



# Opportunities to enhance sugarcane yield and gross margin under climate change through irrigation and planting date adaptation

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## Abstract

Sugarcane is a vital crop for Australia's agricultural sector and regional economies. Although climate warming is expected to enhance sugarcane growth and yield in subtropical New South Wales (NSW), eastern Australia, it remains unclear how adaptive management strategies can be optimized to fully capture these potential benefits and maximize both production and profitability. This study applied the well-validated QCANE model, driven by downscaled projections from 27 global climate models under two Shared Socio-economic Pathways (SSP2-4.5 and SSP5-8.5), to evaluate sugarcane responses to planting date and irrigation adaptations in the major growing regions in northern coastal NSW. The results indicate that, without adaptation, future climate conditions were projected to increase sugarcane yield by 7–29% and gross margin by 3–40% relative to current levels (102–119 t ha<sup>-1</sup>; 2,180–2,818 AU\$ ha<sup>-1</sup>). Additional gains could be achieved with increased irrigation and later planting relative to current practice. Under both emission pathways, the optimal adaptation of combining targeted irrigation and delayed planting, substantially increased yield (38–82%; 157–190 t ha<sup>-1</sup>) and gross margin (31–98%; 2368–4487 AU\$ ha<sup>-1</sup>) by the end of the century, with improvements primarily driven by enhanced water availability and elevated CO<sub>2</sub>. These findings provide evidence-based guidance for growers to implement irrigation and planting adjustments to optimize yields, and for industry stakeholders to adapt operations in anticipation of shifts in peak harvest periods, thereby supporting the future productivity and profitability of the sugarcane sector under changing climate scenarios.

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## Introduction

Sugarcane (*Saccharum* spp.) plays an important role in food security and renewable energy supply worldwide (Heinrichs et al. 2017; Shanthi et al. 2023). However, it is highly sensitive to climate change, as rising temperatures, shifting rainfall patterns, and more frequent extreme events can strongly influence sugarcane growth and yield (Flack-Prain et al. 2021; Linnenluecke et al. 2018; Zhao and Li 2015). For example, rising temperatures were estimated to reduce sugarcane yields by 3–25% in India (Guhan et al. 2024; Singh et al. 2021; Sonkar et al. 2019), whereas climate change was reported to increase yields by 20–24% in Brazil (Marin et al. 2013; Singels et al. 2013). These region-specific responses highlight the uncertainty in both risks and opportunities for sustainable sugarcane production posed by climate change.

Agronomic adaptations, including adjustments to planting dates and applying irrigation, have been identified as effective strategies for managing the impacts of climate change (Haque et al. 2025; Linnenluecke et al. 2018, 2020; Misra et al. 2022). Adjusting planting dates enhances sugarcane growth by aligning physiological development with favorable climatic conditions and reducing climate-related risks, thereby maximizing yield and strengthening crop resilience (Chandiposha 2013; Jodder et al. 2016; Srivastava and Rai 2012; Zhao and Li 2015). For example, Ahmad et al. (2016) reported that advancing the planting date for spring sugarcane and delaying it for autumn sugarcane helped mitigate the adverse effects of rising temperatures in Pakistan by avoiding the coincidence of critical growth stages with heat stress. Similarly, in India, the optimal planting window was identified as March–April, as later planting led to yield losses from high temperatures (Verma et al. 2023). Irrigation is another key strategy that supplements insufficient rainfall, sustaining sugarcane production and reducing inter-annual variability. Several studies have demonstrated its necessity in regions where higher evapotranspiration and variable rainfall patterns intensify water limitations (Jones et al. 2015; Verma et al. 2019). However, there are few studies assessing the potential of adjusting planting date associated with irrigation levels change to maximize sugarcane production under climate change.

Australia is a major sugarcane producer globally (USDA 2025). More than 80% of its production is exported as bulk raw sugar, making the country the second-largest raw sugar exporter after Brazil (DAFF 2023). In Australia, sugarcane cultivation extends for about 2100 km along the eastern seaboard, from tropical Queensland to subtropical northern New South Wales (NSW) (Carlucci et al. 2021; Rahman et al. 2017). Temperature plays a vital role in sugarcane production, governing both successful planting (SRA 2025) and subsequent crop development (Ebrahim et al. 1998;

Inman-Bamber 1994). In tropical regions, the warm post-wet season climate favors mechanical planting during autumn and winter (USDA 2025). In contrast, in subtropical regions such as NSW, planting occurs in spring to avoid low soil temperatures and frost risk in winter that hinder germination and early growth (OGTR 2011; SunshineSugar 2022). Rainfall is also critical for sugarcane growth and yield, as more than half of Australia's sugarcane area relies primarily on rainfall, while supplementary irrigation is used in regions with lower effective rainfall (SRA 2017a, b). However, climate-dependent sugarcane growth and management practices may be affected under climate change. Temperatures in Australia are likely to rise by 1.3–4.4 °C by the end of this century under low- to high-emission scenarios (CSIRO 2025), along with altered rainfall patterns (CSIRO 2024).

Previous research has demonstrated that climate change could enhance sugarcane yield in Australia (Park et al. 2008; Singels et al. 2014). Beyond yield improvements, Sexton et al. (2014) reported that climate change may reduce harvest disruptions during winter due to changes in rainfall patterns, while increasing disruptions in spring in NSW. In the same region, Everingham et al. (2015) highlighted the beneficial effects of elevated CO<sub>2</sub> on sugarcane, particularly through reduced transpiration and alleviated water stress, a finding supported by Stokes et al. (2016), who observed declines in transpiration and stomatal conductance under higher CO<sub>2</sub> concentrations. More recently, Yao et al. (2026) demonstrated that climate warming can increase annual harvest frequency in NSW. Despite these advances, existing studies have primarily focused on the direct impacts of climate change on sugarcane production and growth under fixed specific management practices. The role of adaptive management practices in maximizing both yield and gross margin remains insufficiently explored. To address this gap, the present study shifts the focus from climate impact assessment to adaptive management optimization, thereby bridging the gap between understanding climate impacts and informing practical decision-making.

Process-based crop simulation models have been widely used in sugarcane studies to simulate the complex interactions between management practices and environmental conditions, making them powerful tools for evaluating climate adaptation strategies (Linnenluecke et al. 2018; Shanthi et al. 2023). Well-established process-based models for sugarcane include the Australian models QCANE (Liu and Bull 2001) and APSIM-Sugarcane (Keating et al. 1999; Wegener et al. 1988), the Brazilian SAMUCA model (dos Santos Vianna et al. 2020; Marin et al. 2017; Marin and Jones 2014), and the South African CANEGRO model (Inman-Bamber 1991; Inman-Bamber et al. 1993). In recent years, research has increasingly applied these models to optimize

management practices such as planting dates (Nadeem et al. 2022; Paixao et al. 2021; Verma et al. 2023) and irrigation strategies under climate change (An-Vo et al. 2019; de Oliveira et al. 2018; Farooq and Gheewala 2020). However, these models also have important limitations. For example, the APSIM-Sugarcane model omits respiration processes (Marin et al. 2015), which could lead to overestimated yields under climate change as carbon losses are not fully accounted for. (Bonnett et al. 2006; Singels et al. 2014; van Heerden et al. 2010). CANEGRO and SAMUCA simulate sucrose accumulation empirically from crop growth duration, temperature, and soil water status, but lack an explicit connection between carbon assimilation and sucrose partitioning. (Jones et al. 2011; Marin et al. 2023; Marin and Jones 2014; Singels et al. 2008). However, QCANE presents a more detailed physiological framework that incorporates respiration and explicitly links carbon assimilation with sucrose allocation among plant organs, with growth and maintenance processes modulated by phenology and environmental conditions (Liu 1996; Liu and Bull 2001; Liu and Helyar 2003; Liu et al. 1998).

This study applied the well-validated QCANE model to assess adaptive strategies for sugarcane yield and gross margin under future climate conditions in northern coastal NSW, Australia. Simulations were based on downscaled climate projections from 27 Global Climate Models (GCMs) under the Coupled Model Intercomparison Project Phase 6 (CMIP6). We aim to: (1) evaluate the interactive effects of irrigation and planting date on sugarcane yield and gross margin; (2) identify the most effective adaptation strategy for maximizing yield and gross margin under future climate conditions; (3) quantify the relative contributions of climatic variables and management practices to future yield and gross margin. This study advances current knowledge by providing a novel, quantitative assessment of management–climate interactions under changing climate conditions, identifying optimal management strategies that facilitate the effective use of climate change opportunities, and revealing key drivers of future productivity and profitability. The findings offer practical guidance for optimizing sugarcane production and support the development of climate adaptation strategies to sustain both yields and profitability for the NSW industry.

## Materials and methods

### Study sites

The study was conducted at three representative sugarcane-growing locations in northern coastal NSW: Condong, Broadwater, and Harwood, which correspond to the region's

major milling areas. Detailed descriptions of the sites and their long-term climate characteristics (1981–2020) are provided in Yao et al. (2026). Briefly, the region experiences a humid subtropical climate, with high summer rainfall and comparatively dry winters (Liu et al. 2021; Yao et al. 2026). Condong is the warmest and wettest site, whereas Harwood is the coolest and driest (Yao et al. 2026).

Sugarcane production in northern NSW is predominantly rainfed, supported by the region's high levels of effective rainfall (SRA 2017a, b). The planting season in NSW is typically from August to October (SunshineSugar 2022).

### Climate data

A detailed description of the historical climate datasets, future climate model selection, and downscaling methodology is provided in Yao et al. (2026). In the present study, two Shared Socioeconomic Pathways (SSPs) were considered: an intermediate middle-of-the-road pathway (SSP2–4.5) and a high-emission fossil-fueled development pathway (SSP5–8.5) (IPCC 2021). Soil data for three sites were extracted from the Soil and Landscape Grid of Australia (SLGA) based on the geographic coordinates of each site. The extracted soil properties included bulk density, air dry moisture content, lower limit (LL15), saturated water content, soil texture, organic carbon content, and pH.

### QCANE simulations

#### The QCANE model

QCANE is a comprehensive process-based model capable of simulating interactions among climate, soil, and management practices in sugarcane growth and development (Liu and Bull 2001). It explicitly links CO<sub>2</sub> concentration to photosynthesis, with sucrose serving as the central carbon pool that supplies structural and maintenance requirements on a daily basis (Liu and Bull 2001; Liu and Kingston 1995). This framework enables QCANE to capture the dynamic effects of environmental factors, including elevated CO<sub>2</sub>, rising temperatures, diurnal light variation, and the status of water and nitrogen, on key physiological processes (Liu and Bull 2001). Its comprehensive structure enhances the model's flexibility in simulating sugarcane responses to the combined influences of climate change and management practices. Responses of photosynthesis to CO<sub>2</sub> and temperature have been described by Liu and Bull (2001) and Yao et al. (2026).

The QCANE model describes the allocation of photoassimilates (CH<sub>2</sub>O) to different plant organs based on developmental stage, temperature, and daily growth conditions. Its respiration module includes both growth and

maintenance components, with respiration modeled as a fixed cost consuming about one-third of a unit of  $\text{CH}_2\text{O}$  for each unit of new tissue formed (Thornley and Johnson 1990). In contrast, maintenance respiration increases with biomass and temperature. In later growth stages, the large biomass of sugarcane increases the consumption of assimilated carbon for maintenance respiration, thereby leading to the reduced growth phenomenon (RGP) (Park et al. 2005). In the QCANE model, explicit incorporation of RGP enables a more realistic simulation of biomass and yield dynamics across different growth seasons and environments. This capability is particularly critical under climate change, given the high temperature sensitivity of respiration, which can offset potential productivity gains from factors like  $\text{CO}_2$  fertilization (Bonnett et al. 2006; Singels et al. 2014). Furthermore, QCANE accounts for differences between plant and ratoon crops by specifying different leaf area parameters (0.008 and 0.08), which reflects the role of stubble and root reserves in supporting subsequent crop cycles.

### Modelling scenarios

The model was validated at Condong, Harwood, and Broadwater using observed yields of Q208, the most widely grown sugarcane variety in NSW (Yao et al. 2026). Gross margin, calculated from simulated yields, on-farm sugar prices, and production costs, was subsequently validated and is presented in the Supplementary materials (Fig. S2; Table S2). Simulations for Q208 were conducted at the three sites from 1981 to 2100, encompassing a historical period (1981–2020) and a future period (2021–2100). The future was divided into a near-future (2021–2060; 2040s) and a far-future (2061–2100; 2080s). The sugarcane growth cycle in the simulations comprised one plant crop and three subsequent ratoon crops. In subtropical NSW, low temperatures can slow sugarcane development, resulting in crops requiring two years to reach harvest maturity. A threshold of  $13.5 \text{ t ha}^{-1}$  of sugar yield was applied to decide whether a crop was harvested after one year or extended to a second year (SRA 2024).

All simulations were conducted without nitrogen stress. Eight irrigation levels, ranging from rainfed to 70% of plant available water capacity (PAWC) in 10% increments, were evaluated (Table 1). This design was based on a sensitivity analysis of irrigation effects on sugarcane yield

(Supplementary Fig. S1), which indicated that yield gains plateaued beyond 70% PAWC. Furthermore, to capture seasonal variability under climate change, thirteen planting dates were also tested, scheduled weekly from August to October. Planting later than October was excluded, because current practices already avoid delays beyond September, and higher temperatures in October are unsuitable for germination (SunshineSugar 2022). In future, further temperature increases may make October planting even less viable.

In this study, the QCANE model output was reported as fresh weight, consistent with industry standards for gross margin calculation (ABARES 2022). Additionally, we used the secondary bias correction method to eliminate the non-stationary bias that occurred in the results derived from downscaled GCM data (Yang et al. 2016), with further calculation details provided in the Supplementary materials. The optimal planting window was defined as the period when the yield deviation from the maximum was within 1%. For the historical baseline (1981–2020) under rainfed conditions, this window was designated as the reference optimal planting window ( $\text{PW}_{\text{opt\_ref}}$ ). The associated maximum yield and gross margin were defined as the reference yield ( $Y_{\text{ref}}$ ) and reference gross margin ( $\text{GM}_{\text{ref}}$ ), while the corresponding management practices (rainfed with the respective planting date) were defined as the reference management practices ( $\text{MP}_{\text{ref}}$ ).  $Y_{\text{ref}}$  and  $\text{GM}_{\text{ref}}$  were derived from model simulations and represent long-term average values, because the available observational records span only a limited number of years and are therefore insufficient to represent long-term yield potential. These values were used as benchmarks for comparison with future yields, and projected yield increases indicate improvements beyond historical optimal conditions.

### Gross margins

Gross margins (GM,  $\text{AU\$ ha}^{-1} \text{ yr}^{-1}$ ) were calculated following SRA (2017a, b) and Topp et al. (2022). GM was estimated as the difference between total cane income (CI) and total production costs (TPC). CI at the farm gate was determined by multiplying yield ( $\text{t ha}^{-1}$ ) by the on-farm cane price ( $\text{AU\$ t}^{-1}$ ). TPC comprised management expenses (ME), and irrigation costs (IC). Detailed assumptions for cane prices and cost components are provided in Supplementary Table S3, while irrigation-related expenses are reported in Supplementary Table S4.

### The calculation of yield and gross margin change

To evaluate the effects of management practices on sugarcane yield and gross margin under future climates,  $Y_{\text{ref}}$  and  $\text{GM}_{\text{ref}}$  were used as fixed benchmarks. Changes in future

**Table 1** Management practices used in this study

| Management practices | Management levels                                                                   |
|----------------------|-------------------------------------------------------------------------------------|
| Irrigation           | No irrigation (rainfed), and irrigation from 10% PAWC to 70% PAWC in 10% increments |
| Planting date        | Weekly intervals from 1 August (01-Aug) to 31 October (31-Oct)                      |

yield ( $\Delta Y_{future}$ , %) and gross margin ( $\Delta GM_{future}$ , %) were then calculated relative to these benchmarks using Eqs. (1), (2):

$$\Delta Y_{future} (\%) = \frac{(Y_{future} - Y_{ref})}{Y_{ref}} \times 100\% \quad (1)$$

$$\Delta GM_{future} (\%) = \frac{(GM_{future} - GM_{ref})}{GM_{ref}} \times 100\% \quad (2)$$

where  $Y_{future}$  and  $GM_{future}$  represent the simulated sugarcane yield and gross margin, respectively, under different management combinations for the 2040s and 2080s in SSP245 and SSP585 scenarios.

### Statistical analysis of climatic and management factors affecting yield and gross margin

We applied multiple linear regression (Eq. 3) to quantify the contribution of climatic and management factors to projected changes in sugarcane yield and gross margin under climate change. The predictors included mean temperature ( $\Delta T$ , °C), rainfall ( $\Delta Rf$ , mm), solar radiation ( $\Delta Rad$ , MJ m<sup>-2</sup>), atmospheric CO<sub>2</sub> concentration ( $\Delta CO_2$ , ppm), and irrigation amount ( $\Delta Irr$ , mm). The regression equation was expressed as:

$$\Delta Y_{adapt\_opt} \text{ or } \Delta GM_{adapt\_opt} = a \times \Delta T + b \times \Delta Rf + c \times \Delta CO_2 + d \times \Delta Rad + e \times \Delta Irr \quad (3)$$

where  $\Delta Y_{adapt\_opt}$  and  $\Delta GM_{adapt\_opt}$  are the projected changes in optimal yield and gross margin, respectively, and a, b, c, d, and e are the estimated regression coefficients. Model performance was evaluated using the coefficient of determination ( $R^2$ ), with statistical significance tested at  $p < 0.05$ , 0.01, and 0.001.

Partial coefficients of determination (partial  $R^2$ ) was derived to evaluate how much each predictor explained the variance in yield and gross margin, defined as:

$$\text{Partial } R^2 = \frac{R_{full}^2 - R_{reduced}^2}{1 - R_{reduced}^2} \quad (4)$$

**Table 2** Optimal planting window and long-term average maximum yield and gross margin of sugarcane during the baseline period (1981–2020) at Condong, Broadwater, and Harwood

| Site       | Optimal planting window (PW <sub>opt_refer</sub> ) | Maximal yield (Y <sub>ref</sub> , t ha <sup>-1</sup> ) | Maximal gross margin (GM <sub>ref</sub> , AU ha <sup>-1</sup> ) |
|------------|----------------------------------------------------|--------------------------------------------------------|-----------------------------------------------------------------|
| Condong    | Sep 5–Oct 3                                        | 119 (Sep 12)                                           | 2818 (Sep 12)                                                   |
| Broadwater | Sep 19–Oct 17                                      | 117 (Oct 3)                                            | 2743 (Oct 3)                                                    |
| Harwood    | Sep 19–Oct 17                                      | 102 (Oct 3)                                            | 2180 (Oct 3)                                                    |

where  $R_{full}^2$  represents the  $R^2$  for the model including all predictors.  $R_{reduced}^2$  refers to the model with the predictor of interest removed.

## Results

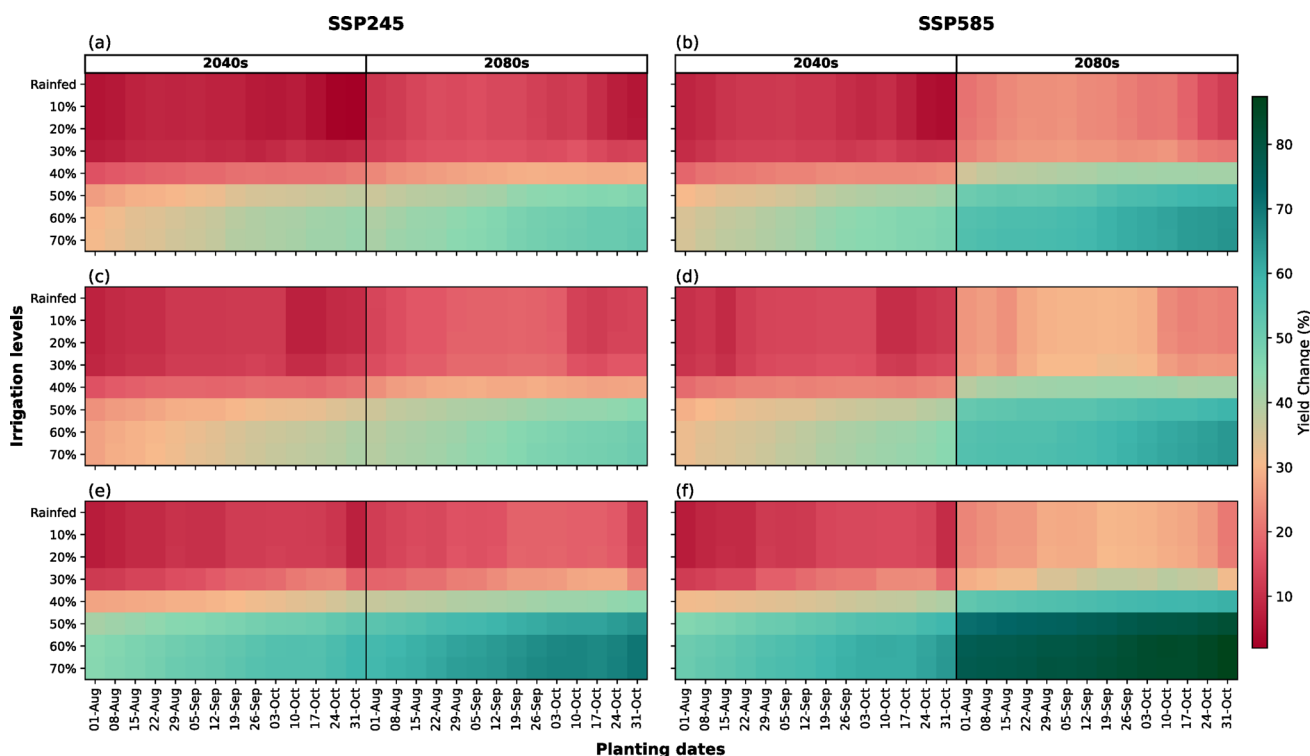
### Long-term optimal planting window, yield, and gross margin

During the baseline period (1981–2020), the optimal planting window (PW<sub>opt\_refer</sub>) at Condong was from September 5 to October 3, with the highest 40-year average yield ( $Y_{ref}$ ) of 119 t ha<sup>-1</sup> and average gross margin (GM<sub>ref</sub>) of 2818 AU\$ ha<sup>-1</sup> achieved from planting on September 12 (Table 2 & Supplementary Fig. S3). At Broadwater and Harwood, the PW<sub>opt\_refer</sub> spanned September 19 to October 17, with the highest values from planting on October 3, yielding 117 t ha<sup>-1</sup> and 2743 AU\$ ha<sup>-1</sup> at Broadwater, and 102 t ha<sup>-1</sup> and 2180 AU\$ ha<sup>-1</sup> at Harwood.

### Projected sugarcane yield changes under climate change across various adaptations

Projected sugarcane yields without adaptation increased by 7–18% under SSP245 and by 11–29% under SSP585 compared with  $Y_{ref}$  under MP<sub>ref</sub> (rainfed with planting on September 12 at Condong and October 3 at Broadwater and Harwood) across the three sites (Fig. 1). While Fig. 1 shows the multi-model average yields for clarity, inter-model variability for each scenario is provided in the standard deviation (SD) heatmaps in Supplementary Fig. S4. The future optimal planting window (PW<sub>opt</sub>) was estimated as August 17–September 21 at Condong, August 29–October 3 at Broadwater, and September 19–October 24 at Harwood. Relative to the PW<sub>opt\_refer</sub>, PW<sub>opt</sub> advanced by about 21 days at Condong and Broadwater but showed no advance at Harwood. At all three sites, the range of optimal planting window was extended by approximately 7 days.

Varying irrigation levels and planting dates resulted in contrasting yield responses under the two emission pathways. At low irrigation (10–20% PAWC), yield gains were negligible (<1% compared with rainfed), and modest at 30% PAWC (<15%). Under these conditions, the PW<sub>opt</sub> generally remained consistent with rainfed management. In contrast, increasing irrigation from 30% to 50% PAWC substantially boosted yields at each increment, with the most gains (16–23%) between 40% and 50% PAWC. Beyond 50% (60–70% PAWC), additional irrigation produced only slight improvements (<5%) before yields plateaued. At 50% PAWC, yield reached approximately 95% of the maximum obtained at 70% PAWC (Fig. 1), indicating that 50% PAWC



**Fig. 1** Projected sugarcane yield changes under different irrigation levels and planting dates for Condong (a, b), Broadwater (c, d), Harwood (e, f) in NSW. Simulations are based on 27 GCMs under SSP245 and

SSP585 scenarios for the near-future (2040s) and far-future (2080s). All yield changes are calculated relative to  $Y_{\text{refer}}$  (maximum yield under historical climate)

represented the optimal irrigation level. Delaying planting from August to October consistently enhanced yields, while no clear  $PW_{\text{opt}}$  was observed. Therefore, irrigation at 50% PAWC combined with the latest planting date (October 31) was identified as the optimal adaptation ( $\text{Adapt}_{\text{opt}}$ ). The sugarcane yield achieved under  $\text{Adapt}_{\text{opt}}$  was referred to as the optimal yield ( $Y_{\text{adapt}_{\text{opt}}}$ ). Increases in  $Y_{\text{adapt}_{\text{opt}}}$  ranged from 38 to 65% in the 2040s to 2080s under SSP245 and from 39 to 82% under SSP585 across the three sites.

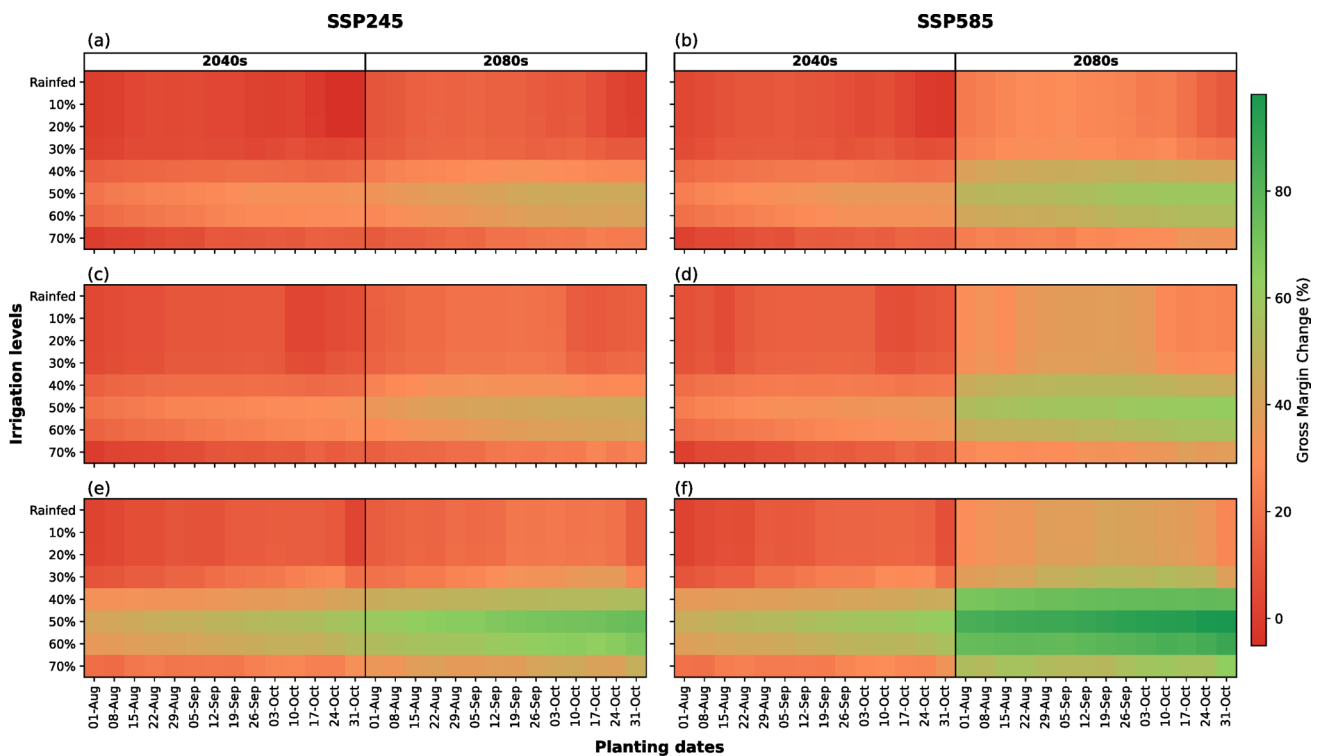
### Projected gross margin changes under climate change across various adaptations

Projected gross margins increased by 3–22% from the 2040s to the 2080s under SSP245 compared with  $GM_{\text{ref}}$  under  $MP_{\text{refer}}$  across the three sites (Fig. 2), with a greater increase of 9–40% observed under SSP585. Figure 2 shows multi-model average gross margins for clarity, while inter-model variability for each scenario is provided in the SD heatmaps in Supplementary Fig. S5. Across management combinations, gross margin responses closely followed yield patterns. Gross margin increases peaked at 50% PAWC irrigation, with further water inputs producing diminishing returns. Delayed planting also consistently improved gross margins. The optimal adaptation ( $\text{Adapt}_{\text{opt}}$ ) was the same as for yield, combining 50% PAWC irrigation with the

latest planting date (October 31). Under  $\text{Adapt}_{\text{opt}}$ , the optimal gross margin ( $GM_{\text{adapt}_{\text{opt}}}$ ) increased by 31–75% in the 2040–2080 s under SSP245 and by 35–98% under SSP585 across the three sites.

### Yield and gross margin under optimal adaptation

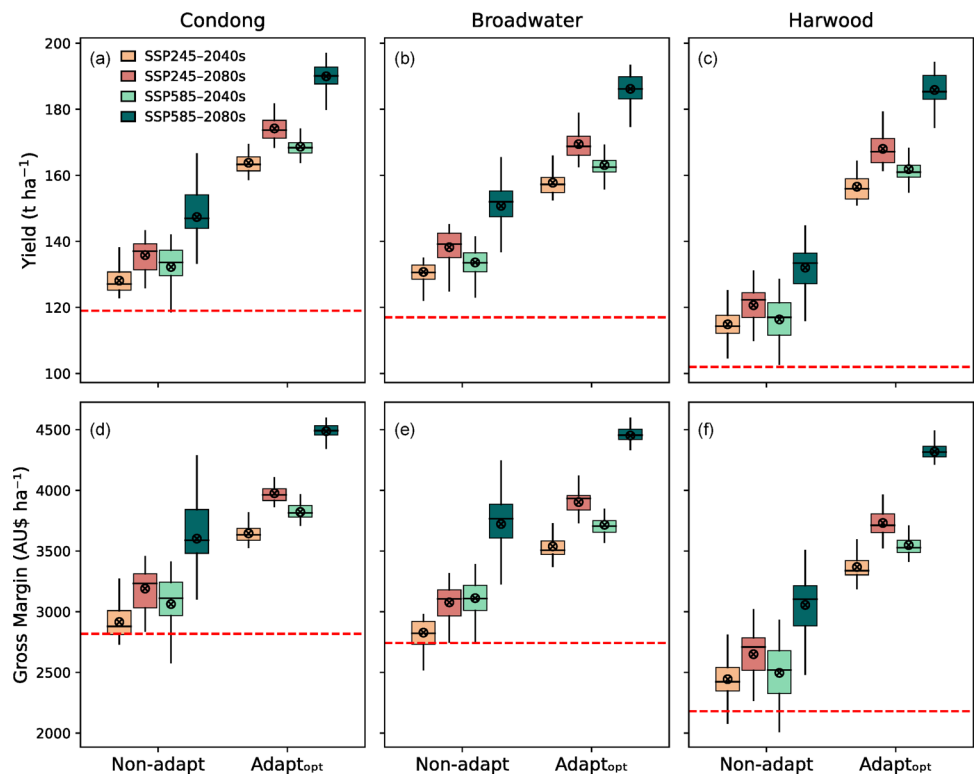
The combination of 50% PAWC irrigation and planting on October 31 was identified as the optimal adaptation ( $\text{Adapt}_{\text{opt}}$ ) for both yield and gross margin under future climate conditions. Across the three sites in NSW, average yield and gross margin without adaptation were projected to exceed the  $Y_{\text{ref}}$  and  $GM_{\text{ref}}$  under historical climate (Table 2), with yields ranging from 114 to 138 t ha<sup>-1</sup> under SSP245 and 116–151 t ha<sup>-1</sup> under SSP585 (Fig. 3). Corresponding gross margins ranged from 2444 to 3190 AU\$ ha<sup>-1</sup> under SSP245 and from 2496 to 3723 AU\$ ha<sup>-1</sup> under SSP585. Under  $\text{Adapt}_{\text{opt}}$ , both yield ( $Y_{\text{adapt}_{\text{opt}}}$ ) and gross margin ( $GM_{\text{adapt}_{\text{opt}}}$ ) increased substantially, with yields of 157–174 t ha<sup>-1</sup> under SSP245 and 162–190 t ha<sup>-1</sup> under SSP585. Corresponding gross margins reached 2368–3976 AU\$ ha<sup>-1</sup> under SSP245 and 3549–4487 AU\$ ha<sup>-1</sup> under SSP585.



**Fig. 2** Projected sugarcane gross margin changes under different irrigation levels and planting dates for Condong (a, b), Broadwater (c, d), Harwood (e, f) in NSW. Simulations are based on 27 GCMs under

SSP245 and SSP585 scenarios for the near-future (2040s) and far-future (2080s). All yield changes are calculated relative to  $GM_{refer}$  (maximum gross margin under historical climate)

**Fig. 3** Projected sugarcane yield (a–c) and gross margin (d–f) without adaptations (Non-adapt: rainfed, Sep 14 planting at Condong, and Oct 5 planting at Broadwater and Harwood), and with optimal adaptation ( $Adapt_{opt}$ : 50% PAWC irrigation and October 31 planting across all three sites). Results are shown for the near-future (2040s) and the far-future (2080s) based on 27 GCMs under SSP245 and SSP585 scenarios for the three regions. Horizontal dashed lines represent  $Y_{refer}$  and  $GM_{refer}$  (maximum yield and gross margin under historical climate). Box plots show the interquartile range (25th–75th percentile), with whiskers spanning the 10th–90th percentiles. The internal line and crosshair mark the multi-model median and mean, respectively



### Drivers of sugarcane yield and gross margin change

We used multiple linear regression to quantify the influence of future climate factors and irrigation on sugarcane yield and gross margin under  $Adapt_{opt}$  (Tables 3, 4). The model accounted for 98–99% of the variation in both yield and gross margin. All climatic factors positively affected yield, with irrigation,  $[CO_2]$ , temperature, and rainfall showing statistically significant contributions to increases in both yield and gross margin across all sites. Among all variables, changes in irrigation ( $\Delta Irr$ ) were the dominant driver of variation in both yield and gross margin, explaining 82–89% (partial  $R^2=0.82-0.89$ ) and 71–79% (partial  $R^2=0.71-0.79$ ) of the variance across sites, respectively. Following  $\Delta Irr$ , changes in  $[CO_2]$  ( $\Delta CO_2$ ) were the second most influential variable and the predominant climatic driver, with partial  $R^2$  values for yield ranging from 0.34 to 0.63 and for gross margin from 0.38 to 0.66. By comparison, temperature and rainfall had weaker yet significant ( $p<0.05$ ) influences on yield and gross margin, whereas solar radiation exhibited no statistically significant effect.

Regression coefficients indicated site-specific sugarcane responses to future climate change (Tables 3, 4). Condong was most sensitive to  $\Delta CO_2$ , with  $\Delta Y_{adapt\_opt}$  and  $\Delta GM_{adapt\_opt}$  increasing by 55 kg ha<sup>-1</sup> ppm<sup>-1</sup> and 1.86 AU\$ ha<sup>-1</sup> ppm<sup>-1</sup>, respectively. In contrast, Broadwater was least sensitive to  $\Delta CO_2$ , with corresponding increases of 33 kg ha<sup>-1</sup> ppm<sup>-1</sup> and 1.20 AU\$ ha<sup>-1</sup> ppm<sup>-1</sup>. Broadwater and Harwood had similarly high sensitivity to  $\Delta Irr$ , with yield increases of 124–125 kg ha<sup>-1</sup> per mm of irrigation and gross margin gains of 3 AU\$ ha<sup>-1</sup> per mm, while Condong was comparatively less responsive to  $\Delta Irr$ , with yield increasing by 106 kg ha<sup>-1</sup> per mm of irrigation and gross margin by 2.35 AU\$ ha<sup>-1</sup> per mm.

### Discussion

Projected climate change in NSW, characterized by rising temperatures and slightly reduced yet variable rainfall, was consistent with earlier Australian studies based on both global and regional climate models (AdaptNSW 2024; Nishant et al. 2021; Wang et al. 2018; Wang et al. 2022). Under future climate conditions, sugarcane yield and gross margin were projected to increase even without adaptation, with yield rising by 7–29% and gross margin by 3–40%. These positive responses to climate change were consistent with previous findings in Australia (Everingham et al. 2015; Sexton et al. 2014; Singels et al. 2014). In this study, we further found that the  $PW_{opt}$  without adaptation shifted earlier from early spring (September) to late winter (August) at Condong and Broadwater. This shift was driven by higher

**Table 3** Multiple linear regression coefficients for the relationship between projected yield changes under optimal adaptation ( $\Delta Y_{adapt\_opt}$ , 50% PAWC irrigation and October 31 planting across all three sites) and changes in temperature ( $\Delta T$ , °C), rainfall ( $\Delta Rf$ , mm), solar radiation ( $\Delta Rad$ , MJ m<sup>-2</sup>), CO<sub>2</sub> concentration ( $\Delta CO_2$ , ppm), and irrigation ( $\Delta Irr$ , mm)

| $\Delta Y_{adapt\_opt}$ | Site       | $a$ ( $\Delta T$ ) (kg ha <sup>-1</sup> °C <sup>-1</sup> ) | $b$ ( $\Delta Rf$ ) (kg ha <sup>-1</sup> mm <sup>-1</sup> ) | $c$ ( $\Delta CO_2$ ) (kg ha <sup>-1</sup> ppm <sup>-1</sup> ) | $d$ ( $\Delta Rad$ ) (kg ha <sup>-1</sup> m <sup>-2</sup> ) | $e$ ( $\Delta Irr$ ) (kg ha <sup>-1</sup> mm <sup>-1</sup> ) | $R^2$ | Partial $R^2$ |             |               |              |              |
|-------------------------|------------|------------------------------------------------------------|-------------------------------------------------------------|----------------------------------------------------------------|-------------------------------------------------------------|--------------------------------------------------------------|-------|---------------|-------------|---------------|--------------|--------------|
|                         |            |                                                            |                                                             |                                                                |                                                             |                                                              |       | $\Delta T$    | $\Delta Rf$ | $\Delta CO_2$ | $\Delta Rad$ | $\Delta Irr$ |
|                         | Condong    | 897*                                                       | 6.06*                                                       | 55.03***                                                       | 8.65                                                        | 106***                                                       | 0.99  | 0.09          | 0.05        | 0.63          | 0.00         | 0.89         |
|                         | Broadwater | 858*                                                       | 8.09*                                                       | 33.24***                                                       | 19.53                                                       | 124***                                                       | 0.98  | 0.08          | 0.05        | 0.34          | 0.00         | 0.82         |
|                         | Harwood    | 1126*                                                      | 14.48*                                                      | 40.91***                                                       | 5.29                                                        | 125***                                                       | 0.99  | 0.10          | 0.06        | 0.55          | 0.01         | 0.85         |

Significance levels: \* $p<0.05$ , \*\* $p<0.01$ , \*\*\* $p<0.001$

late-winter temperatures, which reduced cold stress, accelerated emergence, and promoted subsequent establishment, ultimately enabling substantial yields. Additionally, sugarcane planted in late winter aligned its grand growth stage (4–10 months after planting) with the wetter season from December to May (Liu et al. 2021), a period of rapid canopy expansion and biomass accumulation when crop water demand is highest and largely determines final yield (Baillie 2004; Gascho 1985; Nyati 1996). In contrast, at the southern Harwood, despite regional warming, future temperatures remained lower than in the two northern sites due to both cooler historical baselines and smaller increases. As a result, winter conditions failed to support the rapid early growth required to achieve spring-level yields, and  $PW_{opt}$  remained unadvanced. Additionally, the  $PW_{opt}$  broadened in the future, indicating greater flexibility in planting decisions and helping to reduce the risk of yield loss from unfavorable weather events.

We further assessed the combined adaptations in irrigation and planting dates to make full use of the potential benefits from climate change and optimize both sugarcane yield and gross margin. At the 10–30% PAWC irrigation, yield and gross margin only slightly improved compared with rainfed conditions. This was because irrigation events were nearly absent, as illustrated in Supplementary Figs. S6–S7, indicating that soil water rarely fell below 30% PAWC due to high levels of effective rainfall at these sites (SRA 2017a, b). Increasing irrigation had a pronounced effect on yield, with the greatest benefit observed at 50% PAWC, which was consistent with the previous study that irrigating at 50% PAWC, corresponding to 50% stem elongation, produced optimal yields in Australia (Ridge 2001). The results indicated that moderate irrigation effectively offset water deficits projected under variable rainfall, particularly when sugarcane was planted in October, as its late grand growth stage (June–October) with high water demand occurred during the drier season (June–November) (Liu et al. 2021). The optimal response at 50% PAWC reflected a balance between meeting crop water demand and achieving efficient water use under future climate conditions. This conclusion is further supported by gross margin results, which also peaked at this level. Beyond 50% PAWC, economic returns declined because the additional irrigation costs were greater than the small yield gains. These findings highlight the importance of identifying an optimal irrigation threshold that maximizes both yield and profit, especially under future climate scenarios with greater variability and constraints on water availability and costs.

Planting date was a critical management factor influencing future sugarcane yield. With sufficient irrigation, delaying planting from August to October increased yields, contrasting with rainfed conditions where planting in

October reduced yield after the optimal window. This was because delaying planting enabled sugarcane growth under higher temperatures in October and the following summer, shortening the periods of emergence, tillering, and canopy establishment, and allowing more time for the subsequent grand growth stage. This supported greater biomass accumulation and sucrose production, contributing to higher yields despite missing the peak rainfall months. Therefore, irrigation was essential for achieving the benefits of late planting, as it compensated for rainfall deficits and enabled crops to fully capitalize on the favorable thermal and radiation conditions associated with delayed establishment.

Statistical analysis further identified irrigation as the dominant driver of sugarcane production under climate change, whereas rainfall was less influential. This was because natural rainfall provided the primary water supply but lacked the reliability and control of irrigation. Both irrigation and rainfall directly determined water availability, which constituted the primary limiting factor for sugarcane yield (Inman-Bamber 2004; Singels and Bezuidenhout 2002). Under climate change, rising temperatures would raise crop water demand through increased evapotranspiration, and intensify water stress under reduced and more variable rainfall conditions (Jones et al. 2015). Water deficits restrict leaf expansion, reduce light interception, and suppress photosynthesis, thereby constraining biomass accumulation (Carr and Knox 2011; Gonçalves et al. 2019; Inman-Bamber 2004; Ma et al. 2021). Therefore, ensuring adequate water availability was essential for supporting physiological functions and enhancing yield. In addition,  $CO_2$  concentration also had a substantial influence on yield, ranking second only to irrigation. Elevated  $[CO_2]$  can promote sugarcane growth via the  $CO_2$  fertilization effect, enhancing photosynthesis and biomass accumulation, and ultimately leading to the yield improvement (De Souza et al. 2008; Reddy and Hodges 2000; Vu et al. 2006). Studies in Brazil and Australia indicated yield increases of 10–40% due to this effect (Biggs et al. 2013; De Souza et al. 2008). Furthermore, higher  $[CO_2]$  can partially reduce transpiration through stomatal closure, improving water use efficiency under rising temperatures and declining rainfall (Marin et al. 2013; Singels et al. 2014). Although sugarcane is a warm-season crop, temperature was a less significant factor influencing yield and gross margin because the crop growth was largely constrained by water availability, and adequate irrigation further reduced the temperature effects. In contrast, solar radiation was not identified as a significant driver of yield variation, as its projected change (–2% to 4%) was relatively small compared with other climatic variables (Yao et al. 2026). This finding was consistent with Ruan et al. (2018), who reported limited effects of solar radiation on sugarcane production in a future climate. Furthermore, in high-radiation environments

**Table 4** Multiple linear regression coefficients for the relationship between projected gross margin changes under optimal adaptation ( $\Delta GM_{\text{adapt\_opt}}$ , 50% PAWC irrigation and October 31 planting across all three sites) and changes in temperature ( $\Delta T$ , °C), rainfall ( $\Delta Rf$ , mm), solar radiation ( $\Delta Rad$ , MJ m<sup>-2</sup>), CO<sub>2</sub> concentration ( $\Delta CO_2$ , ppm), and irrigation ( $\Delta Irr$ , mm)

| Site                            | $a$ ( $\Delta T$ ) (AU\$ ha <sup>-1</sup> °C <sup>-1</sup> ) | $b$ ( $\Delta Rf$ ) (AU\$ ha <sup>-1</sup> mm <sup>-1</sup> ) | $c$ ( $\Delta CO_2$ ) (AU\$ ha <sup>-1</sup> ppm <sup>-1</sup> ) | $d$ ( $\Delta Rad$ ) (AU\$ ha <sup>-1</sup> MJ m <sup>-2</sup> ) | $e$ ( $\Delta Irr$ ) (AU\$ ha <sup>-1</sup> mm <sup>-1</sup> ) | R <sup>2</sup> | Partial R <sup>2</sup> |             |               |              |              |  |  |  |  |
|---------------------------------|--------------------------------------------------------------|---------------------------------------------------------------|------------------------------------------------------------------|------------------------------------------------------------------|----------------------------------------------------------------|----------------|------------------------|-------------|---------------|--------------|--------------|--|--|--|--|
|                                 |                                                              |                                                               |                                                                  |                                                                  |                                                                |                | $\Delta T$             | $\Delta Rf$ | $\Delta CO_2$ | $\Delta Rad$ | $\Delta Irr$ |  |  |  |  |
| $\Delta GM_{\text{adapt\_opt}}$ |                                                              |                                                               |                                                                  |                                                                  |                                                                |                |                        |             |               |              |              |  |  |  |  |
| Condong                         | 33*                                                          | 0.17*                                                         | 1.86***                                                          | 0.27                                                             | 2.35***                                                        | 0.98           | 0.10                   | 0.05        | 0.66          | 0.00         | 0.79         |  |  |  |  |
| Broadwater                      | 32*                                                          | 0.23*                                                         | 1.20***                                                          | 0.73*                                                            | 3.00***                                                        | 0.98           | 0.08                   | 0.04        | 0.38          | 0.00         | 0.71         |  |  |  |  |
| Harwood                         | 42*                                                          | 0.50*                                                         | 1.53***                                                          | 0.19                                                             | 3.04***                                                        | 0.99           | 0.11                   | 0.05        | 0.65          | 0.01         | 0.78         |  |  |  |  |

Significance levels: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$

like Australia, solar radiation rarely constrains sugarcane growth, thus exerting minimal impact on biomass (Wang et al. 2022).

Several uncertainties and limitations of this study should be acknowledged. First, the simulations were conducted under idealized conditions, without incorporating potential biotic stresses such as pests and diseases, or extreme weather events including heatwaves and cold spells. These stress factors can substantially constrain sugarcane growth and yield in future climates (AdaptNSW 2024). Such simplification could lead to an overestimation of productivity in the projections (Hussain et al. 2018; Zhao and Li 2015). Second, substantial yield and gross margin increases were projected, but these gains may be constrained in practice by increased nutrient requirements (e.g., N, P, and K uptake) and a higher risk of crop lodging, which were not explicitly considered. Consequently, the projected outcomes represent an upper-bound potential under optimized management conditions. Third, current sugarcane production in NSW is mostly rainfed, with supplementary irrigation applied only under extreme conditions (Everingham et al. 2015; SRA 2017a, b), making the highest simulated irrigation levels challenging to achieve under present conditions. However, as the industry is concentrated along the Clarence, Richmond, and Tweed rivers (SunshineSugar 2022), future infrastructure improvements and more efficient irrigation strategies could help approach these potential yields. These results highlight the gap between current practices and the theoretical yield potential under optimal irrigation. Finally, this study identified an optimal adaptation strategy under fixed irrigation and planting dates. However, such an assumption is unrealistic in practice. In commercial production, the harvest season extends over several months to align with the mill crushing period, requiring planting schedules to remain flexible and adjust to actual conditions. Therefore, the optimal management practices reported here should be regarded as reference points rather than prescriptive recommendations for growers. Future research should explore management systems by incorporating flexible planting and harvesting schedules and integrating additional practices that can enhance sustainability, such as fallow legumes, reduced tillage, mill mud application, and trash blanket retention (Biggs et al. 2013; Drewry et al. 2008; SRA 2008; Thorburn et al. 2011). This would allow assessment of adaptive strategies at the whole-farm scale and better capture the dynamics of commercial sugarcane production under changing climate conditions.

Our study provides evidence-based guidance for advancing sustainability in sugarcane production. Growers are suggested to adjust irrigation practices and delay planting to optimize yield and resource use under future climate conditions. As a result, mills may need to revise their operational plans, since peak harvesting and processing periods

could be shifted. At the policy level, the findings highlight the importance of investing in irrigation infrastructure and supporting the adoption of adaptive practices. Furthermore, breeding programs should prioritize developing sugarcane cultivars with improved water-use efficiency and enhanced drought tolerance to better cope with variable rainfall. Together, these strategies contribute to the long-term sustainability and resilience of the sugarcane industry and provide a foundation for designing future adaptation measures tailored to local production systems.

## Conclusion

This study evaluated the interaction effects of irrigation and planting date on sugarcane yield and gross margin under future climate scenarios in northern coastal NSW. The results indicate that climate change is likely to enhance sugarcane production, with further gains achievable through adaptive management. In particular, the combination of 50% PAWC irrigation and October planting was identified as the optimal strategy, substantially increasing both yield and gross margin, with improvements primarily driven by irrigation and elevated CO<sub>2</sub>.

By integrating agronomic and economic outcomes, this study provides a novel assessment of management–climate interactions and highlights the importance of adaptive strategies in maximizing future productivity and profitability. The findings have practical implications for growers in optimizing irrigation and planting schedules, for mills in planning harvest and processing operations, and for policymakers in supporting adaptive practices and infrastructure investment. However, the results represent an upper-bound potential, as simulations were conducted under idealized conditions and did not fully account for biotic stresses, operational constraints, or the feasibility of large-scale irrigation. Future research should incorporate more realistic farm management, including flexible planting systems and additional adaptation practices, to improve the applicability of these results.

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ing—review & editing. Jonathan K. Webb: Writing—review & editing, Supervision. Keyu Xiang: Writing—review & editing. Alfredo Huete: Writing—review & editing. Lihong Wu: Methodology. Quan Hao: Methodology. Qiang Yu: Writing—review & editing, Supervision.

**Data availability** The daily climate data including temperature, rainfall, and incoming downward shortwave radiation for 1981–2020 were downloaded from SILO (<https://www.longpaddock.qld.gov.au/silo/>). The original data on soil properties were acquired from the SLGA (<https://esoil.io/TERNLandscapes/Public/Pages/SLGA/>). The monthly future projections for radiation, precipitation, maximum and minimum temperature were obtained from 27 GCMs via the Lawrence Livermore National Laboratory (LLNL) (<https://esgfnode.llnl.gov/search/cmip6/>). On-farm sugarcane price and agricultural management costs used for gross margin calculations were obtained from the ABARES (<https://www.agriculture.gov.au/abares/research-topics/surveys/sugar>). All data will be made available by the authors upon reasonable request.

## Declarations

**Conflict of interest** The authors declare no competing interests.

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