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Improving productivity of Australian wheat by adapting sowing date and genotype phenology to future climate

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ABSTRACT

With global food demand predicted to grow by 50–80% by 2050, timely strategies are required to best adapt to the projected changes in agriculture. In this study, we illustrated how adaptation strategies not requiring additional inputs (sowing date and genotype choice) could be used to minimise the impact of projected stresses and raise wheat productivity in Australia. Yield and abiotic stresses impacting productivity of wheat crops were quantified *in silico* for the 1990s (1976–2005) and the 2050s (2036–2065) across the Australian wheatbelt using a modified version of the Agricultural Production Systems sIMulator (APSIM) and 33 Global Circulation Models (GCMs) under the Representative Concentration Pathways (RCP) 8.5. Two adaptation strategies were assessed: adaptation of sowing dates and/or adaptation of cultivars of contrasting phenology (i.e. fast-spring, mid-spring, slow-spring and fast-winter cultivars). For a given cultivar, optimum sowing windows associated with highest long-term yield were projected to shift to earlier dates by 2050 at most locations, with an average shift of 9.6 days for a mid-spring cultivar. Sowing early maturing cultivars enabled further increase in projected yield in major parts of the wheatbelt. In the tested conditions, sowing and cultivar adaptation allowed simulated crops to minimise the impact of abiotic stresses while limiting the shortening of the grain filling period due to global warming. Thanks to CO_2 fertilisation and proper adaptation, the frequency of severe frost, heat and drought stress was reduced in all regions, except in the West where severe drought was projected to occur more frequently in the 2050s. This allowed a national yield increase of 4.6% with reduced risk of crop failure at most locations. While the study focused on stress avoidance through adaptations (sowing dates and choice of cultivar phenology), breeding for enhanced drought and heat tolerance appeared promising avenues to further improve wheat productivity.

1. Introduction

Increasing crop productivity to meet the increasing demand and provide sustainable food security to the world's population is of utmost importance (Young, 1999). Global food demand is predicted to grow by 50–80% by 2050 (Keating et al., 2014) as the world's population is expected to exceed 9.725 billion, with a 39.7% increase in the Australian population relative to 2015 (United Nations, 2015). Australia, one of the top four wheat-exporting countries in the world (Workman, 2018), is expected to be able to continue to significantly contribute to food security globally by enhancing adoption of adaptation and mitigation strategies against climate change

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(Grundy et al., 2016).

In Australia, average temperature increased by 0.9 °C since 1910 (CSIRO and Bureau of Meteorology, 2015) while most of the change occurred after 1950, with the warmest years recorded in the last decade (Collins and Della-Marta, 1999; Suppiah et al., 2001; Ababaei and Chenu, 2020). Climate models project substantial increase in climate variability and the frequency of temperature extremes by the end of the 21st century (IPCC, 2012; Thornton et al., 2014). Under the Representative Concentration Pathways (RCP) 8.5, which is the pathway the most consistent with the current pace of global emissions, an increase by 2.8–5.1 °C is projected in Australian annual mean temperature by 2080–2099, with a possible decrease in spring and winter rainfall (CSIRO and Bureau of Meteorology, 2015).

Globally, a 6% yield loss in wheat has been projected for each extra degree in global mean temperature, if no CO_2 fertilization, effective adaptation in management practices nor crop genetics were considered (Asseng et al., 2015; Zhao et al., 2017). From 1990 to 2015, simulated water-limited potential yield of wheat in Australia have declined by 27% likely due to reduced rainfall and increased temperature that were only partly compensated by a positive impact of increased atmospheric CO_2 concentration ($[CO_2]$) (Hochman et al., 2017). Global warming has complex effects on crops, due to changes in occurrence and intensity of abiotic stress factors, CO_2 fertilisation, and acceleration of crop development at higher temperatures (e.g. Lobell et al., 2015). For current farming practices, wheat yield in Australia has been projected to decrease by 2050 under RCP4.5 and RCP8.5 (Wang et al., 2018; Ababaei and Najeeb, 2020), even when ignoring direct impact of heat and frost on grain set and size.

In wheat as in most cereals, water and heat stress around pollination can hamper successful grain set while after the reproductive phases they impact grain size (e.g. Tashiro and Wardlaw, 1990; Stone and Nicolas, 1994; Barnabás et al., 2008; Asseng et al., 2011; Hatfield et al., 2011; Eyshi Rezaei et al., 2015). In northeast Australia, the relative importance of heat stress as compared with drought is expected to increase over time, although the drought is expected to remain a major issue if no adaptation is considered (Lobell et al., 2015).

In wheat growing regions like in Australia or Canada, a single frost event after head emergence has the potential to dramatically affect yield by damaging stems and killing whole heads (Frederiks et al., 2012). Frost occurrence has significantly decreased over the last decades in almost half of the north-eastern part of the Australian wheatbelt, while increasing in other regions with, in addition, an extension of the frost season (Zheng et al., 2015a; Crimp et al., 2016). Increased temperatures from global warming are expected to accelerate crop development, which could counter-intuitively increase the chance of frost at sensitive post-heading stages (Zheng et al., 2012). Yield losses due to frost have already increased over the last decades in major regions of the wheatbelt (Zheng et al., 2015a; Crimp et al., 2016).

Another key factor is CO_2 enrichment, which increases photosynthetic activity and water use efficiency (Fitzgerald et al., 2016; Wang et al., 2017; Christy et al., 2018). Elevated $[CO_2]$ has a positive effect on crop yield and could compensate partly or fully the adverse effect of other components of climate change in C3 crops (Lobell et al., 2013; Christy et al., 2018; Webber et al., 2018).

To have a thorough understanding of the magnitude and spatiotemporal distribution of climate change, both (i) key climatic factors, and (ii) adaptation strategies (genotype or management) need to be considered. Process-based crop models are valuable tools for this purpose (White et al., 2011) as they account for interactions between crop processes and the environment, and allow the extrapolation of results from a limited number of experiments to a wide range of conditions, including to environments and management scenarios not observed experimentally (Hammer et al., 2006; Ewert et al., 2015; Chenu et al., 2017). In addition, crop models can be applied to multi-site long-term assessments, leading to comprehensive genotype × environment × management samplings particularly important to quantify spatial variability, climate uncertainty, and adaptation strategies (e.g. Watson et al., 2017; Holzworth et al., 2015; Zheng et al., 2018).

Effective adaptation to climate change could lead to a net increase in wheat productivity in the future. Among suggested adaptation strategies are those which do not need any additional inputs such as earlier sowing, adoption of later-maturing spring cultivars, or adoption of winter cultivars in cooler environments (Zheng et al., 2012; Ababaei et al., 2014; Hasegawa et al., 2014; Ghahramani et al., 2015; Liu et al., 2017; Flohr et al., 2018b; Wang et al., 2018). Other strategies include, for instance, management practices related to soil water conservation (Kirkegaard and Hunt, 2010; Rebetzke et al., 2013), and breeding for better adapted genotypes e.g. with higher transpiration efficiency (Chenu et al., 2018; Christy et al., 2018; Collins et al., 2021), greater stay-green (Christopher et al., 2016) or beneficial morphological traits (Rebetzke et al., 2013; Hunt et al., 2018).

Here, the impacts of climate change on wheat yield and adaptation strategies relative to sowing date and cultivar phenology were assessed over 1976–2005 (hereafter 'the '1990s') as the base period, and 2036–2065 ('the 2050s') under RCP8.5 at 60 locations across the Australian wheatbelt. Simulations were undertaken with a modified version of the Agricultural Production Systems sIMulator (APSIM), which accounts for impacts of frost and heat on grain set and size. To consider the uncertainty in climate projections, climate scenarios from 33 global circulation models (GCMs) were used. Overall, (i) the frequency and impact of current and projected drought, heat and frost on wheat yield were assessed, (ii) optimum sowing windows for cultivars with contrasting phenology were determined for the base and future climate scenarios, (iii) the top-performing cultivars in terms of long-term average yield were selected at each location for both the 1990s and 2050s, and (iv) the impact of climate change on wheat yield was quantified for different adaptation strategies. The study was carried out for three spring wheat cultivars with contrasting phenology (fast-spring, mid-spring, and slow-spring) and a fast-growing winter cultivar (fast-winter) recently released in Australia, which appears promising for southern environments (Flohr et al., 2018b).

2. Materials and methods

2.1. Climate scenarios

Historical daily weather data, including maximum and minimum temperature, solar radiation and rainfall, were obtained at 60 locations (Fig. 1a, Table S1) from the SILO patched point dataset (Jeffrey et al., 2001) for the period 1975–2006. Locations were selected to represent the four major wheat-producing regions (North-East, South-East, South, and West) across the Australian wheatbelt. Each location represented 1300–2300 km^2 of average wheat planted area over 1975–2006 (Chenu et al., 2013).

Monthly projections of precipitation and minimum and maximum temperatures from 33 GCMs (Table S3) were obtained from the Coupled Model Intercomparison Project 5 (CIMIP5; Taylor et al., 2012). Downscaling to a daily time step was performed by transforming the daily historical (i.e. base) temperature and rainfall values by their projected future local monthly means for 2050 (i.e. change factor method), thus constructing future scenarios for 2036–2065 (‘the 2050s’). No change was applied on solar radiation.

Atmospheric [CO_2] was set at 354 ppm for the base period (1976–2005) and 541 ppm for the 2050s, as projected by the RCP8.5 scenario, which assumes ‘business as usual’ CO_2 emissions. In APSIM-wheat, elevated [CO_2] linearly increases transpiration efficiency from a cultivar-specific reference value at 350 ppm by 37% when [CO_2] reaches 700 ppm. Moreover, radiation use efficiency (RUE) is related to [CO_2] via a temperature response function (Reyenga et al., 1999) according to which the RUE at 20 °C increases by 14% when [CO_2] level increases to 541 ppm by 2050 (Zheng et al., 2015b)

2.2. Simulation setup

The APSIM-wheat model (Keating et al., 2003; Holzworth et al., 2014), which has been widely tested for wheat crops in Australia (e.g. Asseng et al., 2001; Lilley and Kirkegaard, 2007; Chenu et al., 2011) was used (version 7.9) to simulate wheat growth and development under different climate scenarios. As the current release version of APSIM does not account for direct impacts of frost and heat shocks on grain number and individual grain weight, such impacts were added as per Zheng *et al.* (2015a) and Ababaei and Chenu (2020).

In the simulations, three spring and one winter wheat cultivars were sown between March 1 and July 31 at 2-day intervals. These included (i) an early-maturing spring or ‘fast-spring’ cultivar (e.g. Axe), (ii) a mid-maturing spring or ‘mid-spring’ cultivar (e.g. Janz), (iii) a late-maturing spring or ‘slow-spring’ cultivar (e.g. Bolac), and (v) a photoperiod-insensitive early-maturing winter wheat cultivar or ‘fast-winter’ cultivar (e.g. Longsword), which has a more stable flowering window across sowing dates compared with spring cultivars or later-maturing winter cultivars in cooler environments (Flohr et al., 2018b, 2018a). The APSIM parameters related to the phenology of these genotypes were taken from APSIM database for spring cultivars and from Flohr et al. (2017) for the winter cultivar (Table S2).

At each location, soil characteristics and fertilisation levels were set to represent local soils and farming practices (Table S1; Chenu et al., 2013). Each year, soil initial conditions were reset on November 1 in all the simulations for both the 1990s and 2050s, with soil nitrogen as per Chenu et al. (2013) and a 20% soil moisture. A small amount of irrigation was applied at sowing, if needed, to raise soil moisture of the soil top layer to the lower limit of plant-extractable soil water so that seeds could germinate the day after sowing.

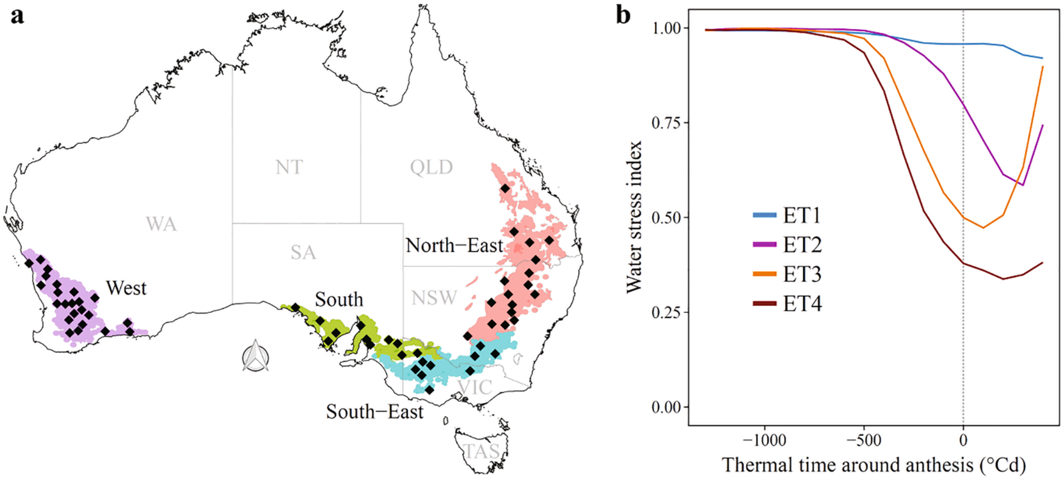

Fig. 1. The Australian wheatbelt and the 60 studied locations in the North-East (red), South-East (blue), South (green) and West (purple) (a) along with simulated water stress index for four drought environment types (ETs) identified across the Australian wheatbelt (b; adapted from Chenu et al., 2013). The water stress index is represented as a function of cumulative thermal time relative to anthesis, from crop emergence to 450°Cd after anthesis, after which senescence greatly reduces plant transpiration. See Figs. S1-S2 for the frequency of ETs in each region and across the Australian wheatbelt.

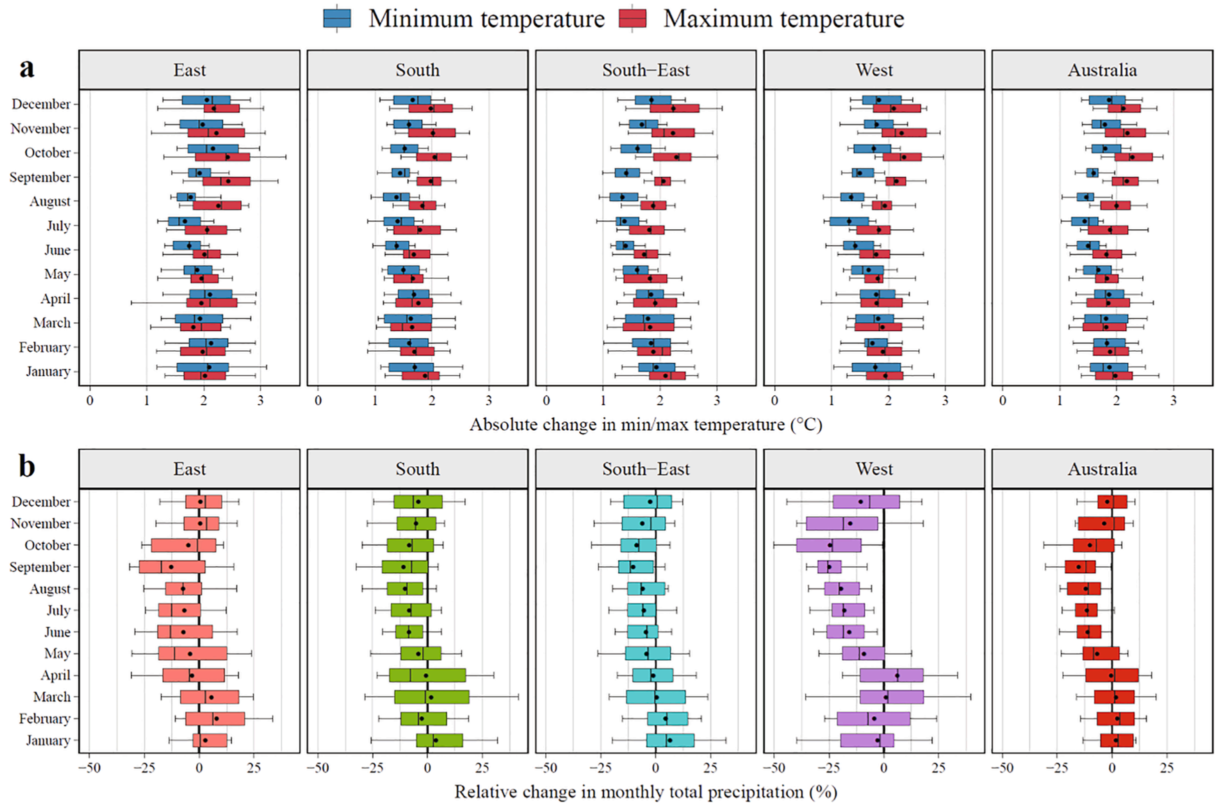

Fig. 2. Absolute changes in monthly-mean daily maximum and minimum temperatures (a) and relative changes in monthly-cumulative precipitation (b) projected by 2050 (relative to the 1990s) with the 33 GCMs under RCP8.5 across the Australian wheatbelt and its regions. Data correspond to averages in each region or in the Australian wheatbelt for each of the 33 GCMs. Black circles correspond to the multi-GCM mean. Boxplots show the 10th and 90th quantiles (whiskers), 25th and 75th quantiles (boxes), median (black line) and average (black dot) across the 33 GCMs.

2.3. *Abiotic-stress characterization*

Water stress was quantified daily using the water supply–demand ratio as a stress index, where crop water demand is the daily amount of water the crop would transpire in the absence of soil water limitation, and water supply is the soil water extractable by the roots depending on their depth and soil physical properties (Chenu et al., 2013). Lower values of water supply–demand ratio correspond to more severe stress. The daily patterns of water stress from all simulations were compared to the four drought patterns representative of the Australian wheatbelt (drought ‘environment types’, Fig. 1b; Chenu et al., 2013) and classified across environment types based on the Euclidean distances. Drought impact on yield was quantified as the overall percentage of drought-induced yield loss in each region, as follows:

$$DroughtImpact = 100 \times \frac{Y_{wlp\text{-}ET1} - Y_{wlp\text{-}all}}{Y_{wlp\text{-}ET1}}$$

where $Y_{wlp\text{-}all}$ represents the average water-limited potential yield (i.e. yield from the standard APSIM excluding modifications related to direct impacts of frost and heat stress on grain number and grain weight) across all simulations within each region, and $Y_{wlp\text{-}ET1}$ is the regional average water-limited potential yield across the simulations classified as ET1, which represents simulations with minimal drought stress (Lobell et al., 2015). The national drought impact was calculated as a weighted average of the regional drought impacts with the number of locations in each region as a weighting factor (as the selected locations represented similar planting area).

The impact of heat shocks was calculated as the heat-induced yield loss in each simulation with a similar equation as for drought using water-limited potential yield (Y_{wlp}) and heat-stressed grain yield (Y_{heat}, considering direct impact of heat stress without frost; see Ababaei and Chenu (2020) for details):

$$HeatImpact = 100 \times \frac{Y_{wlp} - Y_{heat}}{Y_{wlp}}$$

Frost impact was estimated as in Zheng *et al.* (2015a). Briefly, a sensitivity factor (0–1) was applied which linearly declines from 1.0 (no sensitivity) at late-booting (Zadoks stage Z45; Zadoks et al., 1974) to 0.1 (i.e. 90% yield loss for each frost event) at mid-heading (Z55). The highest level of frost sensitivity was maintained until the beginning of dough development (Z80), when plant sensitivity starts to decrease, and the sensitivity factor linearly increases from 0.1 and reaches 1.0 at the end of dough development (Z89). A frost event was defined as a day when minimum temperature measured with a Stevenson screen (as climate data used in this study) was below −1°C.

2.4. *Adaptation strategies*

Optimum sowing windows (OSWs) were defined for each cultivar × location combination for (i) the base (1990s) and (ii) future (2050s) periods. The OSW per cultivar × location for the 2050s was determined by considering all 33 GCMs together. The determination of OSWs for both the base and future periods was done by selecting the best sowing dates per season (step 1), removing those that did not correspond to long-term top yields (step 2), identifying the time period (window) when most of sowing dates occurred (step 3). In Step 1, for each cultivar × location × season, sowing dates corresponding to the top 50% of yields (from all the tested sowings from March 1 and July 31) and had sufficient moisture in the soil profile at sowing were identified. In regions with summer-dominant rainfall, a minimum plant available water in the soil (PAW) of 50 mm was required for sowing in Coonamble, Dubbo, Gilgandra, Merriwagga, Urana, Wellington and Yanco; while 80 mm was required in Condobolin, Dalby, Emerald, Goondiwindi, Gunnedah, Meandarra, Moree, Narrabri, Nyngan, Parkes, Roma, Wagga Wagga and Walgett (Chenu et al., 2013). In the rest of the wheatbelt, sowing occurred without any requirement for soil moisture. In step 2, only selected sowing dates from step 1 that corresponded to the top 25% of 30-year average yields were kept. Note that any specific sowing date could be selected more than once (as the selection was done season per season in step 1). In step 3, the OSW was defined as the period between the 25th and the 75th percentiles of all selected sowing dates from step 2. Any gaps longer than 14 days within the OSWs were removed by selecting only the part of the OSW either before or after the gap which corresponded to the higher long-term average yield.

A cultivar was discarded at a particular location for the 1990s and/or 2050s when either (i) the 30-year average yield of $<$500 kg ha^{-1} or (ii) simulated yield was zero in$>$30% of the simulated seasons, in both cases for sowing at the beginning, median date and end of the OSW.

The best cultivar at each location for the 1990s and 2050s was selected by comparing the 30-year average yields of the studied cultivars sown on all sowing dates (at 2-day intervals) within their respective OSWs when sufficient soil moisture was available.

Different adaptation scenarios were compared (Table 1). For the 1990s and 2050s, crops were first simulated for all genotypes separately with local OSWs (denoted by ‘S’) selected for the 1990s (‘1990-S_{90}′ and ‘2050-S_{90}′ scenarios) or for the 2050s (‘2050-S_{50}′ scenario). In addition, the best site-specific cultivars (denoted by ‘C’) were simulated in combination with these four sowing time scenarios: (i) the OSWs and the best cultivars selected for the 1990s (i.e. ‘1990-S_{90}-C_{90}′ and ‘2050-S_{90}-C_{90}′), (ii) the OSWs selected for the 1990s and the best cultivars selected for the 2050s (‘2050-S_{90}-C_{50}′), (iii) the OSWs selected for the 2050s and the best cultivars selected for the 1990s (‘2050-S_{50}-C_{90}′), and (iv) the OSWs and the best cultivars selected for the 2050s (‘2050-S_{50}-C_{50}′). OSWs were always location- and cultivar-specific.

2.5. *Computation and analysis*

Approximately 38 million simulations (60 locations × (33 + 1) climate scenarios × 4 cultivars × 77 sowing dates × 2 versions of the crop model × 30 years) were performed using Tinaroo, a High-Performance Computing (HPC) cluster. The R programming language version 3.4.3 (R Core Team, 2017) was used for data organization and analysis.

3. Results

3.1. *1.8 °C warmer and 10% drier growing season by 2050*

Over the wheat growing-season (April–November), total precipitation is projected to decline by 9.7% and mean temperature to rise by 1.8 °C on average across the Australian wheatbelt by 2050, with a wide range of variations across climate models (Fig. 3). The projected increases in maximum and minimum temperatures were 2 and 1.6 °C on average, respectively. Large spatial variability was

Table 1
Adaptation scenarios in terms of cultivar (‘C’) and/or management (sowing date, ‘S’) for the 1990s (base) and 2050s. The optimum sowing windows were location- and cultivar-specific for the 1990s or 2050s. Best cultivars were selected based on long-term average yield, at each location, for the 1990s or 2050s.

Scenario	Climate	Cultivars	Sowing windows
1990-S_{90}	1976–2005 (the 1990s)([CO_2] = 354 ppm)	All cultivars	Optimum windows for the 1990s
1990-S_{90}-C_{90}		Best cultivars for the 1990s	Optimum windows for the 1990s
2050-S_{90}	2036–2065 (the 2050s) projected by	All cultivars	Optimum windows for the 1990s
2050-S_{50}	33 GCMs under RCP8.5 ([CO_2] = 541 ppm)	All cultivars	Optimum windows for the 2050s
2050-S_{90}-C_{90}		Best cultivars for the 1990s	Optimum windows for the 1990s
2050-S_{90}-C_{50}		Best cultivars for the 2050s	Optimum windows for the 1990s
2050-S_{50}-C_{90}		Best cultivars for the 1990s	Optimum windows for the 2050s
2050-S_{50}-C_{50}		Best cultivars for the 2050s	Optimum windows for the 2050s

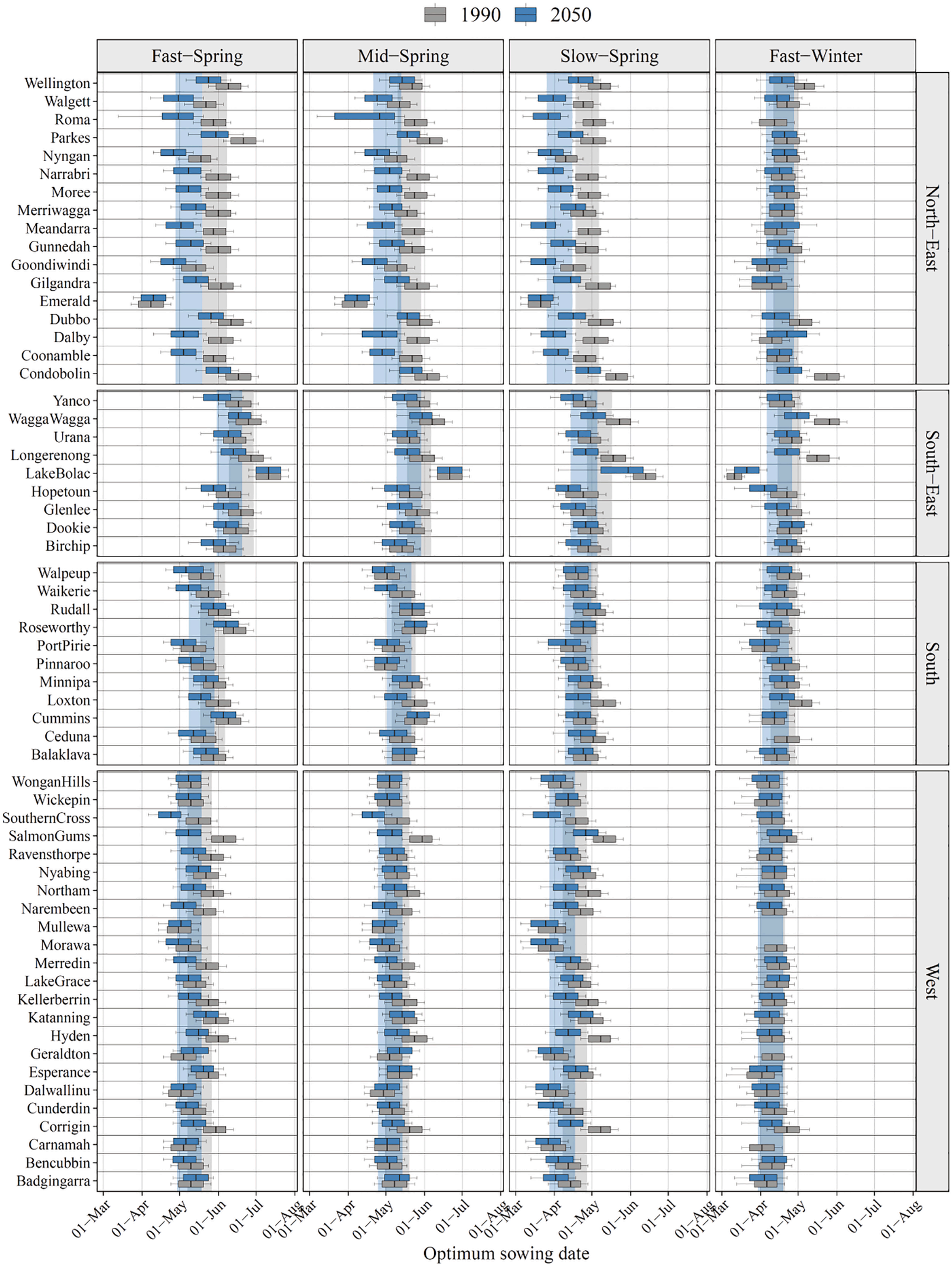

Fig. 3. Location-specific and regional optimum sowing dates and optimum sowing windows (OSWs) in the 1990s and 2050s for an early-maturing (Fast-Spring), a mid-maturing (Mid-Spring) and a late-maturing (Slow-Spring) spring cultivars and a fast-maturing winter cultivar (Fast-Winter). Boxplots show the 10th and 90th percentiles (whiskers), 25th and 75th percentiles (boxes) and median (black line) for the optimum sowing dates. OSWs were defined within the range of the 25th and 75th percentiles of the optimum sowing dates (i.e. boxes of the boxplots). Shadings show the regional average OSWs.

observed. The most adverse effects were projected for the West in terms of seasonal precipitation with a decline of 15.3%, and in the North-East in terms of temperature, with a 2 °C increase.

3.2. Earlier or maintained optimum sowing windows (OSWs) by 2050

In all regions and most of the locations, OSWs were projected to shift earlier in the 2050s compared with the 1990s, at least for spring cultivars (Fig. 3 and Fig. S3). For these cultivars, projected shifts were greatest in the North-East, while for the fast-winter cultivars projected shifts tended to be greater in the South-East and South. In the 2050s, OSWs of fast-spring:mid-spring/slow-spring:fast-winter were projected to start 21.4:19.4/23.1:6, 9.7:8.4/13.1:8.7, 9.2:4.0/7.0:6.7 and 8.3:5.5/10.5:1.8 days earlier on average across 33 GCMs in the North-East, South-East, South and West, respectively (12.4:9.6/13.8:4.8 days earlier across the Australian wheatbelt). The average shift in the beginning of the OSWs were estimated to be 9.9 days earlier than in the 1990s across all locations, GCMs and studied genotypes.

The durations of the OSWs, which reflect how many days farmers have for optimum planting, averaged 20.2 and 21.3 days for spring cultivars across the wheatbelt in the 1990s and 2050s, respectively (Fig. S4). The OSWs durations were typically maintained or increased in the 2050s. Least changes were observed in the West (by 0.2, 0.0, 0.7 and 0.4 days) and South (by 0.9, 0.6, 1.8 and 1.2 days), while in the North-East and South-East, the regional average duration of OSWs were projected to change by 1.7, 3.3, 2.0 and 2.9

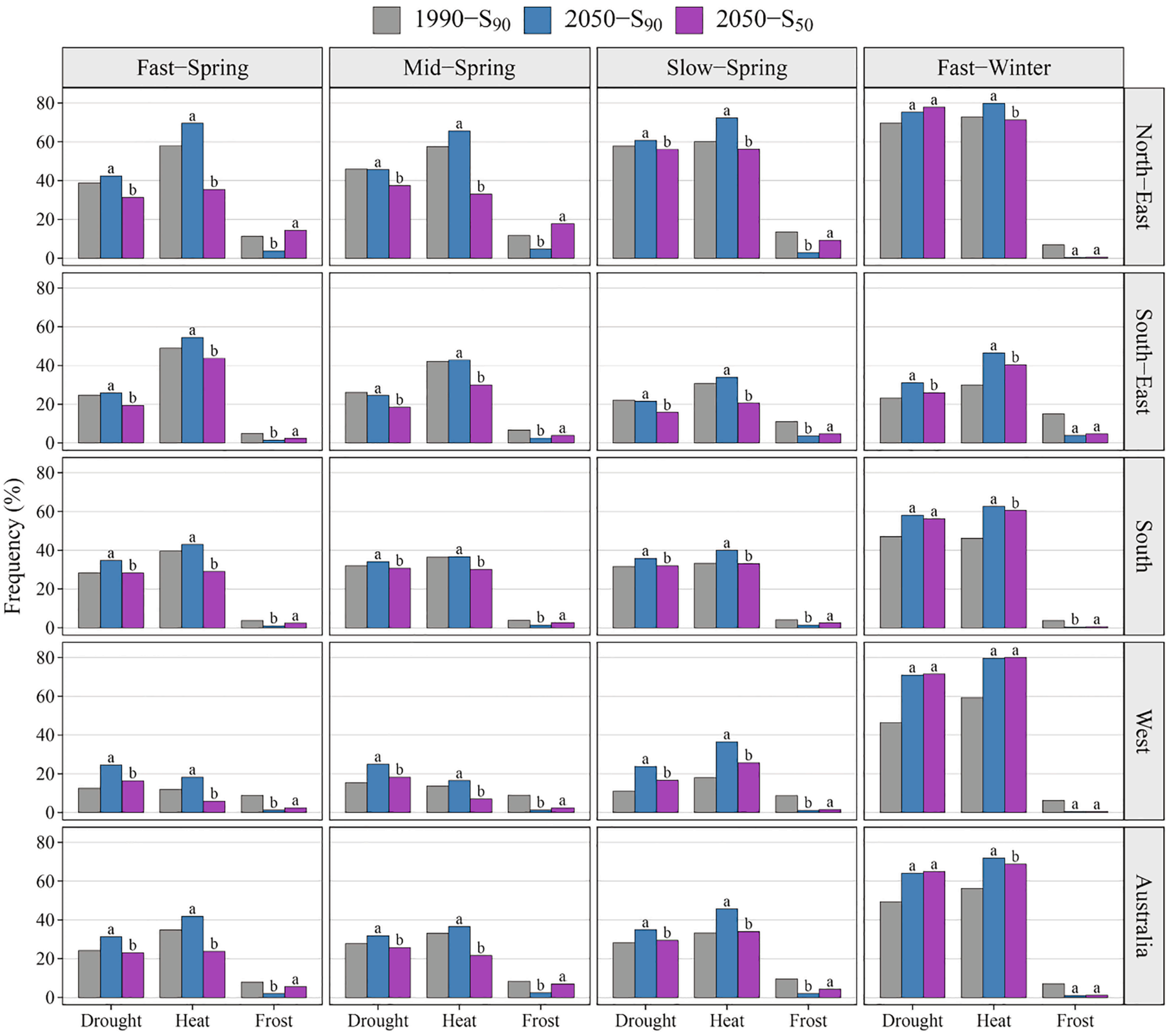

Fig. 4. Regional and national average frequency of severe droughts (ET3 and ET4) and severe heat and frost events (yield loss > 10%) on yield in Australia for an early-maturing (Fast-Spring), a mid-maturing (Mid-Spring) and a late-maturing (Slow-Spring) spring cultivars and a fast maturing winter cultivar (Fast-Winter) in the 1990s and 2050s. For the 1990s, simulations were done for optimum sowing windows ('1990-S_{90}'), while in the 2050s sowing windows were ('2050-S_{50}′) or not ('2050-S_{90}′) adjusted. Regional and national averages were first calculated for each of the 33 GCMs and then averaged across GCMs. Letters denote significant differences ($P < 0.1$) between projected scenarios.

days and 0.6, 0.7, 1.5 and 1.3 days for the fast-spring, mid-spring, slow-spring and fast-winter cultivars, respectively. Across the wheatbelt, the OSWs of the fast-spring, mid-spring, slow-spring and fast-winter cultivars are expected to last 0.8, 1.1, 1.4 and 1.4 days longer on average, respectively.

3.3. Projected shortening in crop growth cycles

All spring cultivars were projected to have substantially shorter growth cycles in the 2050s (Fig. S5), while the growth duration of the fast-winter cultivar was less affected by global warming. Adoption of OSWs adapted to the 2050s ('2050-S_{50}' scenario) reduced the shortening impact of increased temperatures on growth cycles for all spring cultivars, especially the slow-spring cultivar (as compared with the '2050-S_{90}' scenario). For the '2050-S_{50}' scenario, the growth-cycles of the fast-, mid- and slow-spring cultivars were projected to shorten by 6.4, 9.9 and 0.3 days on average (as compared with the 1990s), respectively across the Australian wheatbelt, with lowest overall impacts in the North-East (2.4, 6.6 and −7.0 days, respectively). The growth-cycle duration of the fast-winter cultivar was maintained or increased in all regions (3.2 days longer across the wheatbelt), with the greatest effect projected in the South and North-East (4.9 and 4.8 days, respectively).

Adoption of OSWs in the 2050s was projected to mainly extend the duration of grain filling for fast- and mid-spring cultivars compared with the '2050-S_{90}' scenario (Fig. S5), due to a shift of the grain filling to a cooler period of the year. Nationally, with adapted

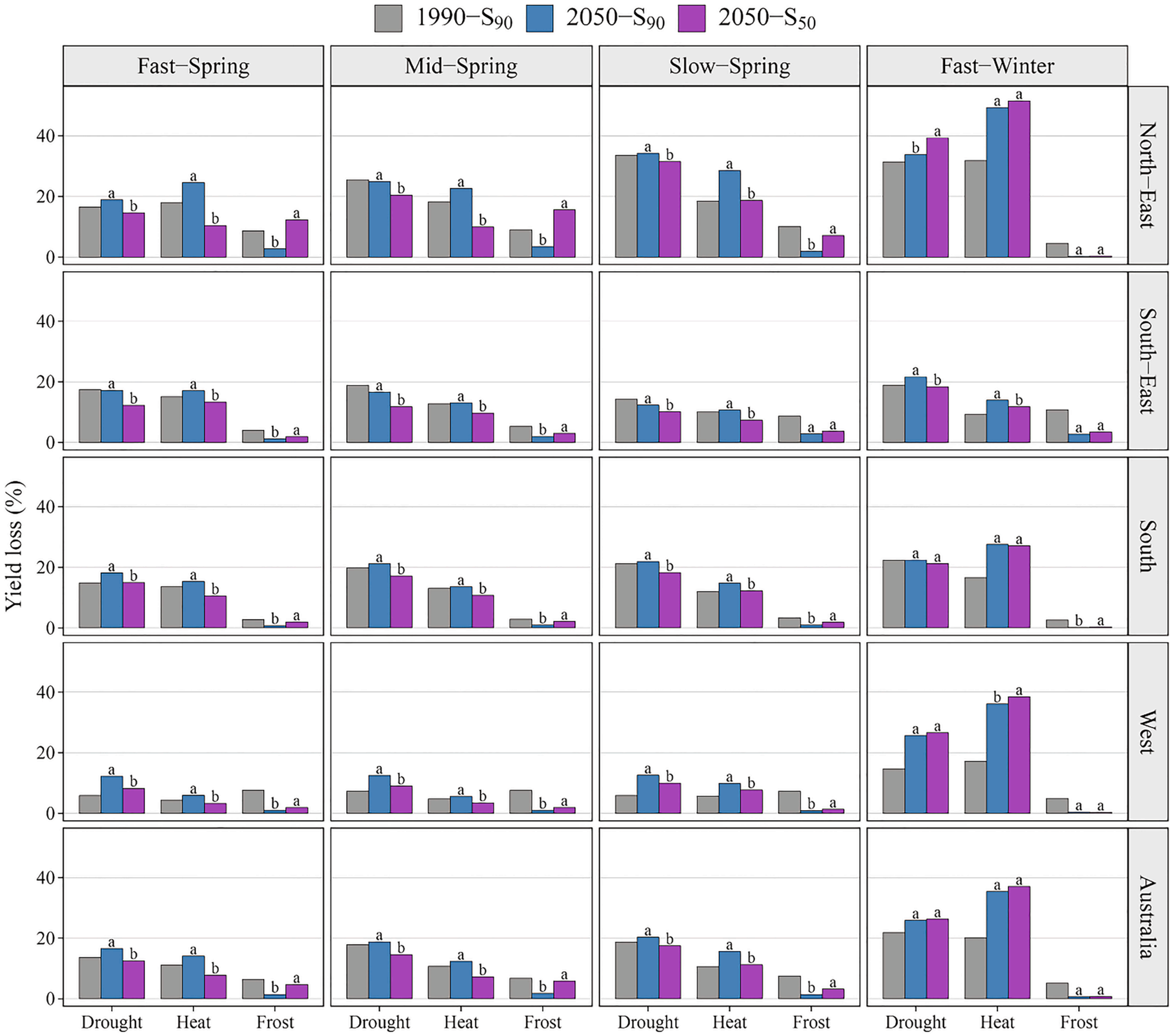

Fig. 5. Regional and national average yield loss due to drought, heat, and frost in Australia for an early-maturing (Fast-Spring), a mid-maturing (Mid-Spring) and a late-maturing (Slow-Spring) spring cultivars and a fast maturing winter cultivar (Fast-Winter) in the 1990s and 2050s. For the 1990s, simulations were done for optimum sowing windows ('1990-S_{90}' scenario), while in the 2050s sowing windows were ('2050-S_{50}') or not ('2050-S_{90}') adjusted. Regional and national averages were first calculated for each of the 33 GCMs and then averaged across GCMs. Letters denote significant differences ($P < 0.1$) between projected scenarios.

sowing ('2050-S_{50}'), the grain filling period is expected to shorten by 3, 2.3, 3.4 and 4 days compared with the 1990s for the fast-spring, mid-spring, slow-spring and fast-winter cultivars, respectively. By contrast, larger changes in the duration of the vegetative phase when adapting sowing ('2050-S_{50}' vs '2050-S_{90}') were projected mostly for the slow-spring and fast-winter cultivars, especially in the North-East and South-East.

3.4. Severe droughts projected to increase in the West but decrease in eastern Australia

The frequency of severe droughts (environment types (ET) 3–4; Fig. 1b) rises with delayed sowing (Fig. S1) and with the duration of crop cycle (i.e. later maturing cultivars face higher risks of severe droughts than earlier maturing ones; Fig. S2) both in the 1990s and 2050s.

In the 1990s, 24.2, 27.7, 28.1 and 49.4% of the simulated crops (i.e. location × year combinations) across the wheatbelt were affected by severe droughts for fast-spring, mid-spring, slow-spring and fast-winter cultivars, respectively (Fig. 4), with a greater occurrence in the North-East. With no adaptation of sowing dates ('2050-S_{90}'), the frequency of severe droughts is expected to increase for most crops in all regions. Adapting sowing dates to future climate ('2050-S_{50}') reduced the projected increases in severe-drought occurrence for all spring cultivars. Overall, the frequency of severe droughts in the 2050s with adapted sowing dates compared with the 1990s is expected to decrease in the North-East and South-East, be maintained in the South, and increase in the West, for all spring cultivars, with the most substantial decrease simulated for the fast-spring cultivar in the North-East. Projected changes in severe-drought frequency were minor for the slow-spring cultivar in eastern Australia, while the fast-winter cultivar is expected to experience severe droughts more frequently by 2050 across the wheatbelt.

In terms of yield, the impact of drought on all studied cultivars is expected to increase by 2050 in the West if no sowing date adaptation is to be adopted ('2050-S_{90}'), while relatively minor changes were projected elsewhere (Fig. 5). When adapting sowing ('2050-S_{50}' scenario), less drought-induced yield losses than in the 1990s are expected in eastern Australia (North-East, East and South) for all spring cultivar, but greater losses were projected in the West. The drought impact due to climate change is expected to slightly decrease, on average across the wheatbelt, for all spring cultivars if adapted sowing time is to be adopted ('2050-S_{50}' vs '1990-S_{90}'). By contrast, drought impact on the fast-winter cultivar was projected to increase in the North-East and West, be maintained in the South-East and slightly decrease in the South ('2050-S_{50}' vs '1990-S_{90}').

3.5. Projected decrease in heat stress for early- and mid-maturing cultivars when adapting sowing time

Heat impact increased with later sowing, later-maturing cultivars and increased temperatures due to global warming (Fig. S6). In the 1990s, 34.8, 33.1, 33.2 and 56.3% of the simulated fast-spring, mid-spring, slow-spring and fast-winter crops with location-specific OSWs experienced > 10% heat-induced yield losses across the wheatbelt (Fig. 4). Regionally, the mid-spring cultivar experienced at least 10% heat-induced yield loss in 57.5, 42.1, 36.4 and 13.7% of the seasons in the North-East, South-East, South and West, respectively. At the extreme, the fast-winter cultivar experienced > 10% heat-induced yield losses in 72.7, 30.0, 46.2 and 59.3% of the simulated seasons.

By 2050 and without adaptation of sowing dates, the national frequency of severe heat (i.e. > 10% yield loss) was projected to increase by 7.0, 3.4, 12.4 and 14.5% for the fast-spring, mid-spring, slow-spring and fast-winter cultivars, respectively ('2050-S_{90}' vs '1990-S_{90}'; Fig. 4). Adapting sowing dates to the 2050s ('2050-S_{50}' vs '2050-S_{90}') was projected to reduce the frequency of severe heat events by 18.1, 15, 11.7 and 3.1% on average across the Australian wheatbelt for the fast-spring, mid-spring, slow-spring and fast-winter cultivars, respectively. Overall, when adapting sowing windows ('2050-S_{50}'), heat stress was projected to become less frequent than in the 1990s for the fast- and mid-spring cultivars, as well as the slow-spring cultivar in the North-East and South-East. By contrast, severe heat stresses are expected to become more frequent in most locations for the slow-spring cultivar in the West, and for the fast-winter cultivar across the wheatbelt except in the North-East.

In terms of yield, heat stress has already substantially affected crops in the 1990s even for sowing dates considered as early (e.g. May sowing of the mid-spring cultivar; Fig. S6). With sowing within the OSWs, heat contributed to national yield loss between 10.6% (slow-spring) and 20.1% (fast-winter; Fig. 5) in the 1990s. Regionally, the largest heat-induced losses were observed in the North-East and to a lesser extent in the South-East. Nationally, spring cultivars experienced an average heat-stress impact ~ 12%, while the fast-winter cultivar experienced 9.2–31.8% of yield loss across regions.

In the 2050s, heat impact was projected to increase for all genotypes and regions if no sowing time adaptation was applied ('2050-S_{90}'; Fig. 5). However, with adapted sowing windows ('2050-S_{50}' vs '1990-S_{90}'), heat impact is expected to (i) decrease for fast- and mid-spring cultivars in all regions and for the slow-spring cultivar in the South-East, (ii) increase for the slow-spring cultivar in the West, and (iii) considerably increase for the fast-winter cultivar in most regions compared with the 1990s. Nationally, heat-induced yield losses were estimated at 11.1, 10.7, 10.6 and 20.1% for the '1990-S_{90}' scenario and 7.8, 7.2, 11.3 and 37.1% for the '2050-S_{50}' scenario for the fast-spring, mid-spring, slow-spring and fast-winter cultivars, respectively.

3.6. Projected decrease in frost damage in most locations

Frost impact decreased with later sowing, later-maturing genotypes and higher temperatures (Fig. S6). In the 1990s and for crops sown within their OSWs, the frequency of frost-induced yield losses of > 10% was considerably lower than the frequency of severe heats and droughts (Fig. 4). Nationally, frost severely affected 7.9, 8.4, 9.4 and 7.1% of fast-spring, mid-spring, slow-spring and fast-winter cultivars crops, respectively. Regionally, severe frost events were more common in the North-East, followed by the South-East, West and South. Without adopting OSWs, the frequency of severe frosts is expected to decline by 2050 for all studied cultivars (Fig. 4) mostly due to projected increase in minimum temperature in all calendar months (Fig. 2a). While adapting sowing windows is expected to be effective in reducing the frequency and impact of severe droughts and heat events, it would come at the cost of slightly increasing the risk of severe frosts, especially in the North-East for the fast- and mid-spring cultivars. Overall, the average frequency of severe frost events under the ‘2050-S$_{50}$′ scenario was estimated at 5.5, 6.9, 4.2 and 1.1% for the fast-spring, mid-spring, slow-spring and fast-winter cultivars, respectively.

Historically, frost contributed to yield loss of the fast-spring, mid-spring, slow-spring and fast-winter crops sown in their OSWs by 6.5, 6.8, 7.5 and 5.2%, respectively (‘1990-S$_{90}$′, Fig. 5). Frost was most impactful on the spring cultivars in the North-East, South-East and West. In the 2050s, frost-induced yield losses are expected to become minimal for all cultivars in all regions, if sowing dates remain unchanged (‘2050-S$_{90}$′, Fig. 5). When adapting sowing windows to optimise yield (‘2050-S$_{50}$′), frost events were projected to still have low yield impact (<5%) except in the North-East especially for the fast- and mid-spring cultivars. Nationally, frost was projected to cause yield loss of 4.7, 5.9, 3.3 and 0.7% for the fast-spring, mid-spring, slow-spring and fast-winter cultivars, respectively, for the

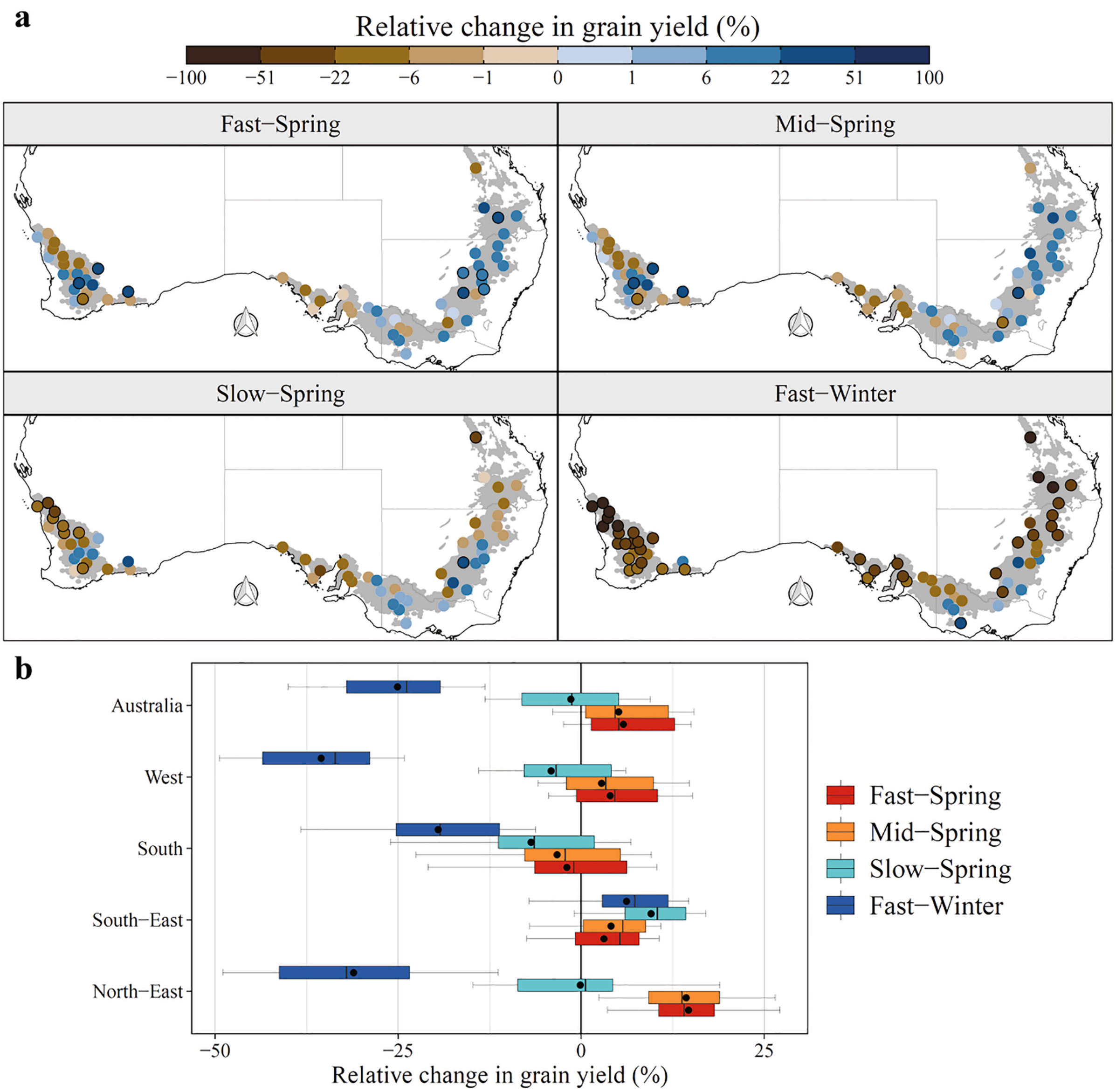

Fig. 6. Projected changes in average yield for an early-maturing (Fast-Spring), a mid-maturing (Mid-Spring) and a late-maturing (Slow-Spring) spring cultivars and a fast maturing winter cultivar (Fast-Winter) (a), and regional and national average relative changes in yield (b) between the 2050s and 1990s. Data correspond to projected change in yield with adapted sowing dates (the ‘2050-S$_{50}$′) compared with the ‘1990-S$_{90}$′ scenario. In (a), points circled in dark grey represent significant changes ($P < 0.1$). Boxplots show the 10th and 90th percentiles (whiskers), 25th and 75th percentiles (boxes), median (black line) and average (black dot) across the 33 GCMs.

‘2050-S_{50}′ scenario.

3.7. *Combinations of abiotic stresses: most crops affected by severe drought were also affected by severe heat stress*

For spring wheat in the 1990s, crops were not affected by any severe abiotic stress (drought, heat or frost) in about 50% of the simulated seasons (Fig. S7). With adapted sowing windows (‘2050-S_{50}′), such favourable conditions are expected to increase in the 2050s for the fast- and mid-spring cultivars in all regions, and for the slow-spring cultivar in the South-East. In both the 1990s and 2050s, most crops affected by severe droughts (ET3-4) were also affected by severe heat events (yield impact $>$ 10%), except in the West for spring cultivars. For the fast-winter cultivar, severe heat with or without severe drought impacted the crops in over 50% of the simulations in both the 1990s and 2050s, except in the South-East where the FW cultivar was not affected by severe drought, heat nor frost in 52 and 42% of the simulations, respectively.

3.8. *Projected increase in yield mainly for fast- and mid-spring cultivars*

Spatial distribution of the projected yield impact (‘2050-S_{50}′ vs ‘1990-S_{90}′) was largely influenced by the planted cultivar (Fig. 6; Fig. S8). For the fast- and mid-spring cultivars, yield was projected to increase in many locations in the North-East, South-East, and the southern part of the West. For these cultivars, the South and the northern part of the West had the largest number of locations with negative impacts. The slow-spring cultivar was projected to experience significant decrease in yield in the northern part of the West (up to 25% reduction), milder yield reductions across the North-East and South, and yield gain in a few locations in the southern part of the West and in the South-East. Largest yield reductions were projected for the fast-winter cultivar in the West and North-East. The yield of the fast-winter cultivar was projected to increase only at a few locations in the South-East, mostly located in cooler environments of the wheatbelt.

Regionally, the average yield of the fast- and mid-spring cultivars, with adapted sowing, are expected to increase the most by 2050 (‘2050-S_{50}′ vs ‘1990-S_{90}′; Fig. 6b) in the North-East (average of 14.7 and 14.3%, respectively), and then West (3.9 and 2.8%) and South-East (3.1 and 4.0%). However, a lot of variability was simulated across GCMs. By contrast, the slow-spring and fast-winter cultivars had projected yield gains only in the South-East (9.5 and 6.1%, respectively) and projected yield losses in the North-East (0.1 and 31.1%), South (6.9 and 19.5%), and West (4.1 and 35.5%).

Nationally, average yields of the fast- and mid-spring cultivars sown within their OSW were projected to increase by 2050 for $>$ 80% of the GCMs (Fig. 6b), mainly due to reductions in frost events. By contrast, the average yields of the slow-spring and fast-winter cultivars are expected to decrease for most or all GCMs, except in the South-East (for both ‘2050-S_{90}′ and ‘2050-S_{50}′). Overall, the national average yield of the fast-spring, mid-spring, slow-spring and fast-winter cultivars were projected to decrease by 0.4, 0.5, 5.3 and 25.9% without adaptation of sowing windows (‘2050-S_{90}′) and change by 5.8, 5.1, -1.4 and -25.1% with adapted sowing time (‘2050-S_{50}′).

3.9. *Towards earlier-maturing genotypes or earlier sowing dates*

Best-performing cultivars in terms of long-term average yields varied depending on the location, time-line (1990s and 2050s) and management scenarios (Fig. 7; Figs. S9-S11). In the 1990s, the slow-spring cultivar was the top-yielding cultivars in most locations, while it was outperformed by fast- and mid-spring cultivars in the northern part of the North-East and few other locations, and by the fast-winter cultivar in the cooler environments of the South-East. In the northern part of the North-East, where late-maturing cultivars frequently failed in both the 1990s and 2050s, the fast- and mid-spring cultivars consistently performed best.

In the 2050s, the top yielders were the same or a faster-maturing type (58 and 59 out of 60 locations for ‘2050-S_{90}′ and ‘2050-S_{50}′, respectively) than in the 1990s (Fig. 7). Top yielders were (i) early- and mid-maturing cultivars (fast- and mid-spring) in the northern parts of the North-East and West, and (ii) longer-maturing cultivars (slow-spring and fast-winter) in the southern part of the North-East, South-East and South. At all locations where the fast-spring cultivar was selected as the top-yielder, the mid-spring cultivar had a similar yield (average yield difference typically lower than 0.2 t ha^{-1}) and vice versa. The fast-winter cultivar was selected as the

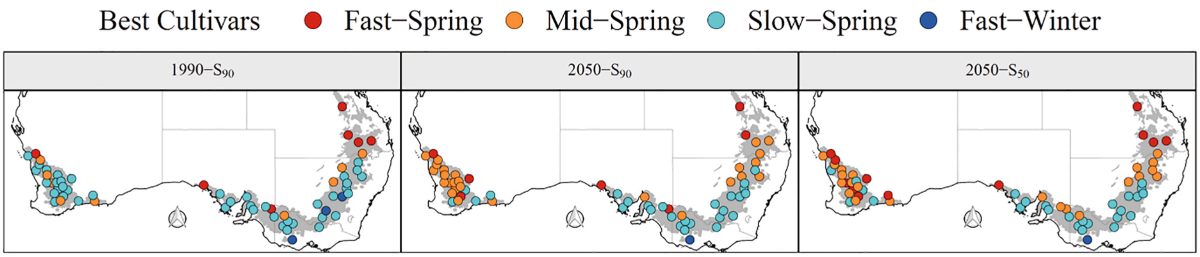

Fig. 7. Best-performing cultivars in terms of long-term average yield selected at each of the 60 locations across the Australian wheatbelt in the 1990s and 2050s with (‘1990-S_{90}′ and ‘2050-S_{90}′) or without (‘2050-S_{50}′) adoption of the optimum sowing windows. The change in the beginning of sowing windows for the best-performing cultivars is presented in Fig. S12. The frequency of situations where each genotypes was the best-performing one is presented in Fig. S11.

second best-performing cultivar in the South-East under all scenarios, with yield frequently similar to the top-yielding cultivar (the slow-spring). In this region, cooler environments require longer crop cycles to achieve higher yield for both current and future climates. OSWs in the 2050s were projected to mostly start later than in the 1990s where the best cultivars for the 2050s had an earlier maturity type than in the 1990s (18 out of the 20 locations with an earlier maturity type), while earlier sowing windows were projected where the best cultivar did not change (33 out of 39 locations with no change in cultivar) or had a later maturity type (1 location; Fig. S12).

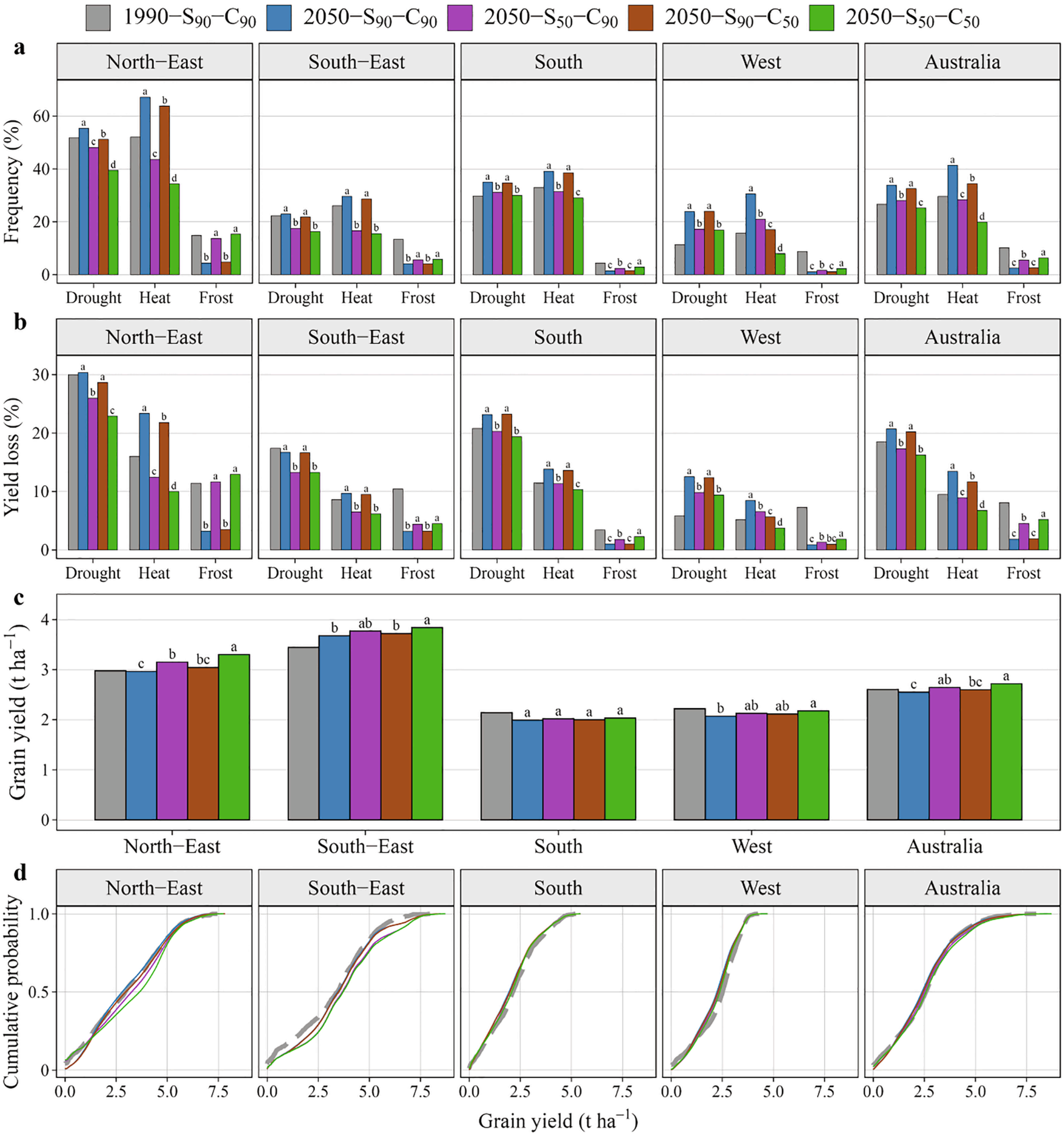

Fig. 8. Frequency of severe abiotic stresses (a), yield loss (b), average yield (c) and cumulative frequency of yield (d) regionally and nationally in the 1990s and 2050s with ('2050-S_{90}-C_{90}′, '2050-S_{50}-C_{90}′ and '2050-S_{50}-C_{50}′) and without ('2050-S_{90}-C_{50}′) adaptation of sowing dates and with ('2050-S_{90}-C_{90}′, '2050-S_{90}-C_{50}′ and '2050-S_{50}-C_{50}′) and without ('2050-S_{50}-C_{90}′) adoption of best cultivars. Regional and national averages were first calculated for each of the 33 GCMs and then averaged across GCMs. Letters denote significant differences ($P < 0.1$) between projected scenarios.

3.10. Site-level adaptation of sowing time and phenology allowed crops to avoid abiotic stresses while maintaining the duration of grain filling

When only the top-yielding cultivars were adopted in the 2050s (i.e. no adaptation of sowing dates; ‘2050-S$_{90}$-C$_{50}$′), the frequency of severe stresses and yield impact of abiotic stresses were projected to increase nationally compared with the 1990s by 5.9 and 1.7% for drought (ET3-4), and 4.8 and 2.2% for heat (yield impact $>$ 10%), respectively, while frost (yield impact $>$ 10%) were projected to decline by 7.6 and 6.1%, respectively, with substantial spatial variability (Fig. 8a-b).

Adapting sowing windows along with the adoption of top-yielding cultivars would reduce the impact of abiotic stress related to climate change. When compared with the 1990s (‘2050-S$_{50}$-C$_{50}$′ vs ‘1990-S$_{90}$-C$_{90}$′), this strategy is expected to allow crops to experience (i) less severe heats in all regions (-9.8% nationally with a 2.7% reduction in yield loss), (ii) less severe frost events in all regions except the North-East (-3.8% nationally with 2.8% reduction in yield loss) and (iii) less severe droughts in most of eastern Australia but more severe drought in the West (-1.4% nationally with 2.3% increase in yield loss; Fig. 8).

In terms of yield, adopting top-yielding cultivars at each location in the 2050s was projected to increase yield from the 1990s by 4.6% if sowing windows were also adapted (‘2050-S$_{50}$-C$_{50}$′) and 2% by only adopting OSWs from the 2050s and keeping the top-yielding cultivars from the 1990s (‘2050-S$_{90}$-C$_{50}$′; Fig. 8c and Fig. 9). Regionally, yield was projected to decrease by 4.1% on average in the South, and increase by 11.8, 10.6 and 1.2% in the North-East, South-East and West, respectively, if OSWs and best cultivars were to be concurrently adopted in the 2050s (‘2050-S$_{50}$-C$_{50}$′). The positive impact of adapted cultivars was associated to (i) shorter vegetative phases, allowing crops to avoid terminal droughts and heat waves and (ii) extended grain filling periods, providing more time for resource assimilation during the grain filling (Fig. 9; Figs. S13-S14).

Importantly, with proper adaptation, climate change was projected to result in reduced risk of crop failure (yield $<$ 0.5 t ha^{-1}) in the South-East, changing from 13.1% in the 1990s to 7.7% in the 2050s (‘2050-S$_{50}$-C$_{50}$′). No substantial changes were simulated for the other regions (Fig. 8d).

4. Discussion

4.1. Earlier sowing or faster-maturing genotypes to adapt to changing climates

In Australia, growers typically target a sowing time late enough to avoid last frosts that can destroy crops (Zheng et al., 2015a; An-Vo et al., 2018), but early enough to reduce impacts of heat and drought (Zheng et al., 2012; Flohr et al., 2017, 2018b). Optimised

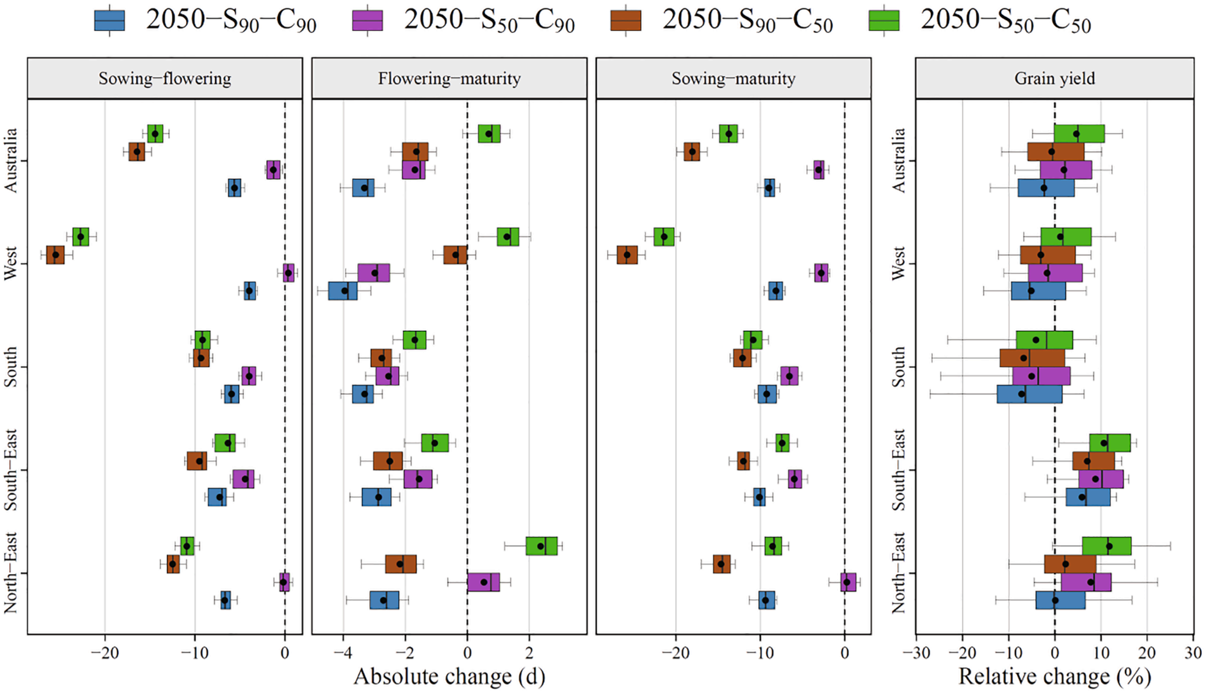

Fig. 9. Projected changes in the duration of growth phases and yield in the 2050s relative to the 1990s regionally and nationally with (‘2050-S$_{90}$-C$_{90}$′ ,‘2050-S$_{50}$-C$_{90}$′ and ‘2050-S$_{50}$-C$_{50}$′) and without (‘2050-S$_{90}$-C$_{50}$′) adaptation of sowing dates and with (‘2050-S$_{90}$-C$_{90}$′, ‘2050-S$_{90}$-C$_{50}$′ and ‘2050-S$_{50}$-C$_{50}$′) and without (‘2050-S$_{50}$-C$_{90}$′) adoption of best cultivars. Boxplots show the 10th and 90th percentiles (whiskers), 25th and 75th percentiles (boxes), median (black line) and average (black dot) across the 33 GCMs. Changes in duration of growth phases at the 60 locations are presented in Fig. S13. See Fig. S14 for relative changes compared to the 1990s.

sowing dates leading to maximised long-term yield for a given cultivar are typically earlier than sowing times currently practiced by farmers (Fig. 3), partly due to growers' risk aversion for relatively rare but devastating frosts (Frederiks et al., 2012). However, over the last decades, growers have begun adapting to recent change in climates and tend to sow wheat earlier than previously in all Australian regions (Flohr et al., 2018b).

To adapt to future climate, earlier planting appears a promising 'avoidance' strategy (Zheng et al., 2012; Hunt et al., 2018, 2019; Wang et al., 2018). Simulations with earlier sowing of specific cultivars allowed in most cases a yield increase for spring wheat in future climates, especially in the North-East (Fig. 3). Adaptation of sowing time partly counteracted the shortening of the crop growth cycle inherent to higher temperatures, and this even led to slightly longer grain filling periods for fast- and mid-spring genotypes in the North-East (Fig. S5). Earlier sowing in the 2050s ('2050-S_{50}′ vs '2050-S_{90}′) resulted in less severe droughts and heat stress, but increased crop exposure to frosts mostly in the North-East (Fig. 4).

In the conditions tested, growing faster-maturity genotypes in the 2050s led to greater average yields at many locations, especially in the West (Fig. 7). Adapting sowing times ('2050-S_{50}-C_{90}′) or cultivars ('2050-S_{90}-C_{50}′) resulted in a respective average yield gain of 4.3 or 1.7% compared with '2050-S_{90}-C_{90}′, or a 7% increase if both strategies were applied concurrently (Fig. 9). Here, adapting sowing time was thus 2.5 times as effective as adapting the phenology type of cultivars in the 2050s across Australia.

While only considering four cultivars (with different pre-flowering development, and potential durations of the grain filling period varying by<100°Cd), the results of this study suggest that adopting faster-maturing genotypes (which had a shorter pre-flowering period but a longer potential post-flowering period in this study; see Table S2) could be a promising option to adapt to climate change at least for parts of the wheatbelt, e.g. in the West and part of the North-East (Fig. 7). Interestingly, adopting the top-yielding cultivars resulted in less severe shortening or even slightly longer grain filling periods, at the cost of a shorter vegetative phase and overall, a shorter crop growth cycle (Fig. 9). In the 2050s, fast- and mid-spring cultivars were found more adapted in the North-East and West, while slow-spring cultivars or fast-winter cultivars remained the top yielders in the South-East and South (Fig. 7). As simulated and observed in field trials by Flohr et al. (2018a and b) and Hunt et al. (2019), fast-winter cultivars have promising adaptive capacity in the South and parts of the South-East, where cooler temperatures fulfil their vernalisation requirements while their longer growth cycle allow more carbon assimilation and greater yield compared with spring cultivars. Hunt et al. (2019) also found advantages of fast- and mid- winter genotypes in southern and western Australia, especially for large Australian farms that could benefit from growing both winter and spring genotypes to increase the period with proper sowing opportunity. In the present study, the slow-spring cultivar also performed well in the South-East and South, where it was selected as the best cultivar in 56 and 42% of the simulated seasons in the 1990s and in 64 and 47% of the seasons in 2050s ('2050-S_{50}′), respectively.

In both the 1990s and 2050s, the duration of the optimum sowing windows was estimated to be around 20 days on average for spring cultivars across the wheatbelt in the current study (Fig. S4). This would allow a grower to sow approximately 2,000 ha of wheat in a season, which is typical for an average Australian farm. However, sowing opportunities were defined irrespective of autumn rainfall (April-May), which are likely to change in major production regions (Fig. 2b). This is likely to impact sowing opportunities, despite that the fact that growers tend to sow wheat deeper to rely less on rainfall for sowing.

4.2. Drought and heat expected to be the dominant yield limiting factors in the future

In the 1990s, heat, drought and frost were all major yield limiting factors (Figs. 4-5, 9; Chenu et al., 2013; Zheng et al., 2015a; Ababaei and Chenu, 2020). For the projected climate scenarios studied here, frost events are expected to become less frequent, while severe droughts and heat shocks are expected to become more frequent (Fig. 4). Even with the tested adaptation strategies, heat and drought are expected to keep strongly impeding wheat productivity across Australia in the 2050s, while frost is expected to remain a substantial issue mainly in the North-East (Fig. 5).

Historically, yield losses due to heat (Ababaei and Chenu, 2020), drought (e.g. Hochman et al., 2017; Fletcher *et al.*, 2020), and even frost (Zheng et al., 2015a, 2015b; Crimp et al., 2016) have increased in recent decades. For all projected climate scenarios tested in the 2050s (33 GCMs), frost impact on yield was reduced across all or almost all (for only a few GCMs) studied sites of the wheatbelt when sowing within OSWs from the 1990s. When adapting sowing windows to projected climates, frost-related yield losses were projected to increase in the 2050s compared with the 1990s only in sites from the North-East and a few sites from other regions (Fig. 5).

For future climates, previous studies agree on the major importance of heat and drought for wheat crops in Australian future (Lobell et al., 2015; Watson et al., 2017). Using current sowing practices (fixed dates or fixed sowing rules) for both the 1990s and 2050s, these two studies projected a substantial decrease in severe droughts in eastern Australia, which was not simulated when using OSWs for the 1990s (Fig. 4). However, when using OSWs for the 2050s, severe droughts were projected to decrease in eastern Australia and to increase in western Australia (Fig. 4), in accordance with projections from Lobell et al. (2015) and Watson et al. (2017), and historical trends from Fletcher *et al.* (2020). Such a reduction in severe droughts in eastern Australia were projected to occur despite reductions in rainfall (Fig. 2b), due to shorter crop growth cycles associated with higher temperatures (i.e. avoidance of terminal drought) and an increase in transpiration efficiency associated with elevated [CO_2] (Watson et al., 2017). When considering both sowing and cultivar adaptations, wheat crops could experience less severe drought, heat and frost by the 2050s in all regions except in the West where drought is still expected to increase (Fig. 9).

4.3. Limitations of such a study

It is essential to keep in mind that the results of this study strongly depend on (i) the crop model used (e.g. heat and frost stress impacts), (ii) the choice of the genotypes tested and their parameterisation (e.g. duration of the pre- and post-flowering periods), (iii) the choice of the management practices (e.g. sowing rules, fertilisation levels), and (iv) the projected climate scenarios. To focus on the latter, there is considerable uncertainty in climate projections (Fig. 3), which translates to high variability in the simulated results (e.g. Fig. 7b). Future [CO_2] is also highly uncertain, particularly later this century, as it depends on a range of geological, economic and technological factors and decisions that are difficult to anticipate (IPCC, 2014, p. 56). The RCP8.5, which is the high end of CO_2 emissions, is arguably the most justifiable choice for short- and mid-term projections, which are critical for breeding and other agricultural adaptations (Chapman *et al.*, 2012).

There is also large uncertainties in projecting future daily weather variations. Daily variations are expected to change along with climate change, particularly with regard to extreme events such as heat waves and floods (IPCC, 2014). Such variations are likely to have major effects not only on water-stress patterns, heat and frost but also on yield and adaptation strategies. By keeping patterns of rainfall, minimum and maximum temperatures broadly the same between the 1990s and 2050s, the projected changes in extreme events are likely to have been underestimated in this study. This is likely to be the case even for radiative frosts, despite the projected increase in minimum temperatures. For instance, frost events often occur during El Niño years, which are drier than average and may tend to become more frequent due to climate change (Stone et al., 1996; Bronya and Hayman, 2008). Historically, the number of frost events has decreased in some regions but increased in others, and the duration of the frost period has substantially increased in recent decades e.g. in southern Australia (Zheng et al., 2015a; Crimp et al., 2016).

4.4. *Australian wheat productivity could increase in the future*

An important finding of this study is that it might be possible to increase Australian national wheat production in future climates with relatively simple-to-implement adaptation strategies (Fig. 9). This stands in contrast to the findings of a number of recent studies. For example, Lobell et al. (2015) simulated negative impacts of 2050 climate scenarios (averaged across 33 GCMs) on wheat yield at all the locations they studied, in eastern Australia. While they used APSIM modified with a similar heat-stress model, they did not account for frost stress and did not endeavour to optimize sowing dates for either the base or future climates. Wang et al. (2018) also used APSIM to simulate the impact of climate change on wheat production across the Australian wheatbelt but did not consider the impact of heat and frost on grain development. While they simulated negative impacts of climate change on wheat yield in all Australian states for the 2050s with the RCP8.5, they concluded that adopting slower-maturing cultivars would help mitigate the shortening impact of increased temperature. In their study, this adaptation strategy along with earlier planting resulted in improved yields by 2050. Considering drought, heat and frost contributions, the current study found that with proper adaptation, average wheat yield is expected to increase nationally with considerable spatial variability at regional level (Fig. 9).

While two adaptation strategies were explored in this study (i.e. sowing time and pre-flowering development), many other adaptation measures could be considered, both in terms of management practices and genetic improvement (e.g. Kirkegaard et al., 2014; Richards et al., 2014; Robertson et al., 2016; Hunt et al., 2018; Kirkegaard, 2019). This includes the selection of genotypes with (i) adapted phenology in terms of pre- and post-flowering durations (Hyles et al., 2020), (ii) enhanced heat and drought tolerance (e.g. Tricker et al., 2018; Hunt et al., 2018), (iii) enhanced ability for seed to germinate at low water potential (Singh et al., 2013), and (iv) longer coleoptile (Rebetzke et al., 2007, 2016) to allow deeper sowing and better crop establishment on soils with a dry surface but enough stored moisture in the subsoil. These latter options may be increasingly important as autumn rainfall (April-May) has been declining in major Australian growing regions (Cai et al., 2012; Cai and Cowan, 2013) and are likely to further decrease by 2050 (Fig. 2b). While this option was not directly addressed in this paper, small amounts of irrigation added at sowing to force germination in the simulations can be considered as an imitation of deep sowing in a wet subsoil, at least in situations when the subsoil would be moist. Some of these adaptation measures are under active investigation by different research teams. They could be examined for the targeted environments using process-based crop models (Kirkegaard et al., 2014; Richards et al., 2014; Chenu et al., 2017).

5. Conclusion

The occurrence and yield impact of severe frost, heat and drought were quantified with a process-based crop model across the Australian wheatbelt for the 1990s (1976–2005) and 2050s (2036–2065). Adaptation strategies based on adaptation of sowing date and/or cultivar phenology were evaluated to maximise long-term simulated yields in the 2050s, but also in the 1990s, thus allowing fair comparison.

Optimum sowing windows in the 2050s were expected to start 9.6 days earlier than in the 1990s on average across the Australian wheatbelt for a mid-maturing spring cultivar. The crop cycle of the studied mid-maturing spring cultivar was projected to shorten by 9.9 and 12.6 days, on average, with and without adaptation of sowing dates, respectively.

Adapting the cultivar phenology to the target climates was associated to a reduced shortening or even an extension of the grain filling, at the cost of a greater shortening of both the vegetative phase and the entire crop growth cycle.

When adapting sowing time and cultivar phenology concurrently, severe droughts, heats and frosts were all projected to decrease in frequency compared with the 1990s, except in the West where more severe droughts would still be expected. This was the result of (i) planting crops earlier than in the 1990s or (ii) growing faster-maturing cultivars in parts of the wheatbelt. Overall, by 2050, early- and mid-spring genotypes were found most suited in the North-East and West, while long-maturing genotypes (slow-spring and fast-winter) performed better in the South and South-East. Nationally, Australian productivity was projected to increase by 4.6% by 2050 compared with the 1990s, if sowing time and cultivar adaptation strategies were adopted concurrently.

The findings of the study highlight the importance of local agronomic measures for adaptation to the current climate and future climate change, and the potential value of breeding programs for improved heat and drought tolerance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2021.100300.

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