting of weather in the coming season) to best manage the nitrogen application could increase the gross margin by \$26~\$79/ha/year compared to management already adjusted to historical climatology. This value could be used to benchmark the potential value of climate forecasts, repre-

senting the upper limit of the added value by seasonal climate forecasting in assisting nitrogen management in the simulated wheat-fallow system (with the crop variety and soil assumed). Simulated potential value of climate forecasts increased with the variability of wheat yield from east to west MDB and flattened when wheat yield variability approached 1.0. It should be emphasised that the estimated potential value of seasonal climate forecasts may be significantly dependent on crop types, cropping systems, management practices and soil types.

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