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Effects of climate trends and variability on wheat yield variability in eastern Australia

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ABSTRACT: Identifying climatic drivers that dominate in determining crop yield variations at a regional scale is important for predicting regional crop production. In this study, a statistical method was used to quantify the relationship between reported shire wheat yields and climate factors during the wheat-growing season across the New South Wales (NSW) wheat belt in eastern Australia from 1922 to 2000. The results show that recent climatic trends have increased wheat yield by 8.5 to 21.2% in 4 different climatic regions of NSW over the last few decades: In the eastern slopes, growing season maximum and minimum temperatures and number of heat stress days (>34°C) were identified as the dominant climatic factors affecting wheat yield, accounting for 36% of its variation. The wheat yield variation in the remaining 3 regions were as follows: 41% in the northern region from maximum temperature, pre-growing season rainfall (December to April), and number of frost days (<2°C); 47% in the south from rainfall, temperature, and number of frost and heat stress days; while in southwest NSW, rainfall was the main factor responsible for 31% of the variation. Frost was less important in the eastern slopes because farmers manage frost occurrence by sowing late and using late-flowering cultivars. However, the opposite occurs in the northern parts of the wheat belt where farmers sow earlier and select short-season varieties to avoid heat stress, but thereby expose their crops to possible frost conditions. Understanding the impact of climate variations on crop yield is important for developing sustainable agricultural production under future climate change.

KEY WORDS: Climate variation · Wheat yield variability · NSW wheat belt · First difference

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1. INTRODUCTION

Inter-annual variability of crop yields is largely determined by climate variables such as temperature, rainfall, and solar radiation (Chen et al. 2004, Rowhani et al. 2011, Trnka et al. 2012, Traore et al. 2013). These climate factors are closely related to and affect grain yield in different ways for different crops; moreover, climate–yield relationships are also region-dependent (Lobell & Asner 2003, Lobell et al. 2005, Tao et al. 2008, Ludwig et al. 2009, Zhang et al. 2010, Potgieter et al. 2013). For example, Zhang et al. (2010) found that solar radiation was the primary climate variable to cause inter-annual variations in rice yield in southern China based on experimental data for the period 1981 to 2005. In Mexico, at least 58% of the wheat yield variability in irrigated systems can be attributed to cool nighttime temperatures during the

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wheat-growing season (Lobell et al. 2005). Lobell et al. (2007) reported that growing season temperatures accounted for at least 29% of year-to-year variation in grain yields for 6 of the most widely grown crops globally; however, in rain-fed conditions, the major climate factor is the variation in seasonal rainfall (Seif & Pederson 1978, Cooper et al. 2008, Traore et al. 2013). Therefore, it is important to identify the major climate factors that cause yield variation for specific crops in specific regions, and quantify their effects. This can provide a foundation for the understanding of regional crop production and variability, and can help in the development of feasible strategies for adaptation of to future climate change (Lobell et al. 2007, Yu et al. 2013).

Wheat is the most important crop in Australia in terms of the gross value of its production. However, Australian wheat yield is extremely variable from year to year across major production regions (Potgieter et al. 2002). In the past decade (2003–2013), New South Wales (NSW) annual wheat production ranged between 2477 and 10 488 kt. Harvested area varied from 2995 to 4322 kha, with wheat yields varying from 0.62 to 2.75 t ha^{-1} (www.daff.gov.au/abares). Although advances in technology and improved crop varieties have been identified as contributing to yield increase, much of the variation in Australian wheat yields is related to growing season rainfall variability. For example, in South Australia ~65% of wheat yield variation has been associated with rainfall variability during April to October, with wintertime rainfall (June to August) being more effective in producing high yields than that during other times (Cornish 1950). However, Seif & Pederson (1978) found that spring rainfall, from 3 wk before flowering to 2 wk after, contributed to 86% of the variation in yield in the central west of NSW. Extreme weather events, such as frost and heat stress, affect wheat yields and represent a significant risk that needs to be managed to maintain profitable production (Asseng et al. 2011, Zheng et al. 2012). Several studies have investigated the climate effects on wheat in Australia using the yield data at a regional level (Potgieter et al. 2002, Hansen et al. 2004), state level (Yu et al. 2013), and national scale (Nicholls 1997). However, there have been few comprehensive studies of the climate–yield relationship at a district or shire level which can provide a higher spatial resolution of yield and climate, including diverse compositions of solar radiation, rainfall, and temperature. Moreover, the results of recent studies on the impact of climate trends in Australia have been contradictory. For example, Nicholls (1997) concluded that 30 to 50% of the Australian wheat yield increase during the period 1952–1992 was caused by a temperature increase. In a multiple linear regression model with 3 climate variables, Nicholls (1997) found that an increase in minimum temperature caused a wheat yield increase with small contributions from rainfall changes. However, Godden et al. (1998) and Gifford et al. (1998) argued that Nicholls's conclusion was not justified and overestimated the effects of climate trends on wheat yields. Gifford et al. (1998) suggested that the response of wheat yield to climate variation, among other factors, is more specific to regional conditions and growing season climate variability.

Statistical models that rely on past observations of climate and crop yields have been widely used to evaluate the impacts of climate change on crop performance (Lobell & Burke 2010a). They are particularly useful when data are insufficient to calibrate dynamic process-based models. The main requirement of statistical models is long time series of historical climate and crop yield data. Among statistical approaches, the multiple linear regression method is traditionally used because it can explain the relative contributions of different climate factors to crop yield with relatively simple multiple linear regression equations (Lobell et al. 2005, 2007, Sheehy et al. 2006, Lobell & Burke 2010b, Rowhani et al. 2011). However, a multiple linear regression method is limited if collinearity among climate factors is excluded when considering individual predictor effects (Sheehy et al. 2006, Lobell & Burke 2010b).

In this study, we systematically investigated climate–yield relationships and the effects of climate variation on wheat yields in 4 geographical-climate regions at shire scale across the NSW wheat belt in eastern Australia during 1922 to 2000. Stepwise regression analysis was used to identify the most relevant climate variables for yield variation, and empirical regression models were then developed to quantify the effect of climate trends on yield. The objectives of this study were to (1) provide a quantitative understanding of the relationship between wheat yield and climate in the past few decades; (2) identify the major climatic drivers for yield variation, and (3) analyze the impact of climate trend on wheat yields.

2. MATERIALS AND METHODS

2.1. Study area

The NSW wheat belt is geographically located in 66 shires of the state in eastern Australia. It has an area

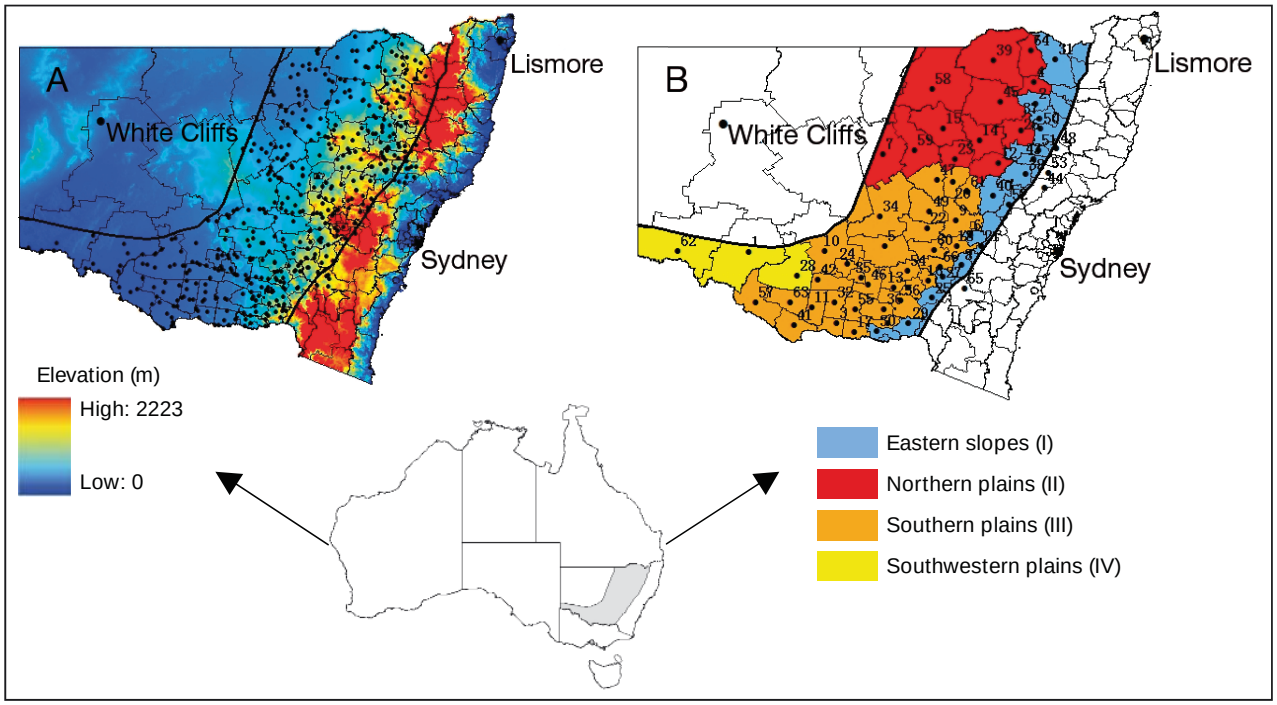

Fig. 1. Spatial distribution of (A) 466 weather stations over 4 regions (I: eastern slopes, II: northern plains, III: southern plains and IV: southwestern plains) in the New South Wales wheat belt including (B) 66 shires used in this study

of 360 000 km^2, accounting for 45 % of the state land area of 809 444 km^2 (Liu et al. 2014). Here wheat is mainly grown under rain-fed conditions. The crop can be sown in autumn or early winter (May to July) to ensure that flowering will take place after the last frost, and maturity will occur before any summer humidity, depending on local climatic conditions (rainfall) and soil types. Wheat usually flowers in early to mid-spring, and matures in late spring to early summer. Although the sowing date and mature date vary, May to November is typical growing season for wheat in eastern Australia (Gomez-Macpherson & Richards 1995). The wheat belt is characterized by variable topography and climate conditions (Fig. 1A). Topographically, the eastern part of the wheat belt is occupied by hills, known as 'slopes', with elevation of >500 m. The other areas are mainly occupied by plains. Climatically, the wheat belt has a broad range of variable environments (Fig. 2). It is warm and dry in the northern and southwestern plains, where growing season

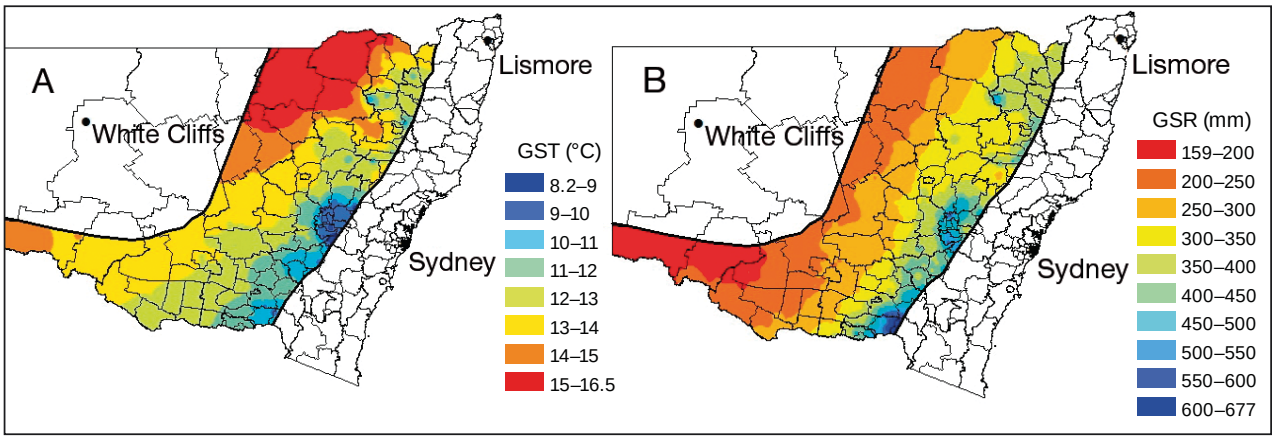

Fig. 2. Spatial distributions of (A) growing season mean temperature (GST) and (B) rainfall (GSR) over the New South Wales wheat belt during 1922–2000

rainfall (GSR) is <250 mm and growing season mean temperature (GST) is >14.0°C. In the southern plains, GSR is ~300 mm and GST is ~12.5°C, while the eastern slopes are wet and cold with >400 mm GSR and <12°C GST. Accordingly, we divided the wheat belt into 4 regions based on the climatic and topographic characteristics obtained from the topographical landscape of a Digital Elevation Model (DEM): the eastern slopes (I), northern plains (II), southern plains (III) and southwestern plains (IV) (see Table 1, Fig. 1B).

2.2. Climate and yield data

For this study, we extracted the historical daily climate data (1922–2000), known as SILO patched point dataset (PPD, www.longpaddock.qld.gov.au/silo/ppd/index.php), for maximum and minimum temperature, rainfall, and solar radiation at 466 weather stations evenly distributed across the NSW wheat belt (Fig. 1A). Wheat yields at shire level during 1922 to 2000 (data in some shires were not available in some years) across the NSW wheat belt were obtained from Fitzsimmons (2001) (Table 1).

To characterize the climate conditions of each shire, we assembled the daily maximum and minimum temperatures, rainfall, and solar radiation during 1922 to 2000 from the weather stations located within the shire (Table 1) and produced shire-averaged daily climate data. We then averaged the calculated daily climate data for the main growing season from May 1 to November 30 to obtain shire-scale climatic variables of the wheat-growing season. Number of days with $T_{max} > 34$°C (boundary to define heat stress) and number of days with $T_{min} < 2$°C (boundary to define frost) (Asseng et al. 2011, Liu et al. 2011, Barlow et al. 2015) during the wheat-growing season were calculated for each shire.

Table 1. Time period of 66 selected shires and number of weather stations for each shire included in this study. Region I: 20 shires, eastern New South Wales (NSW) wheat belt; Region II: 12 shires, North NSW; Region III: 31 shires, South NSW; Region IV: 3 shires, southwestern NSW. ID number = shire number in Fig. 1B

Region	ID	Shire	Stns	Period
I	29	Holbrook	7	1922–1996
	25	Gundagai	4	1922–1996
	27	Harden	2	1922–2000
	65	Yass	7	1922–1996
	8	Boorowa	4	1922–2000
	6	Blayney	5	1922–1996
	21	Evans	6	1922–1996
	52	Rylstone	3	1922–1996
	40	Mudgee	8	1922–1996
	38	Merriwa	7	1922–2000
	44	Muswellbrook	5	1922–1996
	53	Scone	7	1922–1996
	43	Murrurundi	7	1922–2000
	51	Quirindi	8	1922–2000
	48	Nundle	1	1922–1996
	50	Parry	4	1922–2000
	37	Manilla	1	1922–1996
	31	Inverell	10	1922–2000
	2	Barraba	5	1922–1996
	30	Hume	6	1922–2000
II	58	Walgett	25	1966–2000
	39	Moree plains	13	1922–2000
	64	Yallaroi	7	1922–2000
	15	Coonamble	12	1922–2000
	45	Narrabri	14	1922–2000
	26	Gunnedah	11	1922–2000
	14	Coonabarabran	9	1922–2000
	23	Gilgandra	5	1922–2000
	59	Warren	9	1958–2000
	7	Bogan	8	1958–2000
	12	Coolah	7	1922–2000
	4	Bingara	4	1922–1996
III	3	Berrigan	4	1922–2000
	32	Jerilderie	5	1922–2000
	17	Corowa	6	1922–2000
	55	Urana	4	1922–2000
	19	Culcairn	3	1922–2000
	36	Lockhart	6	1922–2000
	56	Wagga	11	1922–2000
	46	Narrandera	9	1922–2000
	35	Leeton	4	1927–2000
	5	Bland	9	1922–2000
	13	Coolamon	6	1922–2000
	33	Junee	10	1922–2000
	54	Temora	3	1922–2000
	16	Cootamundra	5	1922–2000
	11	Conargo	8	1922–2000
	47	Narromine	10	1922–2000
	20	Dubbo	3	1922–2000
	61	Wellington	7	1922–2000
	66	Young	6	1922–2000
	49	Parkes	9	1922–2000
	9	Cabonne	11	1922–2000
	18	Cowra	6	1922–2000
	60	Weddin	6	1922–2000
	22	Forbes	2	1922–2000
	63	Windouran	6	1922–1996
	41	Murray	5	1922–2000
	10	Carrathool	7	1922–2000
	42	Murrumbidgee	7	1922–2000
	34	Lachlan	15	1922–2000
	24	Griffith	7	1927–2000
	57	Wakool	8	1922–2000
IV	1	Balranald	8	1960–2000
	62	Wentworth	5	1968–2000
	28	Hay	14	1961–2000

2.3. De-trending method

The year-to-year variations of crop yield are largely driven by climate (Yu et al. 2001, Chen et al. 2004, Porter & Semenov 2005), but studies have shown that crop management improvements including improved varieties, fertilization development, and biocide application have contributed to crop yield increase in the past decades (Anderson et al. 2005, Asseng & Pannell 2012, Yu et al. 2012). To evaluate the impact of climate variation on crop yield, the yield increase driven by technological improvement needs to be excluded. A first-difference method has been widely used to remove the possible confounding effects of non-climatic factors (Nicholls 1997, Lobell & Asner 2003, Tao et al. 2008, Zhang et al. 2010). This approach can minimize the influence of management factors, enabling the explanation of crop-yield responses to climatic variables from year to year (Lobell & Field 2007, Trnka et al. 2012). The first difference is defined as the difference of a parameter between 2 successive years:

$$\Delta X_i = X_i - X_{i-1},\ i = 1, 2, \ldots n \quad (1)$$

where ΔX_i is the first difference of the parameter X_i for the ith year, and X_{i-1} is the parameter value for the $(i - 1)$th year. The first differences of maximum temperature (ΔT_{max}), minimum temperature (ΔT_{min}), rainfall (ΔR), solar radiation (ΔS), number of frost days ($T_{min} < 2°C$, ΔF), number of heat stress days ($T_{max} > 34°C$, ΔH) and wheat yield (ΔY) for the growing season during the period of 1922–2000 were calculated. Then ΔY, ΔT_{max}, ΔT_{min}, ΔR, ΔS, ΔF and ΔH were used to evaluate the effects of variation in climate on yield.

2.4. Stepwise regression analysis

Stepwise regression analysis is particularly useful to identify major climatic variables affecting crop yield variations (Yu et al. 2001, Liu et al. 2010b). It evaluates all climate variables for their potential contributions to crop yield variation and excludes variables not statistically significant in the multiple regression model ($p \leq 0.01$). Procedures using stepwise regression are relatively cheap to compute, and have the advantage that they allow the use of a small subset of least correlated variables without losing a significant portion of the explanatory power of the data, thus minimizing the effects of multicollinearity on the regression model (Huang & Townshend 2003). The stepwise regression analysis combines both forward selection and backward elimination methods to establish a regression model. Firstly, the procedure starts a forward selection by trying out one explanatory variable at a time and includes it in the regression model if it is statistically significant ($p < 0.01$). The second step uses a backward elimination method to retest the coefficients of the added variables and delete these variables if the test judges them to be insignificant. Because the addition of one variable can lead to a change in the p-value associated with another variable, the third step in the stepwise process will reselect the variables by allowing a variable to enter the equation at one step, deleting the variable at a later step and allowing the variable to reenter at an even later step (Dielman 2001). Finally, the stepwise regression procedure terminates when no more variables can be justifiably entered or removed from the model.

In this study we use the stepwise method to select significant climate variables employing SAS statistical software (v. 9.2). The multiple linear regression model without intercept (intercept forced to zero, to avoid trend effect) (Nicholls 1997) was:

$$Y = a_0\Delta T_{max} + a_1\Delta T_{min} + a_2\Delta R + a_3\Delta S + a_4\Delta F + a_5\Delta H \quad (2)$$

where a_0, a_1, a_2, a_3, a_4, and a_5 represent the regression coefficients to be fit.

3. RESULTS

3.1. Variability of climate and wheat yield

Fig. 3 shows the variation in climate variables during the wheat-growing season from 1922 to 2000 in the 4 regions. Growing season maximum temperature (GST_{max}) had the biggest variability in the eastern slopes (region I) due to a large range of latitudes in this region, ranging from 13.2 to 23.5°C (mean: 18.3 ± 2.1°C; Fig. 3A). For the northern and southern plains (regions II and III, respectively), there were similar variations in GST_{max}, but region II had the highest mean GST_{max} of 21.5°C. In the southwestern plains (region IV) GST_{max} had the least variability (±0.6°C) ranging from 18.4 to 21.3°C (mean: 20.0°C). For growing season minimum temperature (GST_{min}) (Fig. 3B), the patterns of their variations were similar to GST_{max}. GST_{min} varied between 1.6 and 8.2°C (mean: 5.1 ± 1.2°C) in region I, and was highest in region IV, with the value of 7.4 ± 0.6°C.

The largest variability of growing season solar radiation (GSS) (Fig. 3C) occurred in region I, ranging from 2738 to 3961 MJ m^{-2} yr^{-1} (mean: 3294 ± 232 MJ m^{-2} yr^{-1}), while region IV had the smallest

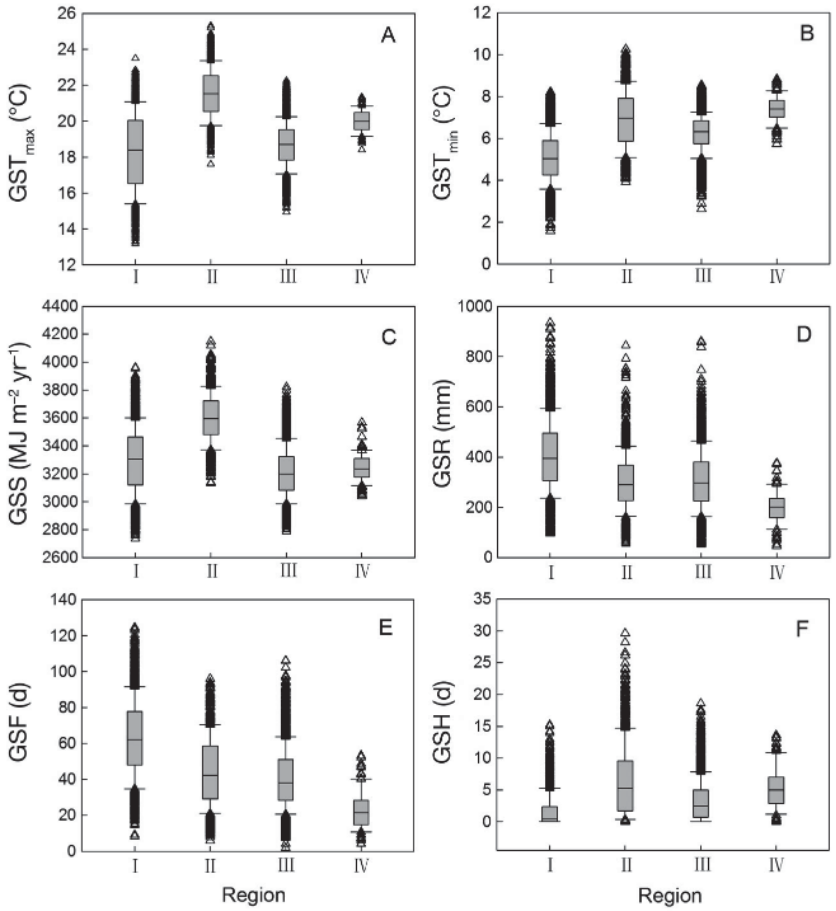

Fig. 3. Mean growing season (A) maximum temperature (GST_{max}), (B) minimum temperature (GST_{min}), (C) solar radiation (GSS), (D) rainfall (GSR), (E) number of frost (GSF) and (F) heat stress days (GSH) for 1922–2000 in 4 regions of New South Wales. Horizontal line: median; box-boundaries: 25th and 75th percentiles; whiskers: 10th and 90th percentiles; triangles: outliers. Regions: eastern slopes (I), northern plains (II), southern plains (III) and southwestern plains (IV)

variability of 3040 to 3567 MJ m^{-2} yr^{-1} (3243 ± 103 MJ m^{-2} yr^{-1}). The largest mean GSS value was 3600 MJ m^{-2} yr^{-1} in region II.

Growing season rainfall (GSR) ranged between 97.6 and 935.1 mm (mean: 407.1 ± 141.4 mm) among all the years and shires in region I (Fig. 3D). The median GSR was 400 mm, 75% of years and shires had more than ~300 mm in this region. Regions II and III had a similar rainfall range with a mean of 302.5 ± 117.8 and 307.2 ± 115.2 mm, respectively. Notably, region IV received less than half of region I's GSR values, ranging between 46.2 and 376.9 mm (199.8 ± 65.9 mm). Rainfall was <290 mm in 90% of years and shires in this region.

The occurrence probability of growing season frost (GSF) and heat stress (GSH) varied greatly across the NSW wheat belt during the period 1922–2000 (Fig. 3E,F). The number of GSF days was highest (63 d) in region I, occurring in >50% of the years and shires due to lower mean temperatures (Fig. 2A). Region II (44 d) had slightly more GSF days than region III (41 d). However, frost days occurred least in region IV (23 d). By contrast, GSH days in regions II and IV occurred during ~5 d in >50% of years and shires due to higher temperatures (Fig. 3F). Regions I and III had fewer heat events due to the relatively low mean temperatures during the wheat-growing season. Spatially, the number of heat days occurred gradually more from south to north and from east to west, which was opposite to the occurrence of frost days (Fig. 4).

Observed wheat yields in all 4 regions varied greatly from year to year (Fig. 5). The largest variability was in region III, ranging from 0.20 to 3.12 t ha^{-1} (mean ± SD: 1.39 ± 0.66 t ha^{-1}. Region I yields varied from 0.44 to 3.32 t ha^{-1} (1.39 ± 0.63 t ha^{-1}). Regions II and IV had lower amplitudes of variations in yield, but yields in region IV had a higher (than region II) mean value of 1.37 ± 0.48 t ha^{-1}. Compared with climate variables, the yield variation among the 4 regions was relatively small, indicating that crop yields were not only affected by climate but also influenced by crop management.

3.2. Wheat yield–climate relationships

Inter-annual wheat yield (ΔY) response to climate variation is consistent across the 4 regions (Fig. 6). ΔY is positively correlated to ΔR and ΔT_{min} while negatively correlated to ΔS, ΔT_{max}, ΔF and ΔH. The correlation coefficients of ΔY with ΔR was 0.55, ΔT_{min} was 0.24, ΔS was −0.51, ΔT_{max} was −0.54, ΔF was −0.36, and ΔH was −0.37 on average in the 4 regions. All of these coefficients were statistically significant at the level of $p < 0.05$. The results suggest that higher rainfall and minimum temperature resulted in higher yield, while higher maximum temperature and solar radiation could lead to lower yield in rain-fed conditions; frost and heat stress had negative effects on wheat yield across the whole wheat belt.

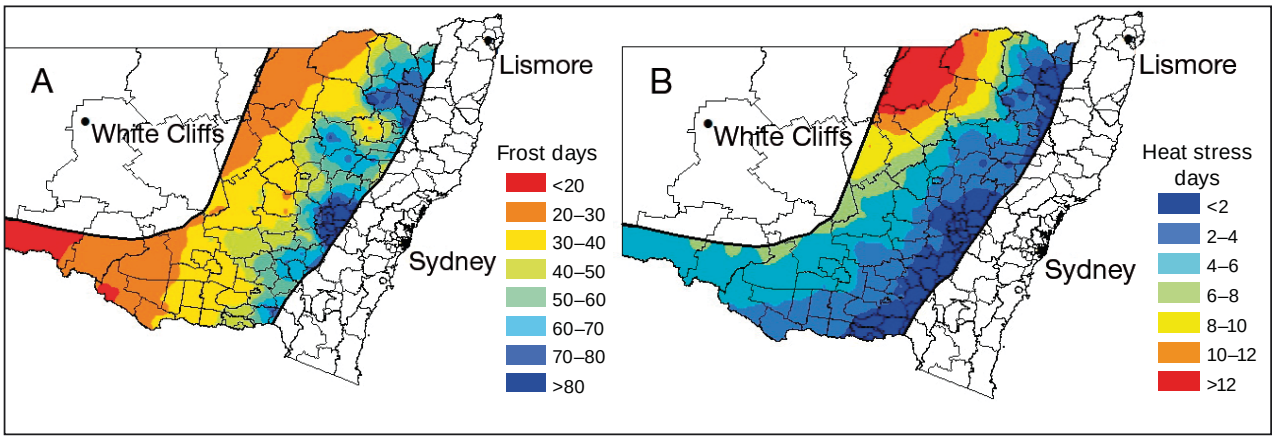

Fig. 4. Spatial distributions of the number of (A) frost (<2°C) and (B) heat stress days (>34°C) during the wheat growing season of 1922–2000 over the New South Wales wheat belt

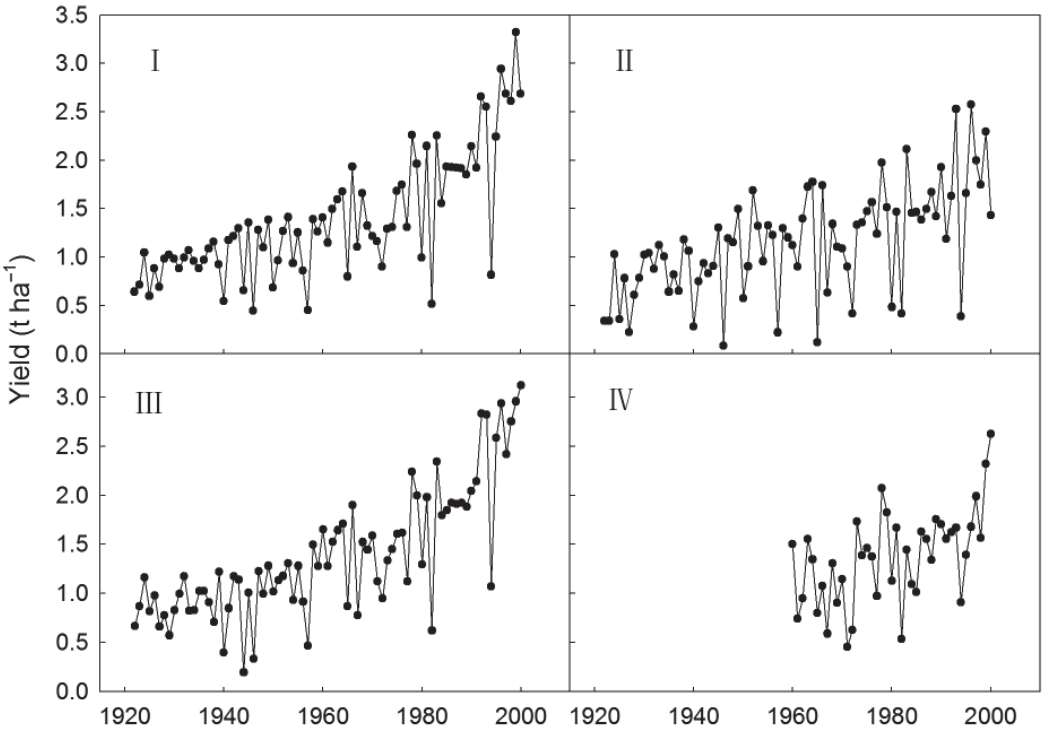

Fig. 5. Averaged wheat yields in 4 regions of New South Wales during 1922 to 2000: eastern slopes (I), northern plains (II), southern plains (III) and southwestern plains (IV). Prior to 1960 statistical data for region IV (3 shires) are not included

Table 2 shows the correlation coefficients of the 6 climate variables ΔR, ΔS, ΔT_{max}, ΔT_{min}, ΔF, and ΔH at each region. Rainfall was positively correlated to minimum temperature but negatively correlated to maximum temperature and solar radiation, number of frost days, and number of heat stress days. For the 4 regions together, the correlation coefficient of ΔR with ΔS, ΔT_{max}, ΔT_{min}, ΔF and ΔH was –0.76, –0.65, 0.51, –0.58 and –0.51, respectively. All of these relationships were statistically significant at the level of $p < 0.01$. Drought years in the wheat belt tended to be less cloudy with higher solar radiation and maximum temperature, but had lower minimum temperature. Higher solar radiation days were always accompanied by lower rainfall over the NSW wheat belt which explains why higher solar radiation could result in lower yield.

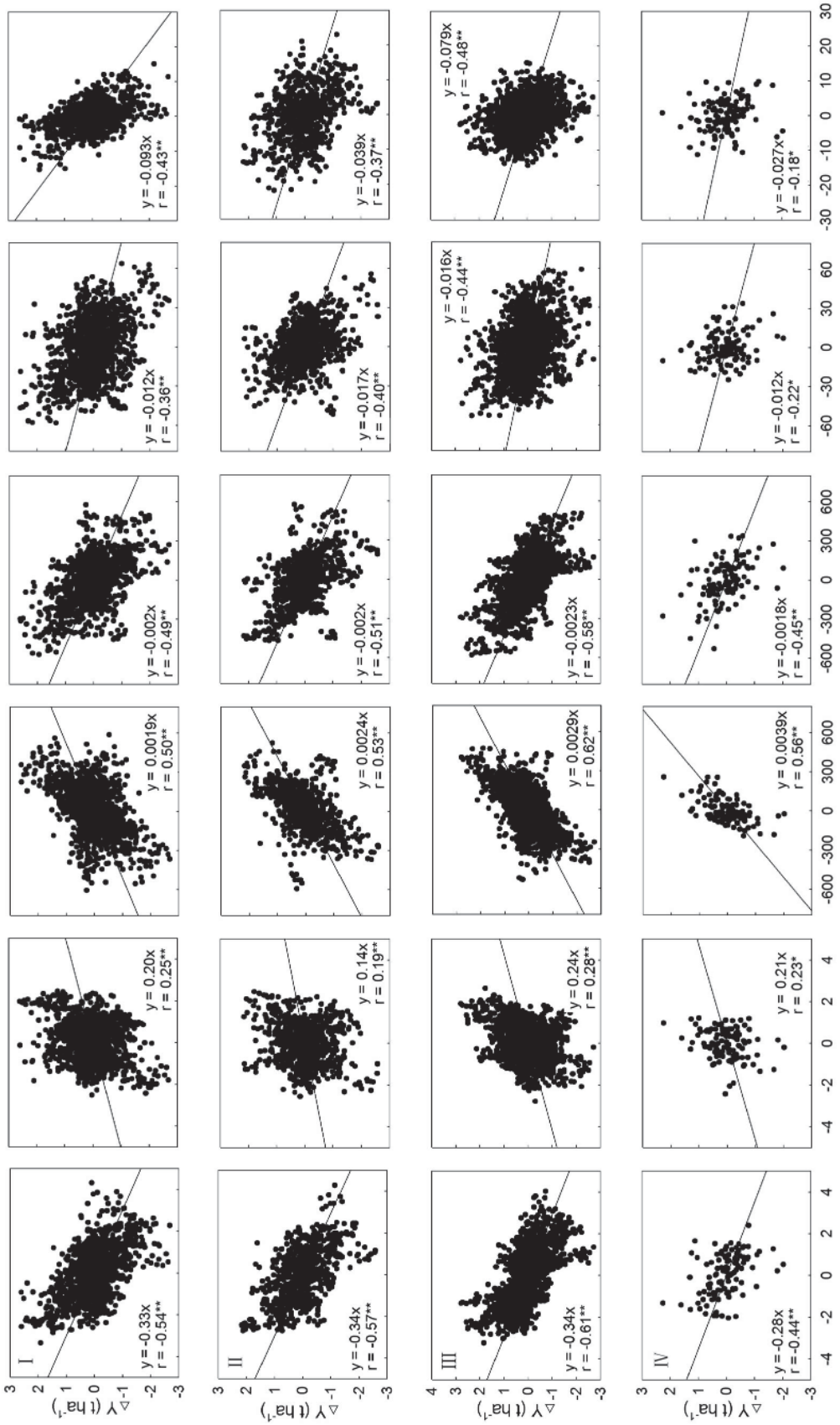

Fig. 6. Correlation of first difference of wheat yield (ΔY) and first difference of growing season maximum (ΔT_{max}) and minimum temperatures (ΔT_{min}), rainfall (ΔR), solar radiation (ΔS) and number of frost (<2°C, ΔF) and heat stress days (>34°C, ΔH) in 4 regions of New South Wales (I: eastern slopes, II: northern plains, III: southern plains and IV: southwestern plains). Included: best-fit regression line and r. $^{**}p < 0.01$, $^{*}p < 0.05$

Table 2. Pearson correlation matrix of different climate variables in 4 regions of New South Wales. $\Delta T_{max/min}$: growing season max./min. temperature; ΔR: rainfall; ΔS: solar radiation; ΔF: frost days (<2°C); ΔH: heat stress days (>34°C). Regions: eastern slopes (I), northern plains (II), southern plains (III) and southwestern plains (IV). *p < 0.05, **p < 0.01

	ΔR (mm)	ΔS (MJ m^{-2})	ΔT_{max} (°C)	ΔT_{min} (°C)	ΔF (d)	ΔH (d)
Region I						
ΔR (mm)	1	−0.75**	−0.63**	0.57**	−0.67**	−0.50**
ΔS (MJ m^{-2})	–	1	0.68**	−0.54**	0.59**	0.58**
ΔT_{max} (°C)	–	–	1	−0.02	0.27**	0.63**
ΔT_{min} (°C)	–	–	–	1	−0.86**	−0.17**
ΔF (d)	–	–	–	–	1	0.27**
ΔH (d)	–	–	–	–	–	1
Region II						
ΔR (mm)	1	−0.80**	−0.63**	0.52**	−0.62**	−0.55**
ΔS (MJ m^{-2})	–	1	0.71**	−0.46**	0.53**	0.60**
ΔT_{max} (°C)	–	–	1	0.11**	0.20**	0.71**
ΔT_{min} (°C)	–	–	–	1	−0.80**	−0.03
ΔF (d)	–	–	–	–	1	0.17**
ΔH (d)	–	–	–	–	–	1
Region III						
ΔR (mm)	1	−0.74**	−0.72**	0.49**	−0.62**	−0.56**
ΔS (MJ m^{-2})	–	1	0.75**	−0.41**	0.47**	0.57**
ΔT_{max} (°C)	–	–	1	0.00	0.31**	0.63**
ΔT_{min} (°C)	–	–	–	1	−0.80**	−0.14**
ΔF (d)	–	–	–	–	1	0.31**
ΔH (d)	–	–	–	–	–	1
Region IV						
ΔR (mm)	1	−0.75**	−0.62**	0.44**	−0.40**	−0.43**
ΔS (MJ m^{-2})	–	1	0.82**	−0.16	0.19*	0.49**
ΔT_{max} (°C)	–	–	1	0.19*	0.05	0.52**
ΔT_{min} (°C)	–	–	–	1	−0.76**	−0.08
ΔF (d)	–	–	–	–	1	0.17
ΔH (d)	–	–	–	–	–	1

Table 3 shows the regression analysis for wheat yields and climate factors. Region I wheat yield variation was primarily dominated by GST_{max} and GST_{min}, and GSH, which amounted to 36% of the variation. In region II, wheat yield variation significantly correlated with GST_{max}, GSF, and pre-growing season rainfall (December to April), explaining 41% of the yield variation. In region III, the major climate factors determining yield were GSR, GST_{max} and GST_{min}, GSF and GSH. These factors contributed to 47% of the variation in wheat yield. However, as the main factor, rainfall caused 31% of wheat yield variability in region IV. When the effects of variations in climate factors on wheat yield were considered in the whole NSW wheat belt, the year-to-year variability in yield was dominated by GSR, GST_{max}, GST_{min}, and GSF, which accounted for 41% of yield variation over the past few decades.

3.3. Effects of climate trends on wheat yield

Table 4 shows the trends in major climatic drivers and their effects on yield increase. The estimated yield change was calculated as the percentage of climate-trend yield change accounting for observed yield increase from 1922 to 2000 according to the regression model in Table 3. In region I, GST_{max} showed a small decreasing trend by 0.0080°C yr^{-1} ($p < 0.05$). GST_{min} significantly increased by 0.011°C yr^{-1} ($p < 0.01$) and GSH decreased but not significantly. These 3 major climatic drivers resulted in 14.8% yield increase. In region II, GST_{max} decreased by 0.0064°C yr^{-1} ($p > 0.05$), pre-growing season rainfall increased by 0.88 mm yr^{-1} ($p > 0.05$) and GSF decreased significantly by 0.16 d yr^{-1} ($p < 0.01$), which could explain the yield increase of 21.2%. In region

Table 3. Results of stepwise regression analysis ($p < 0.01$) between first difference of wheat yield (ΔY) and climatic variables including growing season max./min. temperatures (ΔT_{max}, ΔT_{min}), rainfall (ΔR), solar radiation (ΔS), number of frost (<2°C, ΔF) and heat stress (>34°C, ΔH) days and pre-growing season (December to April) rainfall (ΔR_{pre}) in each region (I: eastern slopes, II: northern plains, III: southern plains and IV: southwestern plains) and the whole New South Wales (NSW) wheat belt during 1922–2000. The 99% CI (lower/upper limit) are shown in brackets

	ΔR (10^{-3} mm)	ΔS (MJ m^{-2})	ΔT_{max} (°C)	ΔT_{min} (°C)	ΔR_{pre} (10^{-3} mm)	ΔF (10^{-2} d)	ΔH (10^{-2} d)	R^2
I	–	–	−0.29 (−0.34/−0.25)	0.18 (0.14/0.22)	–	–	−1.9 (−3.4/−0.35)	0.36
II	–	–	−0.29 (−0.34/−0.25)	–	0.40 (0.02/0.77)	−1.3 (−1.6/−0.96)	–	0.41
III	0.70 (0.35/1.1)	–	−0.23 (−0.27/−0.19)	0.099 (0.03/0.17)	–	−0.35 (−0.62/−0.07)	−1.5 (−2.3/−0.68)	0.47
IV	3.9 (2.4/5.3)	–	–	–	–	–	–	0.31
NSW	0.45 (0.22/0.70)	–	−0.28 (−0.31/−0.25)	0.099 (0.049/0.15)	–	−0.37 (−0.58/−0.15)	–	0.41

Table 4. Trends in observed wheat-growing season climatic variables and their estimated impacts on yield change (%) according to the regression model in Table 3 at 4 regions (I: eastern slopes, II: northern plains, III: southern plains and IV: southwestern plains) across the New South Wales wheat belt during 1922–2000. Variables: max/min temperatures (ΔT_{max}/ΔT_{min}), rainfall (ΔR), pre-growing season (Dec–Apr) rainfall (ΔR_{pre}), number of frost (<2°C, ΔF) and heat stress (>34°C, ΔH) days. $^{**}p < 0.01$, $^{*}p < 0.05$

	ΔT_{max} (°C yr^{-1})	ΔT_{min} (°C yr^{-1})	ΔR (mm yr^{-1})	ΔR_{pre} (mm yr^{-1})	ΔF (d yr^{-1})	ΔH (d yr^{-1})	Estimated yield change (%)
I	−0.0080*	0.011**	–	–	–	−0.0002	14.8
II	−0.0064	–	–	0.88	−0.16**	–	21.2
III	−0.0078*	0.0015	0.72	–	0.086	−0.012	8.5
IV	–	–	0.59	–	–	–	9.3

III, a significant decrease in GST_{max} (−0.0078°C yr^{-1}, $p < 0.05$), and other albeit insignificant climatic drivers, led to a 8.5% yield increase. In region IV, GSR increased by 0.59 mm yr^{-1} ($p > 0.05$) accounting for a yield increase of 9.3%. For the 4 regions together, recent climatic trends have had a positive effect on wheat yield, increasing it by 8.5–21.2% over the last few decades.

4. DISCUSSION

In this study, the year-to-year first-difference method was used for de-trending wheat yield to remove technology effects. This method is easier to calculate compared with other de-trending methods such as robust regression technique (Finger 2010, Newlands et al. 2014), which is, however, superior in handling data with outliers. A stepwise regression model was applied to identify significant or major climate variables ($p < 0.01$) affecting wheat yield variation in 4 contrasting climatic regions across the NSW wheat belt. However, this method does not explicitly address predictor collinearity in the regression model. When multicollinearity exists it affects the regression coefficient estimates, but it does not affect the ability to obtain a good fit of regression (higher R^2), nor the quality of forecasts or predictions from the regression (Dielman 2001). Namely, multicollinearity does not reduce the predictive power or reliability of the model as a whole. Hence, if the regression model is used strictly for forecasting or for an overall estimation of climate effects as in our study, the multicollinearity may not be problematic, but if the contribution of individual variables is estimated, caution should be exerted when interpreting the results.

Inter-annual variability of crop yields is well known to depend on climate factors (Chen et al. 2004). Our results show that wheat yields in the NSW wheat belt positively correlated with growing season rainfall and minimum temperature but negatively correlated with maximum temperature, which is consistent with a previous study conducted for wheat in Australia (Yu et al. 2013). However, Lobell et al. (2005) showed that growing season minimum temperature was the major factor to contribute to yield increase, and had a negative effect on wheat yield variation for irrigated systems in Mexico, which was different from our results in rain-fed environments. In southern Mali cotton production was particularly affected by rainfall distribution (Traore et al. 2013). Zhang et al. (2010) found that irrigation water availability in different regions played a key role in determining a switch of dominant climatic drivers (solar radiation or rainfall) to affect rice yield variations in China. In the eastern Australian wheat belt, which is located in a semiarid region with the climate becoming warmer from south to north and drier from east to west, seasonal rainfall was the major direct factor that affects crop sowing date, water supply and consequently yields. If only considering a single climatic factor, about 31% of yield variability can be attributed to rainfall variation during the wheat-growing season (May to November) across the wheat belt (Fig. 6), which is consistent with previous studies (Cornish 1950, Seif & Pederson 1978, Stephens et al. 1994).

It should be noted that there are interactive impacts of rainfall, temperature and solar radiation on yield variation (Gifford et al. 1998, Yu et al. 2013). For example, growing season solar radiation had a negative effect on wheat yield variation due to a strong negative correlation between rainfall and radiation in our study (Table 2). Here we assumed that solar radiation effects on yield can be attributed to rainfall variation, suggesting an indirect rainfall impact on variability in wheat yields, which was different to temperature as a proxy of radiation and rainfall effects on rice yields in China (Zhang et al. 2010).

Water stress caused by low rainfall and high evaporative demands is the major limitation on wheat yield in many parts of the wheat belt (except

region I) (French & Schultz 1984, Turner & Asseng 2005, Ludwig & Asseng 2006). It should be noted that in regions I and II, ΔR was not selected into the multi-linear equations (Table 3). However, this does not mean that rainfall had no significant impacts on the year-to-year wheat yield variations (see the high correlation in Fig. 6). Rainfall was not identified as a significant factor affecting wheat yield variation probably because its impacts were largely accounted for by those of maximum temperature due to the coherence between the two variables, i.e. maximum temperature was negatively related to rainfall at a highly significant level ($p < 0.01$, Table 2). Moreover, in region I, the wheat-growing season received >400 mm of rainfall, which roughly meets the wheat water demand from May to November for most of the years. Therefore, yields were less correlated to rainfall, and GSR was not selected as a major climate factor to limit wheat yield in this region. Compared with region I, there were more drought impacts in the other 3 regions because of lower rainfall during most growing seasons (Fig. 7). Non-growing season rainfall can contribute to stored soil moisture at the end of summer in region II, which can be used for water uptake of the crop (Angus et al. 1980). In such cases, pre-growing season rainfall can be an important factor on wheat yield variability, while GSR has less of an effect. This is similar to southern Queensland where wheat is predominantly grown on stored water in fine-textured soils with high water-holding capacity (Angus et al. 1980). Most of the water transpired is from the store accumulated during the preceding summer, when rainfall ranges between 300 and 400 mm (December to April). Therefore, the contribution of rainfall to yield variation shifts from winter dominated in region III to summer dominated in region II across the NSW wheat belt.

In addition to rainfall, other climate factors such as GST_{max} and GST_{min} also had significant impacts on wheat yield variation in eastern Australia. In particular, extreme weather events such as frost and heat stress can have a large impact on yield variation (Asseng et al. 2011, Zheng et al. 2012). For dry land wheat in Australia, the damage from early spring frost is a major constraint to yields (Marcellos & Single 1975, McDonald et al. 1983). High temperatures can increase the rate of grain filling and >30°C can result in an acceleration of leaf senescence, which leads to a reduction in yield (Lobell et al. 2012). An earlier study showed that the optimum sowing and flowering dates were determined by the incidence of early spring frosts and high spring temperatures in the NSW wheat belt (McDonald et al. 1983). Although farmers select cultivars for a targeted flowering window, such selection is often based on an average with limited success (Liu et al. 2010a). Our results show that frost was less important in region I but more important in the northern parts of the NSW wheat belt. This can be at least partially attributed to the fact that most farmers in region I manage frost occurrence well by sowing late and using late flowering cultivars to minimize frost risk. However, this also can increase heat stress risk due to delaying the flowering date. Fortunately, the occurrence of heat stress in the eastern region is less frequent than in other regions; hence, farmers can extend the wheat flowering dates far later than in other regions. In regions with a frequent occurrence of heat stress, such as region II, farmers have to sow earlier and plant short-season varieties to avoid heat stress. In turn, this increases the frost risk at anthesis. In Australia, wheat yields can be severely damaged by frost and heat stress when occurring during flowering (Godden et al. 1998, Asseng et al. 2011, Zheng et al. 2012). Farmers in Australia have traditionally been concerned about frost and heat risks but it is often hard to manage them well in extreme cases. One of these extreme cases is late frost. For example, NSW wheat was badly damaged in 2002 when frost occurred in

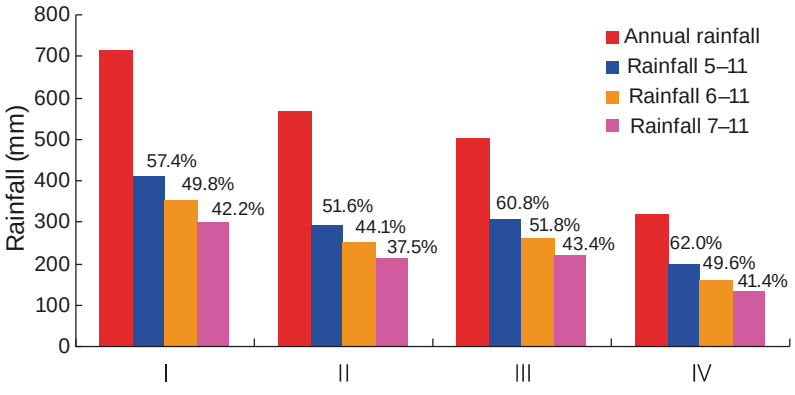

Fig. 7. Seasonal and annual rainfall for the 4 regions in the New South Wales wheat belt: eastern slopes (I), northern plains (II), southern plains (III) and southwestern plains (IV). May–Nov (5–11), Jun–Nov (6–11) and Jul–Nov (7–11) rainfall were calculated as possible growing season rainfall, as wheat sowing date varies depending on time of initial rainfall at start of the season. Values above bars: percentages of annual rainfall accounted for by each season

late October (28 October). In 2013, the winter temperature was ~2°C higher than the long-term average, but frost still occurred (www.bom.gov.au/climate/). Wheat yields were badly damaged in many areas as the higher temperature accelerated crop growth development with early flowering and widespread frost damage.

Several reports have shown that the recent climate trends have had significant impacts on crop yields (Tao et al. 2008, Lobell et al. 2011, Traore et al. 2013). Nicholls (1997) concluded that 30 to 50% of the observed yield increase was due to an increase in minimum temperature and a decrease in the diurnal temperature range resulting in less frost damage in Australia. This contribution of climatic trends to Australian wheat yield increase was considered to be overestimated and attracted serious criticism (Gifford et al. 1998, Godden et al. 1998, Anderson et al. 2005). The correlation of yield variation with minimum temperature was not significant at 5%, and the equation showed, in contrast, that rainfall had a negative effect on wheat yield variation. Mean annual minimum temperature had a larger contribution to yield increase only because it increased mostly between 1952 and 1992 (by 1.02°C) in Nicholls's study. Our results from stepwise regression equations demonstrate that the 8.5 to 21.2% yield increase during the last 78 yr over the NSW wheat belt was due to climatic trends. Unlike the relative short period of data used by Nicholls (1997), we used nearly twice the length of shire data and calculated climate variables during the wheat-growing season. In addition we applied stepwise regression analysis to select significant climate variables in the regression model. Each leading variable in the multiple regression equation had a significant level ($p \leq 0.01$). The climate trend contribution estimated by our method was less than that of Nicholls (1997). It is certain that management changes over time — meaning new cultivars, the development of new land with different soil characteristics, and changes in land use — all affected yield increases across the NSW wheat belt during the past decades.

Our results show that yield variation in the NSW wheat belt is mainly affected by variability of growing season rainfall and temperature, while solar radiation is not a major climate driver (Table 3). Climate change scenarios suggest that eastern Australia is likely to become warmer and drier in the future (Pearce et al. 2007). Although the positive effect of higher CO_2 concentration is likely to benefit rain-fed crop production by improving water-use efficiency (Kim et al. 2003, Asseng et al. 2004, Ludwig & Asseng 2006), this effect may not be sufficient to outweigh the negative effect of increasing temperature and decreasing rainfall (Piao et al. 2010). Farmers in NSW can adapt to rainfall variability. For example, they often avoid sowing wheat crop in drought years with late starts to the growing season or only sow in some areas with sufficient stored soil water. Wheat phenology is expected to accelerate with global warming in the future, resulting in a shorter growing periods. Later maturing cultivars could be used to mitigate the shortening of the phenology and enable the capture of enough solar radiation for biomass accumulation (Zheng et al. 2012). To some extent, earlier maturing cultivars can avoid severe terminal drought, but the risk of heat stress around flowering will still increase due to higher temperatures, potentially resulting in substantial yield losses for heat sensitive cultivars in the future (Semenov & Shewry 2011); therefore, new wheat varieties with improved water-use efficiency and heat resistance will be needed to better adapt to these conditions. Breeding for such traits is particularly important if the projections of rainfall reductions are realized and the frequency of high-temperature days further increases in the future (Asseng & Pannell 2012).

5. CONCLUSIONS

In the eastern Australia wheat belt, wheat yields were positively correlated to growing season rainfall and minimum temperature, while negatively correlated to maximum temperature at a significant level ($p < 0.05$). Recent climatic trends contributed to wheat yield increase by 8.5 to 21.2% in 4 different climatic regions. Rainfall is usually the main climatic driver affecting wheat yield variation in the NSW wheat belt, but it is also affected by temperature and solar radiation.

In the eastern slopes, growing season temperature and number of heat stress days were major factors affecting yield variation. In the northern parts of the wheat belt, important factors were growing season maximum temperature and pre-growing season (December to April) rainfall and number of frost days. In the southern region, growing season rainfall, temperature, and number of frost and heat stress days were the major contributors to yield variation. In the southwestern plains, the main direct climate factor was growing season rainfall. Understanding these effects of climate variations on crop yield is important for developing sustainable agricultural production to adapt to future climate change.

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