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Adapting wheat sowing dates to projected climate change in the Australian subtropics: analysis of crop water use and yield

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Abstract. Projected increases in atmospheric carbon dioxide concentration ([CO_2]) and air temperature associated with future climate change are expected to affect crop development, crop yield, and, consequently, global food supplies. They are also likely to change agricultural production practices, especially those related to agricultural water management and sowing date. The magnitude of these changes and their implications to local production systems are mostly unknown. The objectives of this study were to: (*i*) simulate the effect of projected climate change on spring wheat (*Triticum aestivum* L. cv. Lang) yield and water use for the subtropical environment of the Darling Downs, Queensland, Australia; and (*ii*) investigate the impact of changing sowing date, as an adaptation strategy to future climate change scenarios, on wheat yield and water use. The multi-model climate projections from the IPCC Coupled Model Intercomparison Project (CMIP3) for the period 2030–2070 were used in this study. Climate scenarios included combinations of four changes in air temperature (0°C, 1°C, 2°C, and 3°C), three [CO_2] levels (380 ppm, 500 ppm, and 600 ppm), and three changes in rainfall (–30%, 0%, and +20%), which were superimposed on observed station data. Crop management scenarios included a combination of six sowing dates (1 May, 10 May, 20 May, 1 June, 10 June, and 20 June) and three irrigation regimes (no irrigation (NI), deficit irrigation (DI), and full irrigation (FI)). Simulations were performed with the model DSSAT 4.5, using 50 years of daily weather data. We found that: (*1*) grain yield and water-use efficiency (yield/evapotranspiration) increased linearly with [CO_2]; (*2*) increases in [CO_2] had minimal impact on evapotranspiration; (*3*) yield increased with increasing temperature for the irrigated scenarios (DI and FI), but decreased for the NI scenario; (*4*) yield increased with earlier sowing dates; and (*5*) changes in rainfall had a small impact on yield for DI and FI, but a high impact for the NI scenario.

Additional keywords: climate change, crop modelling, crop water stress, evapotranspiration, irrigation requirements, water use efficiency, wheat.

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Introduction

Global population growth is putting increasing pressure on agriculture to produce more food on less arable land while maintaining productivity and profitability and ensuring environmental sustainability (Rosenzweig and Hillel 1998). Changes in atmospheric carbon dioxide concentration ([CO_2]), air temperature, and seasonal rainfall patterns are expected to affect crop production worldwide (Ludwig and Asseng 2006; Tubiello *et al.* 2007). Increases in temperature make the development of the plants faster, so they reach maturity sooner (Ritchie and NeSmith 1991). In cooler regions, where planting dates cannot be anticipated because of lower temperatures, too much higher temperature between anthesis and maturity will cause the time to senescence to shorten. An increased demand for water in response to higher transpiration rate is also expected (Kimball *et al.* 1995; Reyenga *et al.* 1999). On the other hand, higher [CO_2] may reduce transpiration in some crops by lowering stomatal conductance (Tubiello *et al.* 2000). Projected changes in rainfall patterns might positively or negatively affect crop production. In arid areas, production is likely to increase with additional rainfall, while in humid areas, more rainfall would mean either no significant change in production, or a decrease due to waterlogging, increased leaching of soil nitrogen, and increased greenhouse gas emissions (Ludwig and Asseng 2006; Grace *et al.* 2011). In irrigated agriculture, climate change scenarios are likely to affect the availability and demand for water. Irrigated agriculture occupies only one-fifth of the global cropped area but produces about two-fifths of the food supply. It is important to protect such areas in order to meet the growing demand for food. However, it is not clear whether there will be enough water in the future to meet such demand (Payero *et al.* 2009).

The effects of high [CO_2] on crop yield have been studied in open-field experiments, such as free-air carbon dioxide enrichment (FACE) experiments, and in experiments with open-top chambers (Kimball *et al.* 1997, 2002; Ewert *et al.* 1999; Tubiello *et al.* 1999). However, the influence of future climate change on the soil–plant–atmosphere system, its productivity, and its agronomic management options is difficult to predict and to quantify with field experiments alone. Therefore, process-oriented crop growth models can be useful in simulating the impact of climate change on daily crop growth and development rates throughout the growing season (Keating *et al.* 2003; Basso *et al.* 2011; Grace *et al.* 2011). The strength of these models is their ability to integrate the effects of temporal and multiple stresses on crop growth under different environmental and management conditions (Hammer and Muchow 1994; Batchelor *et al.* 2002; Basso *et al.* 2007). Many of these models have been tested using data from the FACE experiments, concentrating on the effects of high [CO_2] on crop production (Grant *et al.* 1995; Jamieson *et al.* 2000; Boote *et al.* 2011).

Crop simulation models have been applied to provide answers to practical production questions. For example, Ludwig and Asseng (2006) found that interactions between [CO_2], temperature, and rainfall were not linear and their effects on wheat yields varied with soil type and geographical locations. Simulations in subtropical south-east Queensland have shown that the effects of climate change on the production of prime hard wheat would cause reduction in grain protein under increased [CO_2] with an increase in the incidence of 'heat shock' (Reyenga *et al.* 1999). Similar results were found in South Australia for rainfed wheat (Luo *et al.* 2003). Crop simulation models have also been used to investigate the effects of wheat sowing dates as an adaptation strategy to climate change (Ghaffari *et al.* 2002). Tubiello *et al.* (2000) studied the effects of climate change on crop rotations in both irrigated and rainfed systems. They found that climate change would negatively affect crop yield unless current agronomic practices are modified, and the only cropping systems that would be able to adapt to climate change are the ones with irrigation, but they would still be dependent on irrigation water availability (Tubiello *et al.* 2000).

In Australia, agriculture is the major consumer of water, and the state of Queensland uses 2058 GL $year^{-1}$. In south-east Queensland, 78 700 ha of irrigated land is dedicated to grain cereals (Australian Bureau of Statistics 2009). Jones (2000) used probability distributions to quantify the effects of climate change on irrigation requirements in southern Australia, finding that in the next 50 years, 20–60% more irrigation water will be needed compared with current use. Future impacts of climate change and the interaction between changes in [CO_2], temperature, and rainfall are expected to be felt in irrigated agriculture, but the impacts cannot be directly measured (Ludwig and Asseng 2006). Use of simulation models to determine potential impacts of predicted climate change scenarios on irrigated systems will provide information for growers and regional water management bodies to put in place suitable strategies to accommodate changes in crop management and irrigation practices. General predictions of climate change scenarios have been formulated at the global scale by the Intergovernmental Panel for Climate Change (IPCC 2007*a*), and predictions have been made for some regions. The global climate projections of the IPCC are based on a fixed set of realistic greenhouse gas emission scenarios. The multi-model consensus is that there will be an increase in atmospheric [CO_2] and in surface air temperature, although the exact magnitudes of such increases are less certain (IPCC 2007*b*). Information is still lacking on the nature and magnitude of the impact of potential climate change scenarios at the local level and on the best strategies and crop management practices to put in place to effectively adapt to these changes. The objectives of this study were to: (*1*) simulate the effect of projected climate change on wheat yield and water use for the subtropical environment of the Darling Downs, Queensland; and (*2*) investigate the impact of changing sowing date, as an adaptation strategy to future climate change scenarios, on wheat yield and water use.

Materials and methods

Crop growth model

Simulations for different climate change and crop management scenarios (described below) were performed using DSSAT 4.5 (Decision Support Systems for Agrotechnology Transfer) (Hoogenboom *et al.* 2010), which uses the CERES crop model for wheat (Ritchie and Otter-Nacke 1985) to simulate crop development. DSSAT 4.5 is a process-oriented model that simulates crop growth and development as a response to environmental conditions (soil, weather, and atmospheric [CO_2]), genetics, and management strategies. It has an '*Environmental modifications*' procedure that allows simulation of future climate change scenarios by modifying up to eight environmental variables including: daylength (h), solar radiation (MJ m^{-2} day^{-1}), maximum and minimum daily air temperature (°C), precipitation (mm), [CO_2] (ppm), relative humidity (%), and wind speed (km day^{-1}).

Model calibration and validation

The model was calibrated and validated using data from a field experiment with wheat (*Triticum aestivum* L. cv. Lang) conducted during 2008 at the Kingsthorpe Research Station of Agri-Science Queensland, Department of Agriculture, Fisheries and Forestry. Usually, several years are used to test the model genetic coefficients. However, the choice of model calibration and evaluation depends on the objective of the study, in this case to test the model's response to climate change, in particular crop water use. Therefore, it was important to get a proper calibration and subsequent evaluation at different irrigation levels, rather than using several sites or several years but without irrigation treatments. We first used plots with no water and no nitrogen (N) stresses, testing the model under maximum potential conditions. Subsequently, we used another three treatments (termed T60, T70, T85%; see details below), which represent treatments with increasingly lower irrigation amount (T85%). These treatments

Table 1. Measured soil properties for Kingsthorpe (Queensland) and used as input for the DSSAT 4.5 model

Depth (cm)	Sand	Clay (%)	Silt	Bulk density ($g\,cm^{-3}$)	Organic C (%)	pH	Electrical conductivity ($mS\,cm^{-1}$)	Cl	N	P	SO_4-S	N ($kg\,ha^{-1}$)
									($mg\,kg^{-1}$)			
0–10	7	76	17	0.89	1.0	7.3	0.239	92	28	110	24	24.92
10–20	7	76	17	1.03	0.8	7.2	0.416	183	86	77	35	88.58
20–30	7	76	17	1.02	0.6	7.5	0.345	153	61	25	29	62.22
30–40	7	76	17	1.03	0.5	7.9	0.348	126	49	19	27	50.47
40–50	6	76	18	1.03	0.4	8.1	0.355	118	39	32	24	40.17
50–60	6	76	18	1.05	0.3	8.2	0.349	104	36	40	23	37.80
60–70	9	72	19	1.05	0.2	8.3	0.334	104	34	45	20	35.70
70–80	9	72	19	1.01	0.1	8.5	0.320	99	28	49	17	28.28
80–90	9	72	19	1.02	0.1	8.5	0.314	110	24	46	16	24.48
90–100	9	72	19	1.06	0.1	8.5	0.363	97	25	41	15	26.50
100–110	10	73	17	1.07	0.1	8.6	0.308	76	21	43	14	22.47
110–120	10	73	17	1.08	0.1	8.6	0.336	78	18	35	16	19.44

Table 2. Description of variables (temperature, [CO_2], rainfall, sowing dates, and irrigation regime) used for building simulation scenarios

Variable	Levels	Description
Temperature	0, 1, 2, 3	Future increase in air temperature (°C)
[CO_2]	380, 500, 600	Air CO_2 concentrations (ppm): current (380), and future
Rainfall	0, –30%, +20%	Future rainfall changes: 0, historical rainfall data; –30% rainfall; +20% rainfall
Sowing date	121, 130, 140, 152, 161, 171	Sowing dates (day of year): 01 May, 10 May, 20 May, 01 June, 10 June, 20 June
Irrigation regime	NI, DI, FI	No irrigation (NI), deficit irrigation (DI), full irrigation (FI)

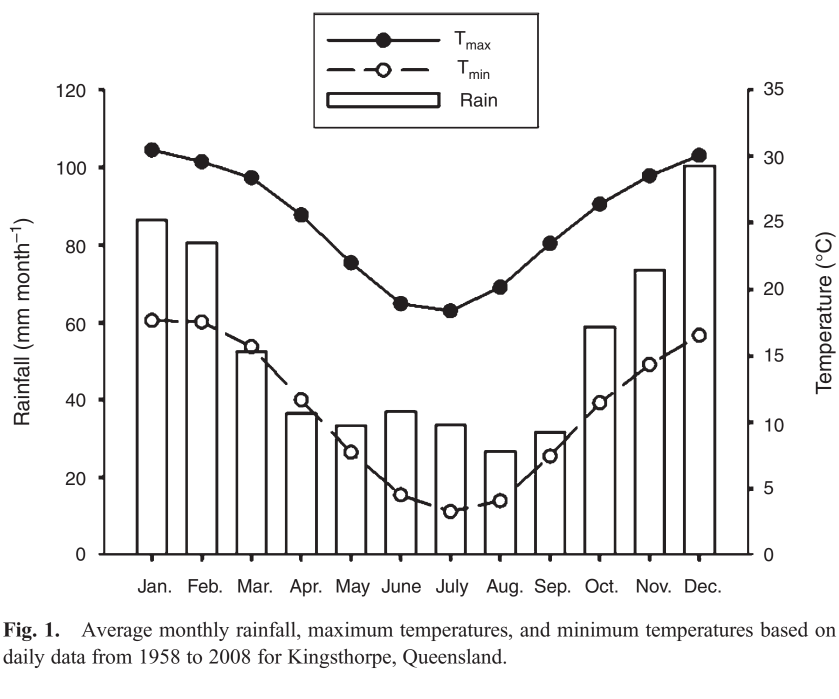

Fig. 1. Average monthly rainfall, maximum temperatures, and minimum temperatures based on daily data from 1958 to 2008 for Kingsthorpe, Queensland.

were used to evaluate the model response to different irrigation levels.

Kingsthorpe Research Station is located in southern Queensland (27°30′44.5″S; 151°46′54.5″E; 431 m above mean sea level), in a subtropical climate. The soil at the site is a Haplic, self-mulching, black Vertosol according to the Australian Soil Classification (Isbell 1996). Soil properties for the site, used as input to the model, are shown in Table 1. From this information, soil water limits needed by the model were calculated using the procedure suggested by Ritchie *et al*. (1999).

The field experiment used a randomised complete block design with four irrigation treatments and three replications, with optimal N fertiliser inputs (200 kg N ha^{-1}). The field experiment had one fully irrigated and three deficit-irrigated treatments. The four irrigation treatments (T50%, T60%, T70%, and T85%) when 50, 60, 70, or 85%, respectively, of the plant-available soil water content was depleted. The fully irrigated treatment (T50%) received 197 mm of irrigation split in six applications; the first deficit-irrigated (T60%) treatment received 154 mm in six applications; the second deficit-irrigated treatment (T70%) received 79 mm in four applications; and the third deficit-irrigated treatment (T85%) received 73 mm in three applications. Irrigations were scheduled based on weekly measurements of soil profile water content (at depth increments of 0.10 m) using the neutron probe method (Dasberg and Dalton 1985). Irrigation was applied using a solid-set sprinkler system. The crop was sown on 6 June and harvested on 10 November 2008.

Model calibration, evaluation, and simulation of different climate change and crop management scenarios were conducted using daily weather data recorded at the Oakey Weather Station by the Australian Bureau of Meteorology (www.longpaddock.qld.gov.au/silo/) for the period 1959–2008. Weather data included solar radiation (MJ m^{-2} day^{-1}), maximum and minimum air temperature (°C), and rainfall (mm day^{-1}).

The cultivar-specific genetic coefficients were obtained by calibrating the model using the T50% treatment, with measurements of developmental stages, harvested grain yield, crop biomass, soil water content, unit grain weight, and grain N.

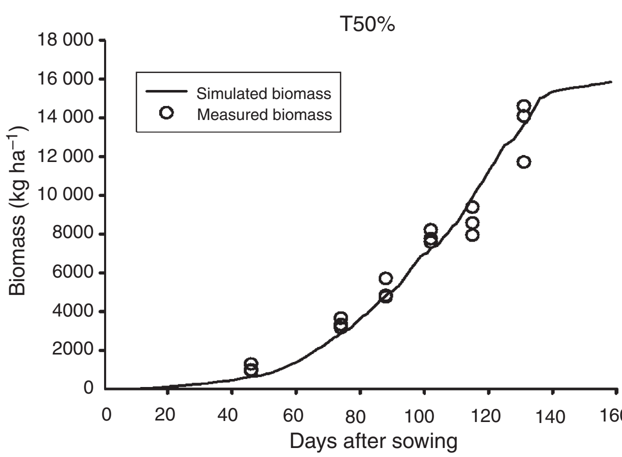

Fig. 2. Total crop biomass measured and simulated by the DSSAT 4.5 for wheat (cv. Lang) under full irrigation (T50% irrigation treatment) at Kingsthorpe, Queensland, for 2008.

The model was evaluated against measured biomass and grain yield of the deficit-irrigated treatments using the root mean square error (RMSE):

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2\right]^{1/2} \quad (1)$$

where y_i is measured value, $\hat{y}_i$ is simulated value, and n is number of pairs of measured and simulated values.

Table 3. Simulated and measured developmental stages, yield, and grain nitrogen (N) for the fully irrigated model calibration plot (T50%) at Kingsthorpe, Queensland

		Simulated	Measured
Emergence	(date)	10 June 08	14 June 08
Anthesis		23 Oct. 08	23 Oct. 08
Maturity		11 Nov. 08	10 Nov. 08
Yield	(kg ha^{-1})	3890	3897
Grain N	(%)	3.01	2.66

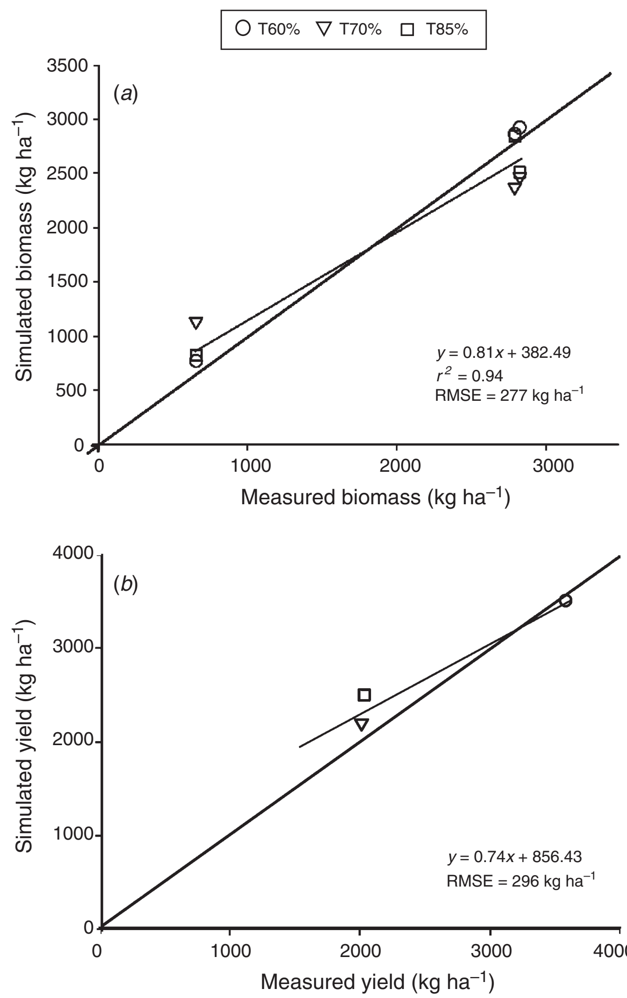

Fig. 3. Evaluation of (*a*) wheat biomass at anthesis, and (*b*) final grain yield for the T60%, T70%, and T85% treatments (irrigation applied when 60%, 70%, and 85% of the plant-available water was depleted, respectively) in 2008 at Kingsthorpe, Queensland, using the CERES-Wheat model in DSSAT 4.5.

Model outputs relevant to this study were grain yield (GY, kg ha^{-1}), evapotranspiration (ET, mm), biomass, days to maturity and to anthesis (after sowing), and '*stress days*.' The model calculated two different effects of water stress, one affecting expansive growth and the other affecting growth and biomass production. First, the model compared the potential transpiration and potential root water uptake. When plants were well irrigated, potential root water uptake was higher than potential transpiration. As the soil water was depleted, potential root water uptake decreased until the first threshold that modulated expansive growth was met. As the soil continued to dry to the point where potential transpiration was higher than potential root water uptake, the second threshold that affected crop growth and biomass production was met (Jones *et al.* 2003). In this study, '*stress days*' represented the number of days when this second threshold was met. From the simulated GY and ET, water-use efficiency (WUE, kg ha^{-1} mm^{-1}) was calculated as:

$$\mathrm{WUE} = \mathrm{GY}/\mathrm{ET} \tag{2}$$

Simulation scenarios

In this study, the consequences of uncertainty in future climate projections and crop management on water use and crop yield were evaluated. Natural climate variability, model uncertainty, and scenario uncertainty are the three sources of uncertainty in climate projections. Of these, model and scenario uncertainty play a dominant role at time horizons of 30–50 years and beyond (Hawkins and Sutton 2009). The multi-model climate projections from the IPCC Coupled Model Intercomparison Project (CMIP3: www-pcmdi.llnl.gov/ipcc/about_ipcc.php) for the period 2030–2070 were used in this study. These projections were based on the low (B1), medium (A1B), and high (A1FI) emission scenarios defined in the IPCC Special Report on Emission Scenarios (Nakicenovic *et al.* 2000). The projected changes in temperature and precipitation differ among global circulation models (GCMs) and emission scenarios. In order to encompass the climate projection uncertainty, it is informative to consider the range of projected change that is implied by the spread of outcomes from all models and all emission scenarios.

Table 4. Days of stress at anthesis (DOS), grain yield (GY, kg ha^{-1}), plant transpiration (Tr, mm), and soil evaporation (Ev, mm) for the first planting date (01 May) at the different combinations of temperature, rainfall, [CO_2], and irrigation regime

NI, No irrigation; DI, deficit irrigation; FI, full irrigation. DOS for the NI and DI scenarios only

Temp. (°C)	Rainfall	[CO_2] (ppm)	DOS	NI			DI			FI		
				GY	Tr	Ev	GY	Tr	Ev	GY	Tr	Ev
0	0	380	3	2910	150	164	4686	304	155	5247	395	159
1	0	380	3	2903	155	156	4719	314	142	5329	408	146
2	0	380	3	2866	159	152	4790	324	133	5424	426	136
3	0	380	3	2859	165	149	4930	337	127	5584	454	128
0	–30%	380	4	2339	110	155	4342	262	155	5240	394	157
1	–30%	380	4	2292	113	149	4369	271	143	5317	408	143
2	–30%	380	4	2242	116	146	4445	279	136	5409	426	133
3	–30%	380	4	2188	120	144	4606	289	131	5566	454	126
0	20%	380	3	3241	178	167	4814	323	156	5252	395	160
1	20%	380	3	3251	183	158	4851	334	142	5335	408	147
2	20%	380	3	3218	189	152	4920	346	133	5433	426	136
3	20%	380	3	3221	196	149	5051	362	127	5601	454	129
0	0	500	3	3498	156	160	5326	307	148	5751	380	157
1	0	500	4	3479	161	151	5323	318	135	5799	395	143
2	0	500	3	3410	165	147	5357	329	127	5864	414	134
3	0	500	3	3385	171	144	5476	341	122	6027	441	127
0	–30%	500	4	2869	115	151	5054	270	147	5741	381	154
1	–30%	500	4	2807	118	145	5039	279	135	5784	395	140
2	–30%	500	4	2741	121	142	5083	288	128	5846	414	131
3	–30%	500	4	2668	125	141	5210	297	123	5988	441	125
0	20%	500	3	3862	184	161	5440	323	150	5757	380	158
1	20%	500	4	3837	189	152	5436	335	137	5814	395	145
2	20%	500	4	3772	195	147	5464	348	128	5877	414	135
3	20%	500	3	3765	202	144	5572	363	123	6037	441	129
0	0	600	4	3995	160	156	5831	308	144	6160	370	155
1	0	600	4	3947	165	148	5790	319	132	6183	385	142
2	0	600	4	3855	170	143	5789	330	124	6215	404	133
3	0	600	3	3812	175	141	5890	342	119	6364	431	126
0	–30%	600	4	3323	119	149	5601	275	141	6149	370	153
1	–30%	600	4	3245	122	142	5555	284	130	6160	385	139
2	–30%	600	4	3166	125	139	5562	292	123	6190	404	130
3	–30%	600	4	3078	129	137	5662	300	119	6336	431	124
0	20%	600	3	4383	188	157	5919	322	147	6163	369	156
1	20%	600	4	4328	194	147	5884	334	134	6199	385	143
2	20%	600	4	4237	199	143	5881	347	125	6234	403	134
3	20%	600	4	4212	206	140	5978	363	120	6375	431	128

In the present study, the 10% of future simulations resulting in the least amount of climate change (10th percentile) and the 10% of future simulations resulting in the largest amount of climate change (90th percentile) relative to the period 1980–2000 were used to constrain the bounds of projected climate uncertainty.

The projected mid-Century temperature change for autumn (March, April, May) and winter (June, July, August) for south-east Queensland ranges from <1°C (10th percentile for the low-emission scenario) to >3°C (90th percentile for the high-emission scenario). For precipitation change, the projected range is from ~30% reduction to 20% increase (CSIRO and BoM 2007). In addition to the uncertainty of temperature and precipitation described above, the underlying uncertainty in projected [CO_2] was taken into account by considering a range of values corresponding to: current atmospheric [CO_2] (~380 ppm), projected [CO_2] with medium emissions (A1B scenario) (~500 ppm by mid-Century), and projected [CO_2] with high emissions (A1Fl scenario) (~600 ppm by mid-Century) (IPCC 2007*a*).

The variables (temperature, [CO_2], rainfall, sowing dates, and irrigation regime) used for building the simulation scenarios are described in Table 2. Simulations for the three irrigation regimes were conducted based on several assumptions. For the no irrigation (NI) regime, no irrigation was applied. For the deficit-irrigation (DI) regime, 25 mm was applied at sowing, 22 mm at first node, 51 mm around the third-node stage, 13 mm at first awn, and two irrigations (39 and 34 mm) just before anthesis. For the full-irrigation (FI) regime, irrigation was applied using the '*Automatic when required*' option of DSSAT 4.5, which applied irrigation when 50% of available soil water in the crop root-zone was depleted.

The temperature change (0°C, 1°C, 2°C, or 3°C) was added to the observed Tmax and Tmin for each day of the simulation. Similarly, precipitation was modified by the percentage change (–30%, 0%, or +20%); since the observational data specify a numeric value at each point in time, trace events were treated in the same way as all other precipitation events.

Table 5. Days of stress at anthesis (DOS), grain yield (GY, kg ha^{-1}), plant transpiration (Tr, mm), and soil evaporation (Ev, mm) for the second planting date (10 May) at the different combinations of temperature, rainfall, [CO_2], and irrigation regime

NI, No irrigation; DI, deficit irrigation; FI, full irrigation. DOS for the NI and DI scenarios only

Temp.	Rainfall	[CO_2]	DOS	NI			DI			FI		
(°C)	(mm)	(ppm)		GY	Tr	Ev	GY	Tr	Ev	GY	Tr	Ev
0	0	380	2	2688	135	168	4459	285	164	4813	365	174
1	0	380	2	2696	140	158	4536	298	146	4931	380	155
2	0	380	2	2679	145	153	4659	310	135	5102	399	142
3	0	380	3	2701	150	151	4809	323	129	5302	426	133
0	–30%	380	2	2140	100	155	4223	248	161	4808	365	171
1	–30%	380	3	2116	102	149	4291	261	145	4925	380	152
2	–30%	380	3	2091	106	145	4402	271	135	5093	399	140
3	–30%	380	3	2060	109	144	4560	281	130	5285	426	132
0	20%	380	2	2994	160	172	4541	302	166	4814	365	176
1	20%	380	2	3012	166	161	4623	315	148	4932	380	156
2	20%	380	2	3017	172	154	4749	330	136	5109	399	143
3	20%	380	2	3056	180	151	4898	346	129	5312	426	135
0	0	500	2	3254	140	164	5035	286	159	5291	350	171
1	0	500	2	3250	146	154	5102	300	141	5400	367	152
2	0	500	2	3215	151	148	5203	314	130	5554	386	140
3	0	500	2	3235	157	146	5330	326	124	5740	414	132
0	–30%	500	2	2654	104	153	4867	254	154	5286	350	168
1	–30%	500	2	2620	107	146	4921	267	138	5394	367	149
2	–30%	500	3	2574	111	142	5010	278	128	5544	387	137
3	–30%	500	3	2533	114	141	5137	287	123	5712	413	130
0	20%	500	1	3582	166	167	5108	300	161	5290	350	173
1	20%	500	2	3587	173	155	5175	315	143	5403	367	153
2	20%	500	2	3573	179	148	5280	330	131	5563	386	141
3	20%	500	2	3599	186	146	5408	347	125	5749	414	133
0	0	600	1	3722	144	161	5499	286	155	5681	338	169
1	0	600	2	3711	150	150	5541	300	138	5778	357	150
2	0	600	2	3663	155	144	5620	314	127	5909	377	138
3	0	600	2	3669	161	142	5730	328	121	6128	404	131
0	–30%	600	2	3089	107	151	5364	257	150	5678	339	166
1	–30%	600	2	3046	110	144	5397	270	134	5770	357	148
2	–30%	600	2	2990	114	139	5467	281	124	5897	377	136
3	–30%	600	2	2945	118	138	5569	291	120	6058	404	128
0	20%	600	1	4067	170	163	5560	298	158	5680	338	170
1	20%	600	1	4057	177	151	5607	313	140	5777	357	152
2	20%	600	2	4028	184	144	5689	328	129	5925	377	139
3	20%	600	2	4038	191	142	5798	346	123	6098	404	132

Results

Monthly long-term averages of rainfall and maximum and minimum air temperatures are shown in Fig. 1. Results of model calibration are shown in Fig. 2 and Table 3. Emergence date was simulated 4 days earlier than the measured one. Anthesis date was well simulated, while the maturity date was simulated 1 day later. Grain yield simulation was 222 kg ha^{-1} lower than the measured one. Grain N difference between simulated and measured was 0.35% (Table 3), and crop biomass was well simulated as shown in Fig. 2. Results of model evaluation are shown in Fig. 3*a*, *b*. There was good agreement between simulated and measured biomass at anthesis (Fig. 3*a*), with a RMSE of 277 kg ha^{-1}. Grain yield was well simulated for the three irrigation treatments, with an overall RMSE of 296 kg ha^{-1}.

The effects of temperature, rainfall, and [CO_2] on yield, plant transpiration, and soil evaporation for the six sowing dates and three irrigation regimes are shown in Tables 4–9. Overall, GY increased from NI to FI for all sowing dates and all of the different temperature, rainfall, and [CO_2] combinations. Grain yield decreased from the first to the last sowing date (Tables 4–9). Stress days increased from the first to the last sowing date, with a minimum of one stress day in May to a maximum of eight in June.

An increase in temperature did not reduce grain yield significantly under the NI scenario for all sowing dates, but it increased GY under the DI and FI scenarios for all sowing dates (Tables 4–9). Reduction in rainfall (–30%) decreased GY for the NI scenario at all three [CO_2], while an increase in rainfall (+20%) increased GY. Grain yield increased under higher [CO_2]. Overall, GY varied between 1793 and 4383 kg ha^{-1} for the NI, 2986 and 5978 kg ha^{-1} for the DI, and 3858 and 6375 kg ha^{-1} for the FI irrigation scenario. The high values of GY were obtained for the first sowing date. Plant transpiration increased from the NI to the FI regime for all scenarios. Transpiration ranged between 89 and 206 mm for the NI, 201 and 363 mm for the DI, and 266 and 454 mm for the FI scenario (Tables 4–9). Soil evaporation varied

Table 6. Days of stress at anthesis (DOS), grain yield (GY, kg ha^{-1}), plant transpiration (Tr, mm, and soil evaporation (Ev, mm) for the third planting (20 May) date at the different combinations of temperature, rainfall, [CO_2], and irrigation regime

NI, No irrigation; DI, deficit irrigation; FI, full irrigation. DOS for the NI and DI scenarios only

Temp. (°C)	Rainfall (mm)	[CO_2] (ppm)	DOS	NI GY	NI Tr	NI Ev	DI GY	DI Tr	DI Ev	FI GY	FI Tr	FI Ev
0	0	380	2	2509	125	170	4247	268	173	4423	337	191
1	0	380	2	2499	129	159	4306	282	152	4526	354	167
2	0	380	2	2502	133	153	4407	294	139	4668	370	153
3	0	380	3	2537	139	150	4617	310	129	4924	398	140
0	–30%	380	2	2048	94	154	4140	237	166	4419	337	188
1	–30%	380	3	2019	97	147	4189	250	147	4521	353	164
2	–30%	380	3	1996	100	143	4281	261	136	4660	370	150
3	–30%	380	3	1990	103	141	4478	274	127	4909	398	138
0	20%	380	2	2770	147	176	4292	282	177	4425	337	192
1	20%	380	2	2772	152	163	4355	296	155	4528	353	168
2	20%	380	3	2786	158	156	4459	310	141	4672	370	154
3	20%	380	3	2848	165	152	4674	329	130	4941	398	142
0	0	500	1	3026	129	167	4760	266	169	4866	320	188
1	0	500	2	3016	134	156	4831	283	148	4979	340	163
2	0	500	3	3008	139	149	4917	296	135	5113	358	149
3	0	500	3	3038	145	146	5114	313	125	5365	386	138
0	–30%	500	2	2533	98	153	4691	239	162	4863	321	185
1	–30%	500	2	2487	101	145	4747	254	142	4976	340	161
2	–30%	500	3	2456	104	140	4823	266	131	5105	358	148
3	–30%	500	3	2443	108	138	5000	279	122	5343	386	136
0	20%	500	1	3304	151	172	4790	278	174	4868	320	190
1	20%	500	2	3311	158	158	4872	295	151	4981	340	165
2	20%	500	2	3317	165	150	4966	309	137	5120	357	151
3	20%	500	2	3383	172	146	5166	329	127	5376	386	139
0	0	600	1	3460	131	165	5161	263	168	5227	308	186
1	0	600	2	3451	138	153	5249	282	145	5348	330	161
2	0	600	2	3427	143	146	5320	296	132	5473	348	148
3	0	600	2	3449	149	143	5501	313	123	5705	377	137
0	–30%	600	1	2946	100	151	5113	240	160	5224	308	183
1	–30%	600	2	2890	103	143	5183	256	139	5345	330	159
2	–30%	600	2	2848	107	138	5243	268	128	5460	348	146
3	–30%	600	3	2833	112	135	5408	281	119	5683	377	135
0	20%	600	1	3747	154	170	5180	273	172	5228	307	187
1	20%	600	1	3754	162	155	5277	292	148	5349	329	163
2	20%	600	2	3751	169	146	5359	307	135	5477	348	149
3	20%	600	2	3817	177	143	5545	328	125	5720	377	138

Table 7. Days of stress at anthesis (DOS), grain yield (GY, kg ha^{-1}), plant transpiration (Tr, mm), and soil evaporation (Ev, mm) for the fourth planting (01 June) date at the different combinations of temperature, rainfall, [CO_2], and irrigation regime

NI, No irrigation; DI, deficit irrigation; FI, full irrigation. DOS for the NI and DI scenarios only

Temp. (°C)	Rainfall (mm)	[CO_2] (ppm)	DOS	NI GY	NI Tr	NI Ev	DI GY	DI Tr	DI Ev	FI GY	FI Tr	FI Ev
0	0	380	6	2338	119	171	3301	233	199	4129	316	206
1	0	380	6	2330	121	160	3341	240	183	4200	330	183
2	0	380	6	2336	124	153	3390	250	169	4306	346	163
3	0	380	6	2359	130	149	3519	265	159	4559	373	149
0	–30%	380	6	1946	91	153	2986	201	195	4126	316	204
1	–30%	380	6	1923	93	145	3009	206	182	4196	330	180
2	–30%	380	6	1912	95	140	3038	213	172	4300	346	161
3	–30%	380	6	1899	98	138	3138	225	163	4542	373	146
0	20%	380	6	2544	139	179	3469	248	201	4132	316	208
1	20%	380	6	2538	141	167	3510	256	183	4202	330	184
2	20%	380	7	2549	145	158	3564	267	168	4305	346	165
3	20%	380	6	2611	153	153	3704	284	157	4551	373	149
0	0	500	7	2811	122	169	3859	234	194	4541	298	204
1	0	500	7	2794	125	158	3900	243	176	4622	315	179
2	0	500	7	2798	129	150	3942	255	162	4727	333	160
3	0	500	7	2820	135	146	4073	271	150	4972	361	146
0	–30%	500	7	2400	94	152	3547	206	190	4539	299	201
1	–30%	500	7	2369	96	144	3575	213	175	4620	315	177
2	–30%	500	7	2352	99	138	3602	222	163	4723	334	158
3	–30%	500	6	2334	102	135	3701	235	153	4968	361	143
0	20%	500	7	3026	141	177	4012	246	197	4542	298	206
1	20%	500	7	3023	145	164	4058	257	177	4624	315	182
2	20%	500	7	3031	150	155	4108	270	162	4728	333	162
3	20%	500	7	3094	158	149	4245	288	149	4973	361	147
0	0	600	8	3205	124	168	4304	232	191	4876	285	203
1	0	600	8	3189	127	157	4353	244	172	4964	303	178
2	0	600	8	3183	132	148	4388	257	156	5066	323	159
3	0	600	8	3210	138	143	4509	275	145	5309	352	144
0	–30%	600	7	2780	96	152	4009	208	186	4875	285	199
1	–30%	600	7	2740	98	143	4044	217	170	4964	304	174
2	–30%	600	7	2723	101	137	4067	228	156	5065	324	155
3	–30%	600	7	2697	105	134	4159	242	146	5307	352	142
0	20%	600	7	3432	142	176	4452	244	194	4877	284	204
1	20%	600	8	3428	147	162	4501	256	173	4965	303	180
2	20%	600	8	3439	154	151	4552	271	157	5066	323	160
3	20%	600	7	3504	162	146	4676	290	144	5314	352	145

between 133 and 180 mm for the NI, 119 and 204 mm for the DI, and 124 and 220 mm for the FI scenario.

For the three irrigation scenarios, GY increased linearly with [CO_2] in the range 380–600 ppm (Fig. 4*a*). Yield increased from 2411 to 3310 kg ha^{-1} for the NI scenario, from 3942 to 4917 kg ha^{-1} for the DI scenario, and from 4574 to 5345 kg ha^{-1} for the FI scenario. The highest GY increase was simulated for the NI scenario and the lowest for the FI scenario (Fig. 4*a*). On the other hand, ET decreased slightly with an increase in [CO_2], from 430 to 424 mm for the DI scenario and from 528 to 499 mm for the FI scenarios, but increased slightly from 285 to 287 mm for the NI scenario (Fig. 4*b*). However, these simulated changes in ET with an increase in [CO_2], especially for the DI (6 mm) and NI (2 mm) scenarios, are so small that in practical terms it can be assumed that no significant change in ET actually occurred. The difference for the FI scenario was 29 mm, which is more significant, representing 5.5% of the ET under the current [CO_2] scenario.

Grain yield increased almost linearly with ET for each [CO_2], with higher yields corresponding to higher [CO_2] (Fig. 5*a*). The slope of the line in Fig. 5*a* increased with [CO_2] from 8.8 kg ha^{-1} mm^{-1} at 380 ppm to 11.1 kg ha^{-1} mm^{-1} at 600 ppm. The WUE for each irrigation scenario increased linearly with [CO_2], and scenarios with more irrigation tended to have lower WUE (Fig. 5*b*). Under the current [CO_2] (380 ppm), WUE was 8.4 kg ha^{-1} mm^{-1} for the NI scenario, 9.1 kg ha^{-1} mm^{-1} for the DI scenario, and 8.6 kg ha^{-1} mm^{-1} for the FI scenario. At 500 ppm, simulated WUE increased to 10.1, 10.5, and 9.7 kg ha^{-1} mm^{-1} for the NI, DI, and FI scenarios, respectively. At 600 ppm, WUE further increased to 11.5, 11.6, and 10.6 kg ha^{-1} mm^{-1} for the NI, DI, and FI scenarios, respectively.

Discussion

The long-term simulation of crop growth and development allowed us to study the effects of projected climate change on

Table 8. Days of stress at anthesis (DOS), grain yield (GY, kg ha^{-1}), plant transpiration (Tr, mm), and soil evaporation (Ev, mm) for the fifth planting (10 June) date at the different combinations of temperature, rainfall, [CO_2], and irrigation regime

NI, No irrigation; DI, deficit irrigation; FI, full irrigation. DOS for the NI and DI scenarios only

Temp. (°C)	Rainfall (mm)	[CO_2] (ppm)	DOS	NI			DI			FI		
				GY	Tr	Ev	GY	Tr	Ev	GY	Tr	Ev
0	0	380	5	2276	116	170	3252	231	200	3952	303	214
1	0	380	5	2264	118	160	3275	240	183	3990	316	192
2	0	380	5	2258	121	152	3343	248	169	4091	330	174
3	0	380	5	2235	126	148	3437	263	158	4304	359	157
0	–30%	380	5	1877	89	153	3006	203	192	3949	303	210
1	–30%	380	5	1867	91	144	3014	211	177	3987	316	188
2	–30%	380	5	1856	93	139	3067	218	166	4087	331	170
3	–30%	380	3	1824	95	137	3133	229	157	4294	358	153
0	20%	380	4	2486	135	179	3387	245	204	3954	303	217
1	20%	380	5	2474	138	166	3421	253	185	3992	316	193
2	20%	380	5	2484	141	157	3488	263	170	4092	331	175
3	20%	380	5	2470	147	153	3601	281	157	4301	358	158
0	0	500	5	2744	118	170	3769	230	197	4350	285	212
1	0	500	5	2717	121	158	3806	240	178	4394	300	189
2	0	500	6	2711	125	150	3873	251	163	4498	317	170
3	0	500	6	2675	130	146	3979	269	150	4715	346	153
0	–30%	500	5	2315	92	152	3528	206	188	4347	285	208
1	–30%	500	6	2293	94	143	3547	215	172	4391	301	186
2	–30%	500	6	2278	96	137	3602	224	159	4498	317	168
3	–30%	500	6	2239	99	135	3681	238	148	4713	347	150
0	20%	500	4	2950	137	177	3911	241	201	4352	284	214
1	20%	500	5	2933	141	164	3942	252	181	4396	300	191
2	20%	500	5	2943	145	154	4010	264	165	4501	317	173
3	20%	500	5	2924	152	150	4134	284	150	4714	346	155
0	0	600	4	3128	120	169	4197	227	195	4672	271	211
1	0	600	5	3090	123	157	4237	239	175	4722	288	187
2	0	600	6	3084	127	148	4302	252	159	4829	306	169
3	0	600	6	3047	133	144	4416	271	144	5046	337	151
0	–30%	600	5	2690	94	151	3949	206	186	4670	272	206
1	–30%	600	6	2657	96	142	3982	218	168	4720	289	184
2	–30%	600	6	2638	99	136	4041	228	154	4831	307	166
3	–30%	600	6	2590	102	133	4126	243	142	5052	338	149
0	20%	600	4	3338	138	176	4316	236	199	4673	270	213
1	20%	600	5	3322	143	162	4358	250	178	4723	287	190
2	20%	600	5	3333	148	152	4433	263	161	4834	306	171
3	20%	600	5	3308	155	147	4561	285	145	5053	337	153

wheat production and water use for the subtropical environment of the Darling Downs, Queensland. We were also able to evaluate the impact of changing sowing dates and applying different irrigation management regimes as potential adaptation strategies for future climate change scenarios. Our results showed that both sowing date and irrigation practice influenced wheat yield and water use.

Our simulations showed that higher temperatures did not reduce GY significantly, because clay soils are less susceptible to the effects of higher temperatures, since its negative effect in terms of reduced length of crop growing season is compensated by an increase in harvest index as demonstrated by Ludwig and Asseng (2006). A reduction in rainfall of 30% caused a decline in GY, especially under the NI scenario and mildly under DI, whereas under FI it was unaffected. Under NI, a reduction in rainfall during the growing season limits top growth and the production of an adequate leaf area, and therefore causes biomass to be translocated later to the grains (Asseng and Van Herwaarden 2003). This area of Queensland had an average growing season rainfall of 262 mm for the 50 years of weather data (Fig. 1); therefore, stored water before sowing is important because under non-irrigation, it is used by crops later in the season.

However, GY tended to decrease from early to later sowing dates, since later sowing dates moved the flowering period towards higher average temperatures, which negatively affected wheat crop yield. Crop phenology accelerated at higher temperatures, which reduced yield. Such acceleration caused smaller plants, shorter reproductive phase, and less radiation interception during the crop growing season (Hatfield *et al.* 2011). Later planting dates moved the anthesis and grain-filling stages towards warmer temperatures with higher risk of water stress. In fact, for the first three sowing dates (1, 10, and 20 May) there were, on average, only three 'stress days', whereas for the last three sowing dates (1, 10, and 20 June) there were, on average, seven stress days (Tables 4–9) for the NI and DI scenarios. Water stress at flowering can severely reduce seed set or influence grain filling, causing low yield (Passioura 2006). For the DI scenario, irrigation was applied around anthesis, but it is possible that the

Table 9. Days of stress at anthesis (DOS), grain yield (GY, kg ha^{-1}), plant transpiration (Tr, mm), and soil evaporation (Ev, mm) for the sixth planting (20 June) at the different combinations of temperature, rainfall, [CO_2], and irrigation regime

NI, No irrigation; DI, deficit irrigation; FI, full irrigation. DOS for the NI and DI scenarios only

Temp. (°C)	Rainfall (mm)	[CO_2] (ppm)	DOS	NI			DI			FI		
				GY	Tr	Ev	GY	Tr	Ev	GY	Tr	Ev
0	0	380	6	2241	117	172	3377	240	196	3862	298	218
1	0	380	7	2214	118	162	3354	247	179	3888	309	197
2	0	380	7	2192	120	155	3402	256	165	3950	321	181
3	0	380	6	2254	132	153	3577	279	155	4317	368	163
0	–30%	380	5	1834	90	154	3181	213	186	3858	298	213
1	–30%	380	6	1816	90	147	3151	220	171	3883	309	193
2	–30%	380	6	1793	92	141	3194	228	159	3948	322	177
3	–30%	380	6	1795	97	144	3309	244	153	4318	368	159
0	20%	380	6	2465	137	180	3485	252	201	3864	298	220
1	20%	380	6	2433	138	169	3469	260	183	3891	309	199
2	20%	380	7	2411	141	160	3517	268	168	3954	322	183
3	20%	380	6	2503	156	158	3712	296	156	4322	368	164
0	0	500	6	2702	120	171	3869	236	194	4249	280	216
1	0	500	7	2660	121	161	3845	246	176	4282	294	195
2	0	500	7	2628	124	152	3891	255	161	4347	308	178
3	0	500	6	2697	137	150	4076	282	149	4733	356	160
0	–30%	500	6	2265	93	153	3674	214	184	4247	281	211
1	–30%	500	7	2235	93	145	3639	222	168	4279	294	190
2	–30%	500	7	2204	95	139	3686	232	154	4343	308	173
3	–30%	500	6	2212	102	141	3830	251	145	4724	357	156
0	20%	500	6	2919	139	179	3959	246	199	4251	280	217
1	20%	500	6	2883	141	167	3950	256	180	4284	293	196
2	20%	500	7	2859	144	157	4003	267	164	4353	308	179
3	20%	500	6	2961	161	154	4212	297	150	4754	357	161
0	0	600	6	3082	122	170	4265	232	193	4564	266	215
1	0	600	7	3031	123	159	4248	243	174	4602	281	193
2	0	600	7	2989	127	151	4289	254	159	4669	297	176
3	0	600	6	3063	140	148	4474	282	145	5062	347	157
0	–30%	600	6	2630	95	153	4088	213	183	4562	267	209
1	–30%	600	7	2593	96	145	4045	223	166	4600	282	189
2	–30%	600	7	2552	98	138	4086	233	152	4666	298	172
3	–30%	600	6	2566	105	139	4238	254	141	5046	347	154
0	20%	600	5	3297	140	178	4332	240	198	4564	266	216
1	20%	600	6	3257	143	166	4324	252	178	4604	281	194
2	20%	600	7	3233	147	155	4383	264	162	4677	297	177
3	20%	600	6	3340	164	152	4605	296	147	5094	347	159

irrigation depth applied for the June sowing dates was not enough to meet crop water demand and avoid water stress at that sensitive stage. The FI scenario, on the other hand, was set to irrigate whenever the crop depleted 50% of the plant-available water content, and therefore, the crop was not stressed at any stage. The reduction in GY for the later sowing dates for this scenario was, therefore, mainly due to the shortening of growing season length.

Our results showed that an increase in atmospheric [CO_2] from 380 to 600 ppm would increase wheat grain yields by 17%, 25%, and 37% for the FI, DI, and NI scenarios, respectively (Fig. 4*a*). Kimball *et al.* (1992) suggested that higher [CO_2] would lead to partial stomatal closure, reducing transpiration and increasing leaf temperature. However, the increase in leaf temperature would then increase internal water vapour pressure, leading to an increase in transpiration, which would counterbalance the initial effect of increased [CO_2] on stomatal closure. These results agree with those of Ludwig and Asseng (2006), who found a yield increase of 31% by increasing [CO_2] to 700 ppm in a water-limited environment. Also, Reyenga *et al.* (1999) reported a grain yield increase of 26–37% under increased [CO_2] in south-east Queensland.

The decrease in ET at higher [CO_2] for the irrigated scenarios agrees with the findings of Andre and du Cloux (1993), who found a reduction in wheat transpiration of 8% at double [CO_2], and with those of Boote *et al.* (1997), who using a crop simulation model found that increased [CO_2] reduced ET by 6–8% for irrigated sites and 4% for rainfed sites. In our study, doubling [CO_2] decreased ET by 6% and 1% for the FI and DI scenarios, respectively, but slightly increased ET by 0.07% for the NI scenario. The slight increase for the NI scenario could be due to changes in the pattern and timing of crop water use as [CO_2] increased. This can be explained because once the stomata are closed as a result of depleted soil water, elevated [CO_2] has no effect on ET; and if soil water is limiting over the crop growing season, the total ET will not be affected (Kimball 2012). Under deficit-irrigated conditions, the onset of crop stress as soil water content is depleted normally causes a decline in the rate of crop water use. Under such conditions, it has been suggested that the impact of high [CO_2]

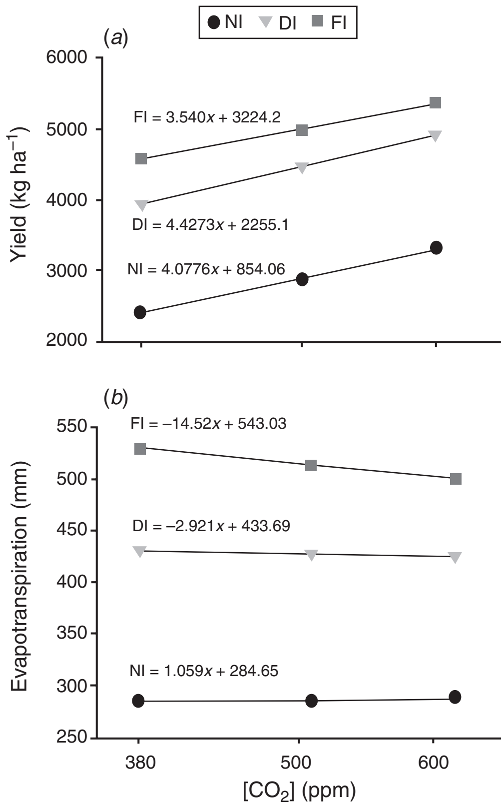

Fig. 4. Relationships between (*a*) grain yield and atmospheric [CO_2], and (*b*) evapotranspiration and atmospheric [CO_2] for three irrigation regimes (NI, no irrigation; DI, deficit irrigation; FI, full irrigation). Each scenario was run at four temperature levels, six sowing dates, and three rainfall changes. Each point represents the average of 50 years simulation for each combination.

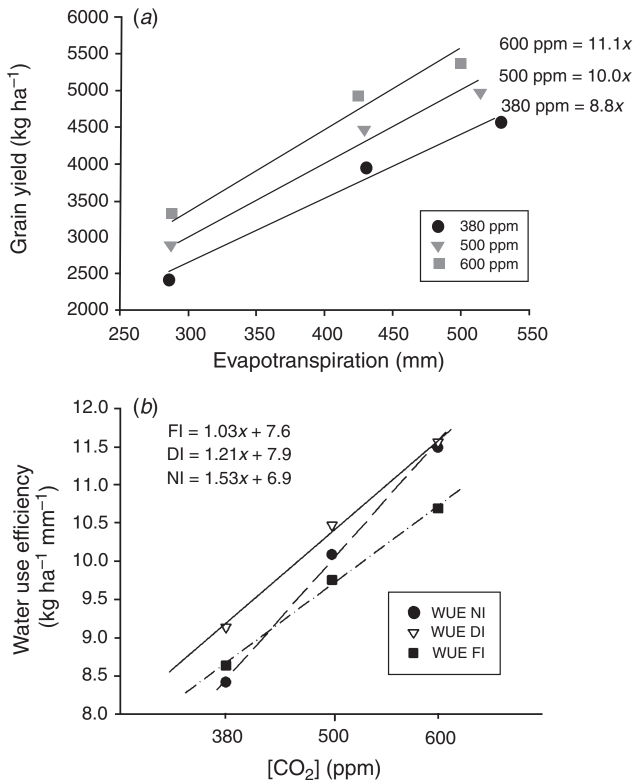

Fig. 5. Relationship between (*a*) grain yield and evapotranspiration for three atmospheric [CO_2] levels, and (*b*) water-use efficiency and atmospheric [CO_2] for three irrigation regimes (NI, no irrigation; DI, deficit irrigation; FI, full irrigation) for wheat at Kingsthorpe, Queensland.

would be to increase soil water content (Hatfield *et al.* 2011). Under the DI scenario, the timing and depth of irrigation applied influenced the water use under increasing [CO_2]. For this scenario, the crop experienced severe water stress during anthesis because the amount of water applied at that stage was not sufficient and affected the magnitude and pattern of crop water use. The implication of these findings is that, under increased [CO_2], the current timing of irrigation applications will need to be adjusted to avoid crop stress during anthesis, which could have a detrimental effect on crop yield.

The slope of the relationship between GY and ET was 8.8 kg ha^{-1} mm^{-1} at 380 ppm and 11.1 kg ha^{-1} mm^{-1} at 600 ppm (Fig. 5*a*). Therefore, increasing [CO_2] from 380 to 600 ppm increased the slope of the relationship by 26%. Figure 5*b* shows that increasing [CO_2] from 380 to 600 ppm increased WUE by 37% for the NI, by 27% for the DI, and by 23% for the FI scenario. These findings agree with results reported by Boote *et al.* (1997) and Allen *et al.* (2003) on soybean and wheat. For the DI and NI scenarios, the positive impact of increased [CO_2] on WUE was mostly due to an increase in crop yield, since the corresponding change in crop ET was quite small. For the FI scenario, on the other hand, the increase in WUE as [CO_2] increased was due to the combination of higher yield and lower ET. As has previously been suggested, increasing [CO_2] reduces crop stomatal conductance, decreasing ET and, consequently, conserving soil water. Wall *et al.* (2006) found that in wheat, such a mechanism enhanced yield, growth, and photosynthesis. In fully irrigated crops, however, Ottman *et al.* (2001) did not find such positive effects. Ritchie and Basso (2008) underlined the crucial role of agronomic management in increasing WUE. They showed that yield increase due to improved management will also lead to a higher WUE when water supply is not limited.

One limitation of this study is the implicit assumption that climate change would affect local variables (i.e. temperature and precipitation) simply by shifting the means of their distributions. The climate change approach adopted in this study (the difference between current and projected future climate is added to individual historical weather variables) is known as the 'Delta method' and is widely used in hydrological climate-impact studies (e.g. Markoff and Cullen 2008; Buytaert *et al.* 2009; Elsner *et al.* 2010; O'Leary *et al.* 2011). Although basing future climate scenarios on historical climate is an approach that has been previously employed (O'Leary *et al.* 2011), it is recognised that such an approach may not be entirely accurate. Future climate scenarios might have more variable rainfall and temperature, which would certainly affect crop production (Mearns *et al.* 1997). However, there is little climate modelling consensus about the exact nature of such higher order, climate-variable changes. An alternative approach to simulate future climate in this study would have been to employ dynamical or a more sophisticated statistical downscaling of GCMs. Such an approach, however, would either be prohibitively computationally expensive (in the case of comprehensive dynamical downscaling) or highly model-dependent, and at any rate would add an additional aspect of uncertainty to the climate projections. Using historical weather data and modifying the rainfall, temperature, and [CO_2] values, however, allowed us to investigate the effect of climate projection uncertainty and show both the interaction between those factors and their separate effects on crop development and water use.

Conclusions

This study highlighted the effects of possible future climate change on crop grain yield and water use in south-east Queensland. Sowing dates and irrigation practices influenced wheat yield and water use. Early sowing dates and targeted deficit irrigation when water is limited are two adaptation strategies for future climate change scenarios. Later sowing dates showed the lowest yield response due to an increase in consecutive days of water stress around anthesis.

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