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Yield gains of irrigated crops in Australia have stalled: the dire need for adaptation to increasingly volatile weather and market conditions

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ABSTRACT

The climate crisis demands the development of innovations that sustainably raise farm-gate profit under increasingly volatile conditions. Here, we review the literature on the Australian irrigated grains sector and show that yield gains have not progressed since 2002. We reveal a concerning trend of increasing demand for irrigation water on the one hand, yet declining availability of irrigation water on the other. We show that yield gains of Australian irrigated crops have not progressed since 2002, although the use of irrigation water has declined since 2013 and water-use efficiency of irrigated crops has marginally increased. These trends suggest that productivity gains realised by the adoption of new technology, skills and practices over time (including new crop genotypes, larger machinery, reduced tillage, automated irrigation sensors etc) have not been enough to overcome background changes in climatic and economic factors that influence yields of irrigated crops at the continental scale. We highlight a cruel irony that despite having the ability to alleviate water stress, farmers with access to irrigation are still very much dependent on rainfall, because low rainfall reduces regional irrigation supply and elevates water prices, making use of irrigation financially unviable. This, together with hastened crop development and higher risk of heat-induced floret sterility, has meant that the climate emergency has detrimentally impacted on yield gains of irrigated crops, although detrimental impacts have been mediated by rising atmospheric CO_2. We conclude that the greatest potential for improving the profitability and water-use efficiency of irrigated crops may be through adoption of integrated combinations of site-specific whole farm packages, including contextualised agronomic, financial and engineering interventions. Appropriate decision support system (DSS) frameworks can help users unpack some of this complexity, enabling land stewards to tactically navigate volatile climatic and market conditions to strategically plan for improved economic resilience and reduced climatic risk.

1. Introduction

In water-limited environments, irrigated crops with adequate nutrition and controlled biotic pressures often yield more grain than rainfed crops on a per unit land area basis (Amiri et al., 2016; Husain et al., 1988; Jaramillo et al., 2020; Kukal and Irmak, 2019; Muleke et al., 2022a; Sissons et al., 2014). For example, average annual grain yields of irrigated crops in Australia are 4 t per hectare (t/ha) compared with 1.8 t/ha for rainfed grains (ABS, 2019b). Many of the drivers underpinning historical productivity changes in Australian rainfed grain yield are applicable to irrigated crops (Pratley and Kirkegaard, 2019), though yield gains of irrigated crops have also been challenged by other factors. National rainfed yields of Australia's main rainfed grain crops (wheat, barley, oats and maize) have risen from 0.4 Mt. in 1861 to 31 Mt. in 2018 (ABARES, 2020b; ABS, 2013), with average yield increasing from 0.25 to 2 t/ha over the same period. These yield gains are amongst the lowest in the world, similar to those of Africa (Fig. 5; Ritchie and Roser, 2020), suggesting that further investigation into the drivers of and constraints to Australian rainfed and irrigated yields over time is warranted.

A common but recalcitrant misconception amongst agricultural practitioners is that higher productivity results in higher profitability. In the context of global food security, growing global population and rising affluence of the middle class (Harrison et al., 2021), higher productivity is surely a good thing in terms of bulk food production and alleviation of

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poverty (UN, 2021). While higher productivity at the global scale may be beneficial in terms of food security, higher yield at the farm level may not result in higher profitability; indeed, in some cases, higher yields may lead to excessive and/or unsustainable use of resources. At the enterprise level, high input costs – such as the cost of irrigation water – and/or low market prices for commodities can decouple potentially positive relationships between yield and profit. In these cases, higher yields result in lower profitability, particularly when water prices are high and grain prices are low (Monjardino et al., 2022; Muleke et al., 2022b).

Climate change exacerbates the 'cost-price squeeze' in irrigated farming systems (Chang-Fung-Martel et al., 2017; Harrison et al., 2017; Harrison et al., 2012a, 2012b). Under hotter, drier and increasingly variable climates, irrigation reserves from dams, groundwater and natural watercourses become limited (Harrison et al., 2014a). In response to both rising vapor pressure deficit and lower supply of water, regional demand for water increases (Bell et al., 2013), accelerating pressure on water reserves and causing water prices to rise. High water prices may deter farmers from using any water at all (Kukal and Irmak, 2019), instead encouraging them to on-sell their allocated quanta on water markets. Further uncertainty is added with climate change, with rising atmospheric greenhouse gas emissions contributing to altered seasonal distributions of rainfall, higher maximum daily temperatures and increased frequencies and intensities of extreme weather events, such as drought, frosts, heat waves and extreme rainfall events (Alcock et al., 2015; BoM and CSIRO, 2018; Harrison et al., 2016b; Harrison et al., 2014b; Phelan et al., 2015). A key aim of the present paper was thus to examine how climate change may impact on irrigated crops, given the bulk of previous research on climate change has centred on rainfed crops.

In many Australian cropping regions, key abiotic stresses that impact crop development and yield include frost in winter and early spring, and water stress coupled with heat stress during spring and summer (Harrison et al., 2011; Langworthy et al., 2018). Occurrence of these stresses during critical development phases can severely penalize yields (Sadras and McDonald, 2012; Sándor et al., 2020). Although water stress is less likely to impact yields of irrigated crops compared with rainfed crops, occurrence of frost and heat stress during flowering can still reduce grain number per spike and grain weight (Ibrahim et al., 2019; Liu et al., 2015; Sehgal et al., 2018), resulting in significant losses in grain yield and quality (Sehgal et al., 2018). Consequently, ensuring that anthesis occurs within an optimal flowering period (OFP) that is sufficiently late to avoid frost but sufficiently early to avoid heat stress is crucial to maximizing yield potential (Liu et al., 2020a; Liu et al., 2020b; Muleke et al., 2022a). While previous research has aimed to quantify OFPs of rainfed crops, little work has been undertaken for irrigated crops. Hypothetically, we would expect OFPs for irrigated crops to be later than those of rainfed crops, assuming that strategic use of irrigation later in the growing season is applied in a fashion that sufficiently alleviates stresses associated with water deficit.

Over 40% of Australian irrigation businesses are situated within the Murray–Darling Basin (MDB) (ABARES, 2020c). Profitability of rainfed and irrigated cropping systems varies across the farm businesses and between years, being driven by commodity prices, yields and variable costs such as repairs, maintenance, and labour. For many farm businesses, commodity prices govern profitability (Stretch, 2014), although water price and usage exert a greater influence on the profitability of irrigated farm business compared with other variable costs (North, 2010). Climate change and seasonal variability increase the volatility of farm financial income through impacts on grain price and water costs (Snow et al., 2021). Over the past decade, prices for major grains and water in Australia have fluctuated significantly. For example, wheat price has varied from AU$210/t[1] to $435/t (ABARES, 2020a) and from $20/ML to $550/ML (ABS, 2020a) respectively.

Against a background of market volatility, climate change and extreme weather events, farmers are faced with the need to make tactical decisions (e.g. crop choice and crop rotation, irrigation scheduling etc.) as well as strategic decisions that influence longer term outcomes (e.g. purchasing of machinery, borrowing large sums of money, approaches to soil carbon and many others; Alcock et al., 2015; Bell et al., 2015; Christie et al., 2018; Harrison et al., 2016a; Ho et al., 2014). Such complexity can lead to 'decision fatigue'; a phenomenon in which farmers become overburdened with important but persistent decisions. To help disentangle and navigate the solution space, various agricultural decision-support systems (DSS) have been developed (Ara et al., 2021). Rinaldi and He (2014) define DSS as software-based systems allowing decision makers to interactively contrast useful information from raw data, documents and knowledge to identify and solve problems and optimise decisions (Ara et al., 2021; Olsson and Andersson, 2006; Van Meensel et al., 2012). For irrigated cropping systems, DSS help users contrast multiple scenarios while controlling externalities, helping unpack some of the complexity in agricultural systems. To date, few studies have examined the impacts of climate change on irrigated cropping systems, presumably due to the tacit assumption that irrigation abates water stress.

The aims of this paper were to: (1) quantify longitudinal changes in Australian grain yields by characterising the historical evolution of the irrigated grains sector, considering major changes in policy, markets and agronomy, (2) illustrate biophysical and economic impacts of climate change and extreme weather events on yields and (3), elicit integrated, holistic systems adaptations that have had the greatest potential for improving profitability and water-use efficiency under hotter, drier and more variable climates.

2. Global irrigated cropping systems: where does irrigation primarily occur, and what types of infrastructure are used?

Perhaps the foremost use of irrigation is for relieving water stress, but irrigation has manifold other purposes, including frost protection (Snyder and Melo-Abreu, 2005), weed suppression (Williams et al., 1990), prevention of soil consolidation (National Geographic, 2022), minimisation of soil compaction (Liu et al., 2016), livestock cooling (Chang-Fung-Martel et al., 2017), dust suppression, sewage disposal and fertigation, the practise of supplying dissolved fertilisers in irrigation water (Kafkafi and Kant, 2005). Irrigated crop yields produce around 2.7 times the yield of comparable rainfed crops (Chellaney, 2014). Irrigated croplands provide >40% of global food production on <20% of the world's cultivated land (275 Million hectares (Mha) i.e. 2.75 Million Sq. km); UNESCO, 2020). In response to the rising global population, the area equipped for irrigation (AEI) has more than doubled, from 161 Mha (1.61 million km^2) in 1961 to 339 Mha (3.39 million km^2) in 2018 (FAO, 2021b). In 2018, approximately 67% of the AEI worldwide was in Asia, 17% in the Americas, 11% in Europe, 4% in Africa and 1% in Oceania (FAO, 2021b). Across 179 countries practicing irrigation in 2017, the largest AEI were those for China (54.1 Mha/0.54 million km^2), India (49.1 Mha/0.49 million km^2) and the United States of America (25.1 Mha/0.25 million km^2) as shown in Fig. 1.

Irrigation may be applied using surface, micro-, drip, flood, or sprinkler-based forms, for example (Table 1). Broadly speaking, irrigation infrastructure can be categorised into two main groups: surface/gravity irrigation; where water is applied to the root zone by gravitational flow over the soil, and pressurised irrigation, where water is applied through a pressurised pipe system with emitters or sprinklers (CDRC, 2012; Holzapfel and Mariño, 2008). In 2017, surface irrigation

[1] All economic values hereafter are given in Australian dollars (AUD) unless stated otherwise.

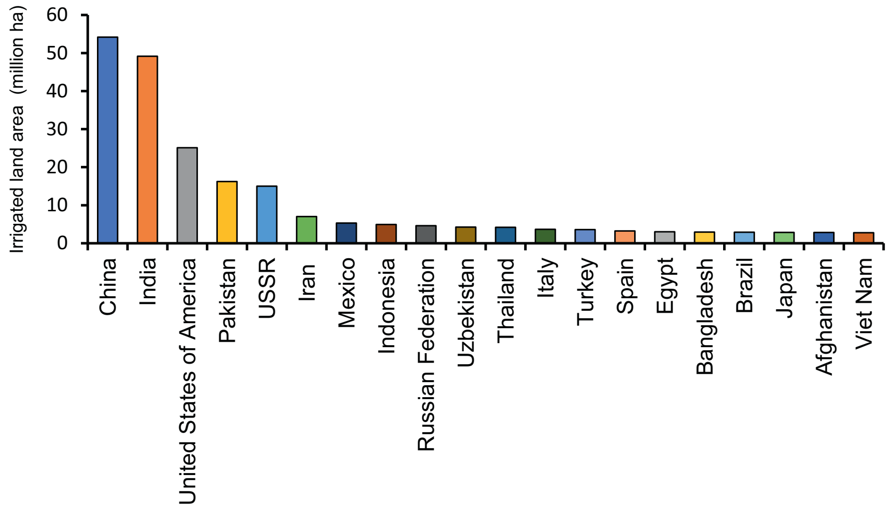

Fig. 1. Top 20 countries with the most land area under irrigation (million hectares) in 2018. Data sourced from: FAO (2021b).

Table 1
Main types of irrigation infrastructure and their extent of application in global agriculture.

Type	Purpose	References
Surface/gravity		
	Surface irrigation is also known as flood, gravity, border-check, or furrow irrigation and has been practiced for thousands of years. Surface irrigation is practiced by flooding an area of land that is bordered so to contain the water. Terraced rice fields are a good example of surface irrigation.	Hoque (2018); Rawitz (1973)
Pressurised systems		
Micro	Micro-irrigation, also referred to as localised irrigation, involves the distribution of water under low pressure through a piped network, in a pre-determined pattern, applied as a small discharge to each plant. Micro irrigation is more commonly used on high-value perennial crops, tree and vine crops, fruits, vegetables, and ornamentals.	Ayars et al. (2007)
Drip	In drip (localised or trickle) irrigation, water is applied at or near the root zone of plants through tubes placed in the field. Above ground drip emitters are commonly used in permanent horticulture (vineyards, fruit trees, etc.) while subsurface drip is installed for pasture or broad acre crops.	CDRC (2012); Goyal (2012)
Sprinkler	In sprinkler irrigation (e.g., solid sets, centre pivots and travelling irrigators), pressurised water is delivered in form of sprays via sprinkler nozzles. Sprinkler irrigation is suitable for most row, field, and tree crops.	Brouwer et al. (1988); Koech and Langat (2018); Megersa and Abdulahi (2015)

occupied 79% of irrigated lands globally (254 Mha/2.54 million km^2); approximately 53% of global surface irrigation occurs in India and China (FAO, 2021b). In 2017, sprinkler irrigation covered 11% of global AEI, the majority of which was in the USA (13 Mha/0.13 million km^2, 36%). Micro-irrigation is practiced in 95 countries on 3.6% (12 Mha/0.12 million km^2) of global AEI, with Brazil (21.5%, 3 Mha/0.03 million km^2) and the USA (2 Mha/0.02 million km^2: 16%) having the greatest areas of micro-irrigation (FAO, 2021a; Scarpare et al., 2016).

3. Irrigated cropping systems in Australia

Irrigated croplands in Australia produce 25% of national agricultural production from <5% of arable land area (ABS, 2020a). Forecasts suggest that increasing food demand will increase Australia grain production from 40 Mt./year in 2020 to 54 Mt./year by 2030 (Kingwell, 2019). These trends will be underpinned by a 40% expansion in irrigated land, increasing Australian water use by 20–30% (Burek et al., 2016). Such trends are a vital part of global food security (UN, 2019) but cannot be continued indefinitely. Increasing demand for water will increase pressure on environmental reserves, increase the risk of superfluous irrigation and increase competition between farmers and between agriculture and other sectors for water (Christie et al., 2020). Collectively, these trends underscore a clear and urgent need for social, economic and environmental solutions that carefully and strategically plan sustainable pathways for future irrigated land use (Harrison et al., 2021; Shahpari et al., 2021).

In Australia, 25 million hectares (0.25 million km^2) are sown with grain crops each year (ABS, 2018). Since 1961, the irrigated grain cropping area has increased from 1 Mha in 1961 to 24 million hectares in 1994 (Fig. 2). Since then, the irrigated grains area has fluctuated between 15 and 25 million hectares due to variable seasonal and water allocation, increased allocation to environmental flows (compared with that allocated for agricultural uses) (Grafton et al., 2011), marked declines in rainfall (Wei et al., 2011) and volatile water prices. Other factors influencing irrigation supply tend to be institutional, including restrictions on international trade, changes in allocation rules in regional and State water sharing plans, and increased access to carry-over (Goesch et al., 2020).

>66% of irrigated land and 40% of Australian irrigation businesses are located in the Murray–Darling Basin (MDB) (ABARES, 2020c). The Basin spans a million square kilometres and provides water to >2.2 million people in the States of New South Wales (NSW), Victoria (VIC), Queensland (QLD) and South Australia (MDBA, 2020). Annually, the MDB consumes two-thirds of all Australian irrigation water to produce 70% of irrigated grain production (ABS, 2020a), the majority of which occurs in NSW and Queensland (58% and 20%, respectively; Table 2 and Fig. 3).

The variability in water price and water storage for the southern MDB is illustrated in Fig. 10. There is an inverse relationship between water availability and price, with low supply corresponding to high

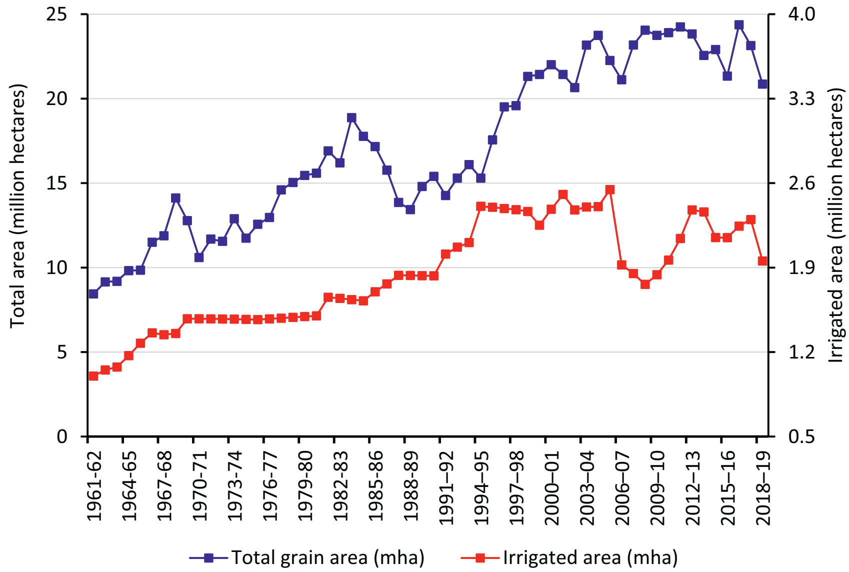

Fig. 2. Total Australian grain cropping area (blue line) and irrigated area (red line) in million hectares (Mha) from 1961 to 2019. Data sourced from ABS (2020a) and FAO (2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
The proportion of area sown to irrigated grains and the distribution of the main irrigated crops in each Australian state. Data sourced from ABARES (2019) and ABS (2020b).

State	Proportion of irrigated area (%)	Crop type
NSW	58	Wheat, barley, canola, oats, lupins, chickpeas, sorghum, cotton, lentils, field-peas, maize, rice, soybeans, sunflower
QLD	20	Wheat, barley, canola, oats, chickpeas, sorghum, cotton, maize, rice, soybeans, mungbeans
VIC	10	Wheat, barley, canola, oats, lupins, chickpeas, sorghum, lentils, field-peas, maize
WA	6	Wheat, barley, canola, oats, lupins, chickpeas, lentils, field-peas, maize
SA	4	Wheat, barley, canola, oats, lupins, chickpeas, lentils, field-peas, maize
TAS	1.2	Wheat, barley, canola, oats, maize
NT	0.02	Rice

prices. Although water supply is influenced by manifold factors, a fundamental driver is seasonal climatic conditions: water supply in the MDB is predominantly driven by rainfall, as precipitation supplies rivers and dams in the region (Goesch et al., 2020). This insight highlights a cruel irony of irrigation farming: like rainfed farmers, irrigation farmers are also very much dependent on seasonal rainfall for prosperous livelihoods.

Carryover effects (temporal displacement of water allocation rights) give irrigators more control on when and how they use their allocated water. Easing of carryover restrictions increased balances in high rainfall years following the Millennium drought (1997 to 2010; BoM, 2015; King et al., 2020). In general, carryover leads to higher water prices in years when carryover reserves are accumulated (typically wetter years) and lower prices in years when carryover reserves are drawn down (typically drier years; Goesch et al., 2020). Carryover has implications for water use and profitability of irrigation water, because often carryover reserves are either sold or used for low profitability enterprises (Goesch et al., 2020).

4. How have Australian grain yields changed over time?

Many factors contribute to Australia's low yield gains over time. Prior to 1900, soil nutrient depletion reduced yield (Fig. 4), although the introduction of superphosphate and trace element fertilisers, fallowing, and new genotypes raised yields from 1900 to 1950. National average yields increased further in the 1960s with the implementation of larger machinery, crop rotations (grain with legume pastures) and increase use of chemical herbicides (Kirkegaard and Hunt, 2010). Trends towards earlier sowing, break-crops and higher N fertiliser use accelerated yield increases in the 1990s (Christie et al., 2020; Flohr et al., 2018; Hunt et al., 2019). Rainfed yield gains after 1990 plateaued due to increasingly severe droughts, such as the Millennium drought between 1997 and 2010 (Heberger, 2011; Hochman et al., 2017).

Agricultural irrigation began in the MDB in the late 1800s, where a lack of reliable water supply due to drought prompted the establishment of the first irrigation schemes on the Yarra River. In the early 1900s, the Australian government allowed expansion of irrigation infrastructure and use in the MDB. From 1950s to 1980s, Australian irrigated cropping systems were characterised by rapid technological development with concurrent salinity management strategies, which improved irrigation efficiency and crop productivity. In the 1990s, introduction of the Murray-Darling Basin Act placed caps on river water diversions for irrigation and the trading of water entitlements to address the over-allocation of water resources. During the period between the 1950s and the 1990s, the irrigated area and grain yield significantly increased across Australia (Batten et al., 2003). The Millennium drought late 1996 to mid-2010 caused record low water flows resulting in hyper-salinisation, a 67% decline in water use and increase in water prices particularly in the MDB (Kirby et al., 2014). In response, irrigated grain yields fluctuated between 2.6 and 4.8 t/ha (Fig. 6). Following the devastation from the Millennium drought in 2010, new water reforms were developed, including the Murray-Darling Basin Plan and the Long-term State Environmental Watering Plan (Cosier et al., 2017). The Indian Ocean Dipole (IOD) drought from 2017 reduced irrigation water use on grains by up to 18%, though regional yields were little affected.

National irrigated grains yield progressed little in the decades following 2002 and were more closely linked to water use than irrigated crop area (Figs. 6, 7 and 8). This suggests that inter-annual variation in national irrigated grain yield has been driven by factors other than area sown. Irrigated water use and national yields dropped during 2009–10 due to prolonged dry conditions during the Millennium drought before rising again to a peak in 2012–13 (high rainfall La Niña years; BoM, 2015). Drivers of irrigated water use are less clear; however, from Fig. 4

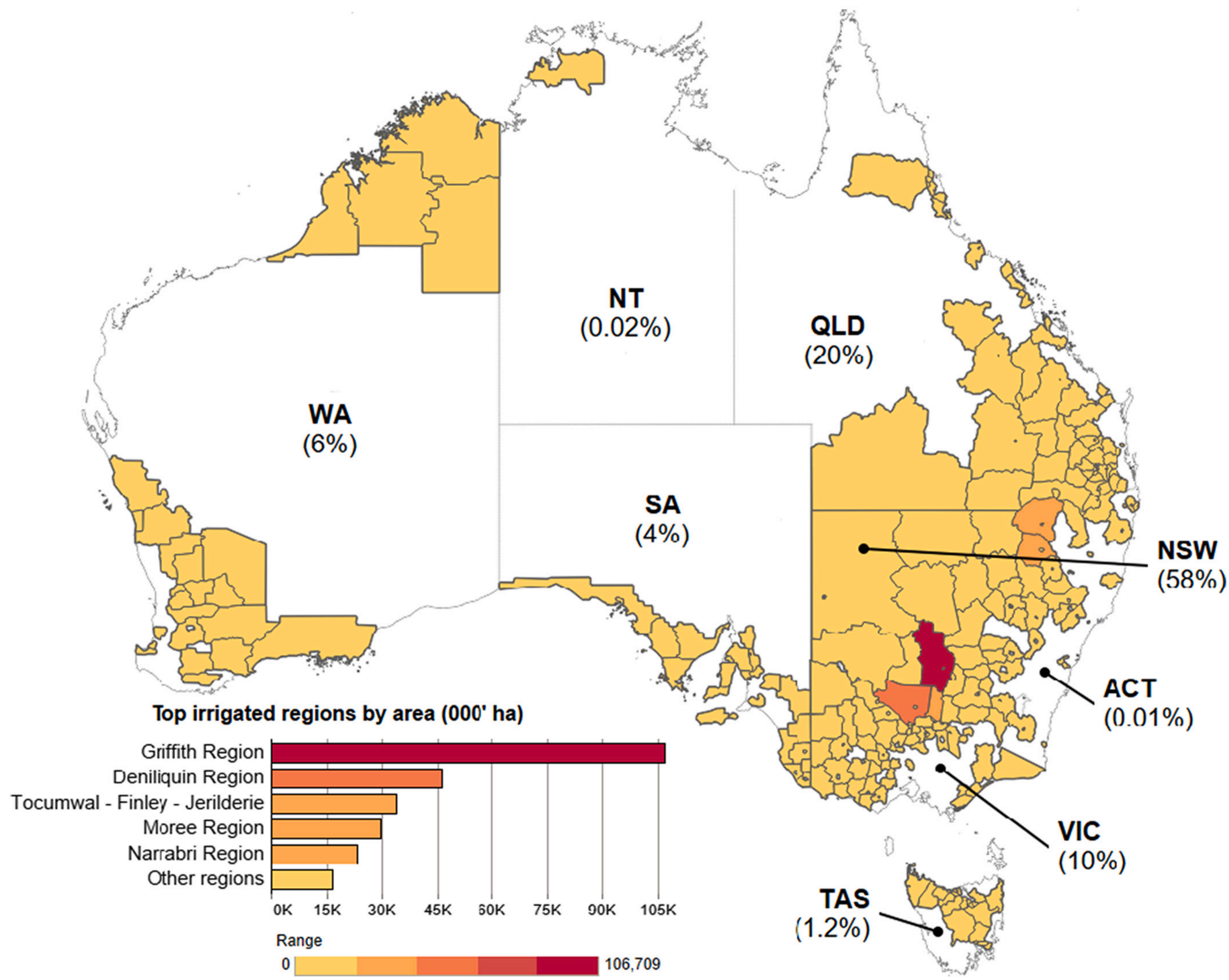

Fig. 3. Irrigated grains regions in Australia. Darker shading indicate higher intensities of irrigated cropping; percentage values show the proportion of grain cropping area sown to irrigated grains in each state. Figure developed using agricultural census data for 2015–16 obtained from ABARES (2019).

we may infer that reduced water use in 2009–11 was partly attributed to high-water prices (>$400/ML) and low irrigation storage that together reduced the ability of farms to use irrigation. The stasis in national irrigation yields may also be linked with other factors, including (1) conversion of irrigated lands to rainfed crops (Kirby et al., 2014; Millar and Roots, 2012), (2) adoption of more water-use efficient crops (Harries et al., 2022; Roth et al., 2013), (3) low research, development, and extension investment in irrigated grains (Hunt et al., 2014; Koech et al., 2021), and/or (4) low adoption of technologies to improve productivity and crop water use efficiency under irrigation (Koech et al., 2021; Maraseni et al., 2012). Collectively, these factors underscore an urgent need to develop, implement and encourage adoption of skills, practices, and technologies that both raise productivity and increase the water-use efficiency of irrigated crops. The development of curated databases of best management practices may be useful in this regard, similar to databases developed elsewhere (e.g. Falster et al., 2021).

5. Impacts of climate change and extreme weather events on the productivity and profitability of irrigated crops

Climate change and extreme events have substantive impacts on enterprise-scale production and economic performance of grain cropping systems (Hatfield and Prueger, 2015; Kukal and Irmak, 2019). Despite this, few studies have examined the impacts of climate change on irrigated crops, perhaps because of the implicit assumption that irrigation negates water stress. As we have shown above, irrigated agriculture is still very much at the mercy of the climate through indirect linkages between the impacts of rainfall on regional water supply and irrigation demand, and consequently water price.

6. Biophysical impacts of climate change

Key abiotic stress factors that impact grain crops are frost events in winter and early spring and water stress and heat stress during spring and summer (Table 3). Occurrence of these stresses during the critical periods of crop development cause severe yield reductions (Falster et al., 2021; Sadras and McDonald, 2012). Post-heading exposure to frost restricts grain number, sometimes causing death of entire spikes (McKenzie et al., 1982). A dryland study by Nuttall et al. (2019) showed that frost (−4 °C) during wheat heading and anthesis reduced grain number and yield by up to 40% and 31% respectively. In contrast, frost stress in irrigated wheat can reduce around 10% of the final yield (Leske and Biddulph, 2022). Heat stress (above 30 °C) during flowering damages floret fertility and can reduce grain weight and grain number per spike (Prasad et al., 2015; Sehgal et al., 2018). Other studies performed under rainfed conditions show that water stress during pre-anthesis and

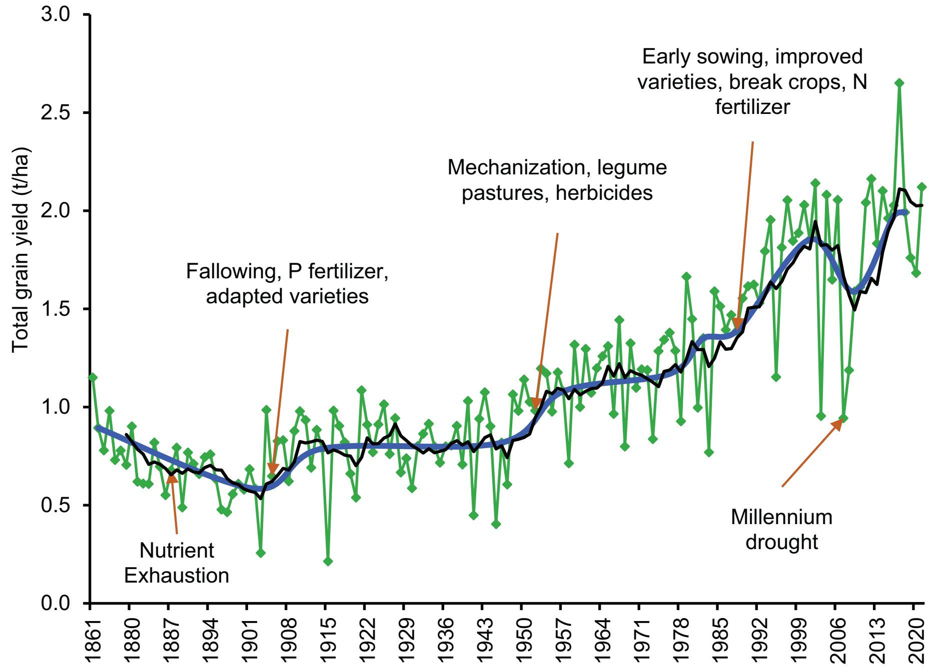

Fig. 4. Average rainfed yields of Australian grain crops (wheat, barley, oats and maize; green dots) with a 7-year moving average (black line) and smoothed trendline (blue line). Timing of key yield change drivers (management and breeding innovations) are indicated by arrows. Data sourced from: ABARES (2020b) and ABS (2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

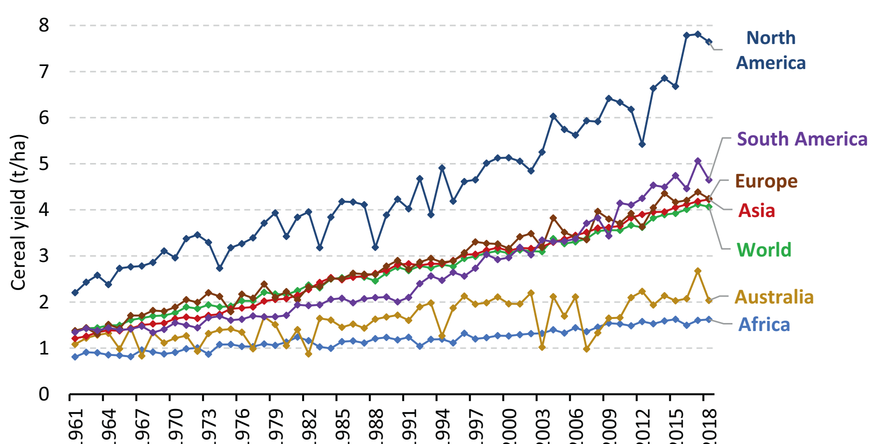

Fig. 5. Average rainfed yields of key grain crops (wheat, rice, maize, barley, oats, rye, millet, sorghum, buckwheat, and mixed grains) in North America, South America, Europe, Asia, Australia, Africa, and the World for the period 1961–2018. Data sourced from: Ritchie and Roser (2020).

at heading reduces grain number per spike by increasing rates of spikelet abortion and pollen sterility (Ji et al., 2010; Liu et al., 2015). For irrigated crops, watering at appropriate periods can negate the detrimental impacts of extreme heat and water stress on crop physiology, phenology and yield, particularly in the spring when crops are reproductive (Muleke et al., 2022a; Siebert et al., 2017; Tack et al., 2017; Vogel et al., 2019).

Increasing temperatures accelerate plant development and shorten the duration between flowering and maturity (Chen et al., 2020). Ababaei and Chenu (2020) showed that higher temperatures driven by climate changes have reduced the lifecycle of wheat by 1.6 days per decade since 1985, penalising yield by 4.6% per decade. Under irrigation conditions, Torrion and Stougaard (2017) found up that phenology of irrigated wheat was slower than that of rainfed wheat], whereby irrigation mitigated the hastening of physiological maturity. Fitzgerald (2020) showed a 56% increase in irrigated wheat under elevated CO_2 (550 ppm); however, yield improvement was accompanied by a 7% reduction in grain protein. Yields of irrigated wheat in the study of Fitzgerald (2020) were higher (1.2 t/ha) compared with those of rainfed wheat (0.7 t/ha) under conditions of elevated CO_2 because irrigation (extra 76 mm water; Fitzgerald, 2020) alleviated water-stress which reduced the shortening of the grain-filling duration thereby allowing the irrigated wheat to sustain photosynthetic production of biomass and grain yield near the end of the growing season.

7. Economic implications associated with climate change

Despite stagnating yield gains of irrigated crops, the gross value of irrigated agricultural production (GVIAP) at the national scale steadily increased between 2000 and 2018 (Fig. 9). GVIAP denotes the gross value of irrigated agricultural commodities at wholesale market prices (ABS, 2019c). Kirby et al. (2014) attribute GVIAP growth to improved

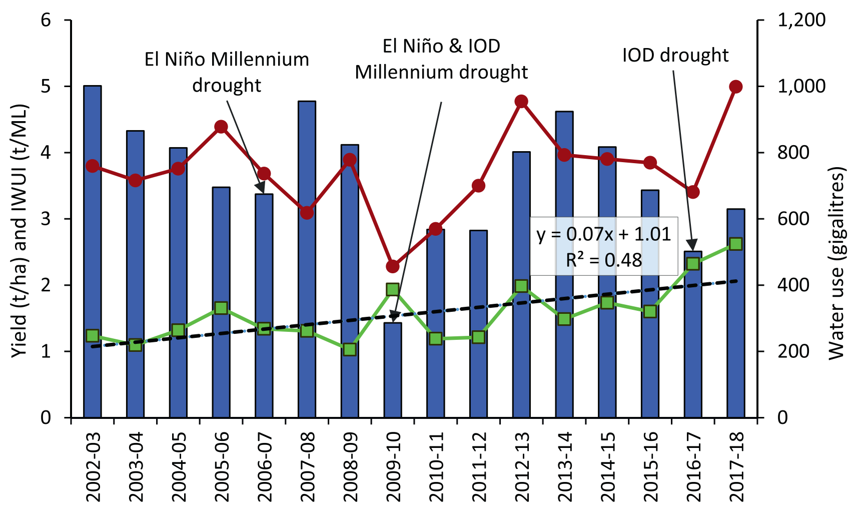

Fig. 6. Trends in irrigated grain yields (red line), water use (blue bars) and Irrigation Water Use Index (IWUI; green line) from 2002 to 2018. The dashed black line represents the long-term trend associated with IWUI (line of best fit). Yields were calculated as the gross value of irrigated agricultural production (GVIAP) divided by grain price. IWUI was computed from total annual grain yield divided by irrigation water applied as an indicator of water-use efficiency (WUE). IWUI shows the relationship between grain yield and megalitre of irrigation water supplied to a farm. Data sourced from ABS (2019a) and ABARES (2020b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

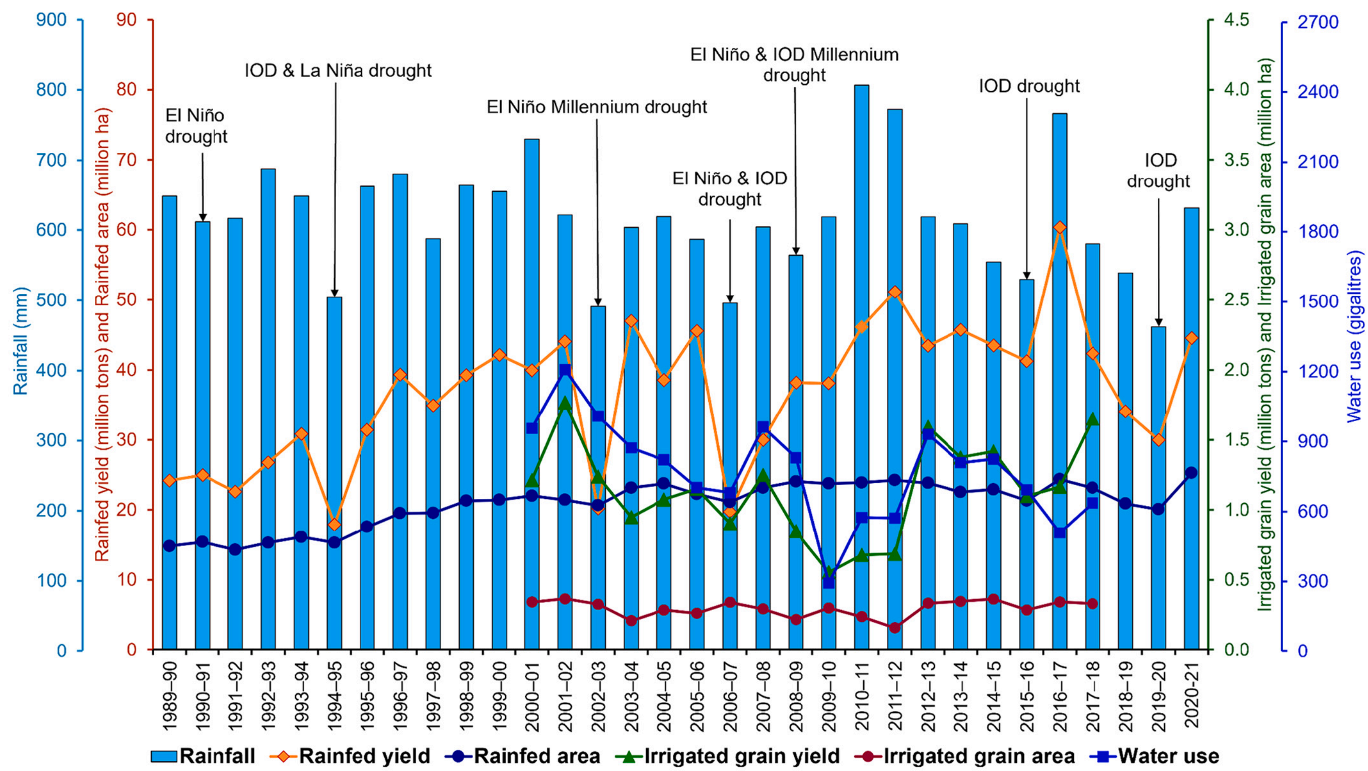

Fig. 7. Trends in nationally averaged yield for rainfed and irrigation grain crops (in million tonnes), area sown for rainfed and irrigated grains (million hectares) and annual rainfall (mm) in across Australia's irrigated regions from 1989 to 90 to 2020–21. Mean irrigated grain yield was estimated as gross value of irrigated agricultural production (GVIAP; gross value of irrigated agricultural commodities at wholesale market prices) divided by grain price. Data sourced from ABS (2019a), BoM (2020) and Jeffrey et al. (2001).

commodity price trends that have compensated for the declines in water availability and/or reduced area of irrigated crops sown in Australia.

At the farm level, droughts have caused high variability of Australian farm revenue through impacts on total factor productivity and farm price index. Total factor productivity (TFP; the conversion efficiency of inputs (e.g. labour, capital, land, water) into outputs over time (Gray et al., 2011) is a key determinant of profitability and an important mechanism for maintaining the international competitiveness of Australian grain crops (Hughes et al., 2017). During the 1980s and 1990s, TFP had strong growth in line with technological developments such as larger machinery, new and improved genotypes, improved water management, increased farm size and a better understanding of harvesting and planning strategies (Jackson, 2010; Knopke et al., 2000). However, from the mid-1990s, cropping TFP growth plateaued due to increasingly severe droughts and climatic variability (Hughes and Lawson, 2017).

Severe droughts and other extreme events limit grain supply relative to demand, increasing farm price index (FPI; measure of the average growth in prices that farmers receive at the farm gate for their product, and in the prices paid for inputs to production; Zammit and Howden, 2020). Enduring droughts during 2002–2003, 2006–07 and 2017–19 caused grain scarcity and increased consumer demand for grain that

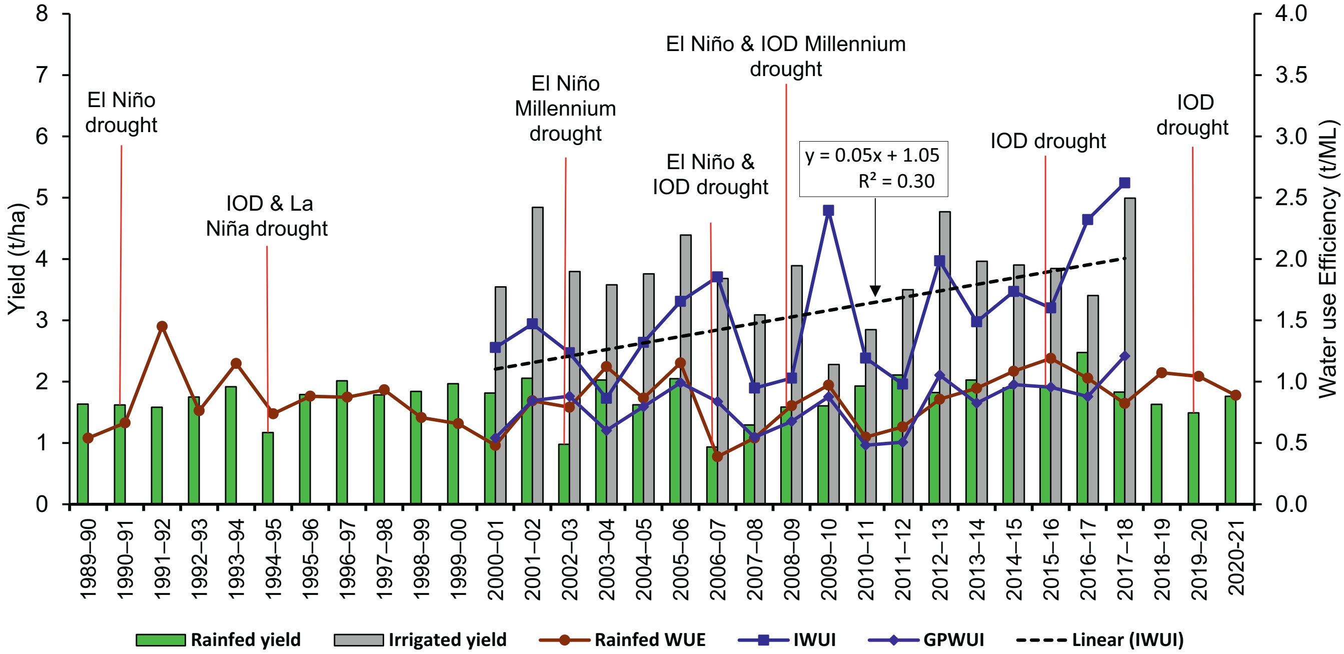

Fig. 8. Association between annual rainfall, average national yield and water-use efficiency of rainfed and irrigated grain crops (t/ha) for Australian irrigated regions from 1989 to 90 to 2020–21. WUE for irrigated grains is shown using Irrigation Water Use Index (IWUI) and Gross Production Water Use Index (GPWUI). IWUI was estimated as total yield (tonnes) per megalitre of irrigation water applied. GPWUI was estimated as total yield (tonnes) per megalitre water including bother irrigation applied and growing season rainfall. Dashed black line shows linear regression fitted to long term IWUI. Data sourced from ABS (2019a), BoM (2020) and Jeffrey et al. (2001).

Table 3
The impact of heat and frost stress at flowering on yield components of grain crops under irrigated and rainfed conditions.

Component	Stress	Impact on crop traits			Crop type	Reference
		Control	Treatment	% change		
Grain number (grains/m^2)	Frost (−4 °C)	15,890	9586	−40%	Dryland wheat	Nuttall et al. (2019)
Yield (kg/ha)		6822	4679	−31%		
Grain number (grains/m^2)		9900	8500	−14%		
Yield (t/ha)	Frost (−4 °C)	4.9	4.4	−10%	Irrigated wheat	Leske and Biddulph (2022)
Floret sterility (%)		28	59	−31%		
Yield (g/plant)	Heat (32/22 °C; max/min)	3.5	2.5	−29%	Dryland wheat	Djanaguiraman et al. (2020)
Grain weight/Thousand Kernel Weight (TKW)	Heat (36/24 °C; max/min)	39 g	21.5 g	−45%	Dryland wheat	Bala et al. (2018)
Floret fertility (%)	Heat (40/16 °C; max/min)	80	74	−6%	Irrigated sorghum	Prasad et al. (2015)
Grain weight (mg)		25	21	−12%		

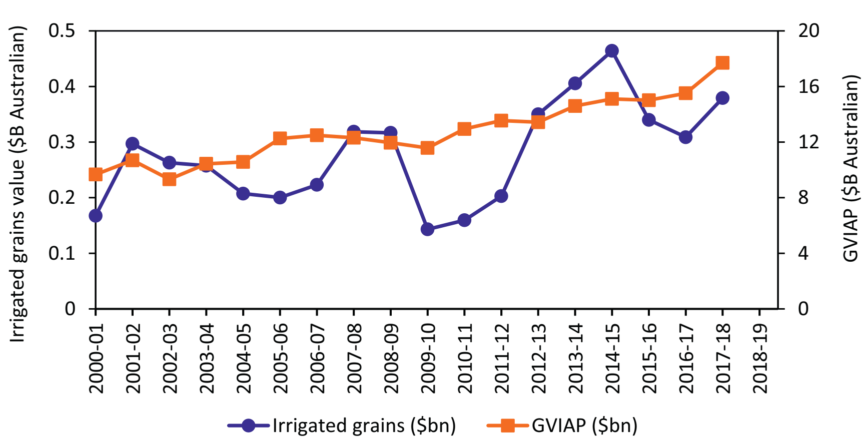

Fig. 9. Australian Gross Value of Irrigated Agricultural Production (GVIAP, orange line, right axis) and farm gate value of irrigated grains (blue line, left axis) in AU $B from 2000 to 01 to 2017–18. GVIAP shows the total economic value of irrigated agricultural production across Australia. Data sourced from: ABS (2020a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

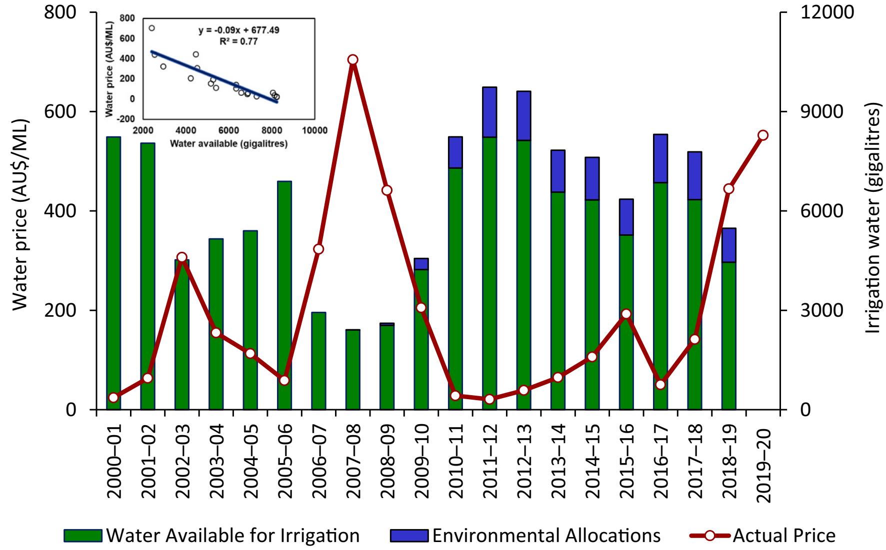

Fig. 10. Actual water prices (line), available irrigation water (green bars) and environmental water allocations for irrigation in NSW Murrumbidgee, southern Murray-Darling Basin (sMDB) from 2000 to 01 to 2019–20. Inset plot shows negative correlation between water price and the available irrigation water per year. Data sourced from Westwood et al. (2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

together elevated FPI and grain prices (Hughes et al., 2019). These trends were also observed during the 2017–19 drought, reducing the quantity of grain traded and decreasing profit by ~47% per farm (Litchfield, 2020). These trends indicate that periods of high FPI can partially offset lower regional yields caused by abiotic stresses (Hughes et al., 2019). However, income from irrigated crops is subject to more uncertainty than that of rainfed crops due to the price, allocation and availability of irrigation water (as discussed in Section 2).

Seasonal climate variability also impacts water prices (Fig. 10). While water supply and demand determine prices for irrigation water, rainfall tends to be the most predominant driver of irrigation prices, because rainfall primarily determines farm water supply (Westwood et al., 2020). For example, during the 2019 drought, the combination of low water allocations in the MDB and high water prices (~$444 per ML) significantly increased costs of production (Westwood et al., 2020).

Water trading often increases during drought (Khan et al., 2010) and may be an adaptation that facilitates income diversification. Trading water reduces dependence on income from grain commodities that may become too costly to produce during drought. However, water trading is subject to policy regulations that limit the extent of water sold/purchased, as well as mechanisms for setting prices. Water trading can also create other economic, social, environmental and ecological tensions (Harrison et al., 2021; Kiem, 2013; Shahpari et al., 2021), including issues of food security, because grain may no longer be the sole business focus of irrigation farmers. Modelling of future scenarios for the Southern Murray Darling Basin has shown that prices for irrigation water could become 50% higher if conditions become drier (Sefton et al., 2020). The same modelling predicts that future inter-regional and inter-sector competition for water will increase as climate change results in hotter and drier conditions in the region, driving up demand for irrigation water. To remain competitive and financially sustainable, Australian irrigators are thus in dire need of systemic and transformative adaptations that raise profitability ($/ML), reduce downside risk and increase the water-use efficiency (kg/mm/ha) of irrigated crops. This is particularly the case under conditions expected with climate change, including increased frequencies of extreme weather events, highlighting a need for advanced decision frameworks that account for and allow comparisons between agronomic, climatic, financial and social factors in a simultaneous manner (Harrison et al., 2020; Shahpari et al., 2021).

8. A simple economic heuristic for exploring irrigated crop profitability

To highlight the drivers of profitability in irrigated crops, we present a simple economic framework in Eqs. (1) or (2) (Eq. (1) is applicable to both rainfed and irrigated crops, while Eq. (2) is applicable only to irrigated crops). Crops with higher profitability have higher yield or grain price relative to variable costs (i.e., costs of fertiliser, repairs, labour, maintenance, sowing and chemical, etc). The profitability of irrigated crops is a function of additional variable costs including water use and water price. Higher profit per unit of water can be derived by higher grain price, yield or lower water use, water cost or variable cost. In cases where land area is limited and water use or price is low, computation of profitability on a per area basis (Eq. (1)) becomes more important. In contrast, where water prices or water use is high, profitability per unit of water comes to the fore (Eq. (2)).

$$Profit\ per\ unit\ area\ (\$/ha) = [grain\ yield\ (t/ha)\ x\ grain\ price\ \$/t] \\ -variable\ costs\ (\$/ha) \tag{1}$$

$$Profit\ per\ unit\ water\ (\$/ML) = \left\{[grain\ yield\ (t/ha)\ x\ grain\ price\ \$/t]-variable\ costs\ \left(\frac{\$}{ha}\right)-[water\ use\ (ML/ha)\ x\ water\ price\ (\$/ML)]\right\}\Big/water\ use\ (ML/ha) \tag{2}$$

An illustration of Australian crop profitability ($/ML) is shown in Table 4. The Table shows trade-offs between potential grain yield, grain prices, variable costs and water use in determining irrigated crop profits. At an overall long-term water price of $138/ML (BoM, 2021), cotton and

Table 4
Illustration of profitability per unit water for selected Australian irrigated grain crops assuming average grain prices, grain yields, irrigation water applied, variable costs and a long-term water price of $138/ML. Commodity prices were sourced from ABARES (2020b) and crop variable costs were adopted from McKellar et al. (2013).

Crop type	Commodity price ($/t or $/bale)[1]	Yield (t/ha or bales/ ha)[2]	Water use (ML/ ha)	Variable cost ($/ha)	Profitability ($/ML)
Cotton	510	13	8	2250	438
Mungbean	1150	2	2	865	436
Corn (maize)	384	12	5	1970	372
Grain sorghum	350	8	4	1260	203
Rice	345	10	5	1715	164
Chickpea	583	3	4	955	89
Wheat	334	5	4	985	58
Soybean	611	3	4	1210	31

[1] Prices for all crops except cotton are in $/tonne. Cotton price is shown as $/bale. The prices are based on an inflation-adjusted time series from the last ten years (2010–2020).
[2] Yield for all crops except cotton shown in tonne/ha. Cotton yield is shown as bales/ha.

mungbean are more profitable per ML water applied. The high bale yield per hectare offsets the high water-use and variable costs, resulting in greater profit for cotton, whereas high mungbean prices sustain high returns on irrigation investments, despite the low yield per hectare. Although the yield per unit of land for maize and rice are similarly high, commodity prices are low relative to the costs of water and other variable inputs to be more profitable in this example. However, these results would change according to water and grain prices, water use, grain yield and variable costs, amongst other factors. Various decision-support systems (DSS) have been developed to help disentangle the influence of these factors on profitability, though many DSS have evolved as a result of a technology push, rather than end-user pull (Ara et al., 2021; Harrison et al., 2020). There is also evidence to suggest that previous DSS do not adequately account for the uncertainty in commodity and water prices, suggesting a need for the development of advanced DSS that couple agronomic, climatic and economic factors into a single package (Ara et al., 2021).

9. Adaptations for improving profitability of irrigated crops under future climates

In light of more frequent exposure to extreme weather events and an ongoing 'cost-price squeeze', farmers must continually adapt just to maintain profitability (Harrison et al., 2017). While yield often increases with cropping intensification (e.g., application of greater nitrogen and irrigation), the rate of increase in variable costs at some point will surpass the rate of increase in yield. When the marginal gain in return is surpassed by the marginal gain in input costs, the profitability of an intervention begins to decline. This is known as the *law of diminishing returns* (Britannica., 2017). It follows that higher yields do not necessarily result in higher profitability, as demonstrated above by cases in which water prices are very high.

A promising pathway for improving irrigated crop yields and profitability may be through optimising flowering periods (OFP; Table 5). The OFP represents the flowering time that minimises the risk of frost and insufficient biomass accumulation (from flowering too early), and heat and drought (from late flowering) (Lilley et al., 2019; Liu et al., 2020a). Generally, annual grain crops have windows when yield is more sensitive to stresses (Sadras and McDonald, 2012). For grain crops, the critical window for determining floret production and the resulting grain number and yield is between stem elongation and shortly after anthesis (Sadras and McDonald, 2012). The OFP is influenced by phenology (genotype; G), location and season (environment; E) and sowing time (management; M), and significant G × E × M interactions influencing grain yield across environments have been identified (Harris et al., 2020; Ibrahim et al., 2019). Flohr et al. (2017) showing that OFPs for a rainfed mid-fast spring wheat genotype in southern Australia varied with site and season, ranging from 22nd August at Minnipa to 6th November at Inverleigh in NSW. Under irrigated conditions however, application of water decreases the impact of soil water stress and would hypothetically result in later OFP, though this hypothesis remains to be conclusively tested. Indeed, a simulation framework that adequately accounts for long term climatic conditions across genotypes and environments typically observed in the broadacre cropping regions of Australia would be ideally placed to examine this proposition. Given that water stress can be relieved by the strategic use of irrigation, but pollen sterility may still be induced by exposure to excessive heat later in the growing season, it remains to be seen how OFPs of irrigated crops compare with those of rainfed crops. Simulated numerical information that quantifies differences between OFPs of rainfed and irrigated crops in Australia could then be used to stipulate best management practices, in which practitioners vary key management interventions (sowing time, use of irrigation, crop type and genotype selection) to maximise the chances that flowering of irrigated crops for their region occurs within the desired calendar window. Questions also remain as to the extent of global warming on crop OFP, as well as the extent to which changes in flowering time may be countered by changes in sowing time.

While many studies have focused on adaptations that reduce yield gaps of individual paddocks or crops, few studies have analysed whole farm 'profit gaps' that consider the most profitable combinations of management practices particularly for irrigated grain crops. Some notable work that has focussed on whole farm adaptation has shown potential for high profitability responses under irrigated environments, including (1) optimising flowering times (Meier et al., 2020), (2) improving the efficiency of irrigation technologies (e.g. up to 64%, AU $2345/ha benefit attained with maize; Scott et al., 2020), (3) improving irrigation uniformity and scheduling (e.g. around 59%, AU$1484/ha for maize; Nascimento et al., 2019) and (4) improved crop rotations (e.g. AU$4751/ha increase in profitability for maize; Montgomery et al., 2017). One way to examine whole farm performance over the long term is through genotype (G) by management (M) by environment (E) analyses. Using suitably constructed whole farm models, G × E × M analyses can facilitate insight into how particular adaptations will perform over the long term in agronomic, environmental and economic dimensions (Christie et al., 2020; Harrison et al., 2019) (Farina et al., 2021; Harrison et al., 2014a; Harrison et al., 2016b; Harrison et al., 2011).

Engineering may represent a transformational adaptation to climate change and extreme weather events if applied in the right context. One example of an engineering solution is irrigation infrastructure, which can improve WUE (Mushtaq and Maraseni, 2011) by optimising production per unit of water through more timely and finite application of irrigation. Irrigation infrastructure can be broadly categorised into two groups (Table 6): (i) surface/gravity irrigation – where water is applied to the root zone by flow over the soil surface by gravity, e.g., furrow, border check, contour bay, siphon, and (ii) pressurised/sprinklers irrigation, where water is applied through a pressurised pipe system and emitters or sprinklers, e.g., centre pivot, lateral move, travelling irrigator, drip (CDRC, 2012). Surface/gravity irrigation technologies are more common in Australia due to their low capital costs and low energy requirements, accounting for 57% of the total irrigation area. Sprinkler/pressurised technologies cover 37% of Australian irrigated land area. A comparison of irrigation costs in Table 7 shows that siphons tend to have lower operating energy, maintenance, and capital setup costs, while drip irrigation has the highest costs. Given that the majority of Australian irrigation is applied through surface technologies, it is possible that more water-use efficient technologies would lead to higher water-use

Table 5
Agronomic, genotypic and engineering adaptations for improving the profitability of rainfed and irrigated cropping systems under historical or future conditions. 'Locality' describes the region in which the study was conducted. Abbreviations are shown at the base of the table.

Adaptation	Comments	Profitability		Crop	Region	Environment			References
		AU$/ha	Δ%[1]			Rainfed	Irrigated	Climate change[2]	
1. Agronomy/biophysical									
Crop rotation	- Cereal double-cropped pulse rotation at prevailing crop prices	337	80%	Sorghum Wheat	QLD, Australia	Yes	No	No	Cox et al. (2010)
	- Maize-maize-sunflower rotation sequence	4751	47%	Maize Sunflower	Northwest Cambodia	Yes	No	No	Montgomery et al. (2017)
N fertiliser rate	- More profitable to use higher N fertiliser rates for higher rainfall deciles and decrease the rate in lower rainfall deciles and/or as the growing season progress	143–652	17–83%	Canola 50 and 100 kg N/ha increments	NSW and SA, Australia	Yes	No	No	Meier et al. (2020)
No-tillage	- No-tillage increase the net return for both corn and soybean production	332	49%	No-Till Corn−Soybean (NTCS)	Mississippi, USA	Yes	No	No	Conway et al. (2020)
Soil and water conservation techniques	- Cultivation of maize crop on borders instead of terraces during short and long rainy seasons - Capturing and storing summer moisture using summer fallow periods	302	47%	Maize	Makanya catchment, Tanzania	Yes	Yes	No	Aluku et al. (2021)
Optimising flowering time	- Optimal combinations of sowing date and variety that achieve optimal flowering periods which increase yield and profitability	322–923	40–93%	Canola Sowing period 1–15 April	NSW and SA Australia	Yes	No	Yes	Ibrahim et al. (2018); Liu et al. (2020a); Meier et al. (2020)
Plant density	- Optimal density that achieves the highest gross margins	32–604 978 316	9–39% 89% 63%	Canola (15–45 plants m^{-2}) Maize (2–8 plants/m^{-2}) Maize (2–8 plants/m^{-2})	NSW and SA, Australia QLD, Australia QLD, Australia	Yes No No	No Yes (90 mm) Yes (270 mm)	No No No	Meier et al. (2020) Peake et al. (2008)
2. Genotype									
Cultivar type	- Greater profitability can be attained with both hybrid and conventional open pollinated (conv-OP) cultivars due to high yield potential	96–662	17–76%	Canola Hybrid - conv-OP cultivars	NSW and SA, Australia	Yes	No	Yes	Meier et al. (2020)
	- Hybrids have a higher profitability than the open-pollinated (OP) seed cultivars.	826	24%	Canola	SA and Victoria, Australia	Yes	No	Yes	McBeath et al. (2020)
Phenology	- Cultivars with slow to medium rates of development are most profitable for early sowings up to the end of April, except where rainfall is low	37–585	5–61%	Canola slow-medium cultivars	NSW and SA, Australia	Yes	No	No	Meier et al. (2020)
3. Engineering and technology									
Efficient irrigation technology and automation	- Irrigation efficiency improvements of existing technology e.g., improvements in border check layout over 250 ha.	485 801 2345	75% 55% 64%	Wheat Canola Maize	NSW, Australia	No	Yes	No	Scott et al. (2020)
Irrigation uniformity and scheduling	- Scheduling based on (option 1) simplified water balance in the soil proposed by FAO 56 (Allen et al., 1998) and (option 2) farmer's 15 years' experience.	773 1484	67% 59%	Maize, option 2. Maize, option 2 and 90% coefficient of uniformity (CU).	Albacete, Spain	No	Yes	No	Nascimento et al. (2019)

AU$/ha = Australian Dollars per hectare.
[1] Relative % change in profitability was estimated relative to the control/baseline in each study reviewed in Table 3. For example, if the baseline = $115/ha and adaptation = $150/ha, then % relative gain in profit was estimated as [(150–115)/115] *100 = 30%.
[2] Climate change denotes impacts of the changes in the mean surface temperature, atmospheric CO_2 and precipitation.

Table 6
Distribution area (hectares) of irrigation type by State in Australia–2008–09 (ABS, 2012).

	NSW	Vic	Qld	SA	WA	Tas.	NT	Aust.	%
Surface/gravity									
Surface	308,133	196,978	262,673	17,328	13,919	4067	542	803,640	44%
Drip above-ground	45,309	48,935	21,914	79,511	17,390	3003	1239	217,301	12%
Drip sub-surface	4995	5791	10,556	2459	1401	45	338	25,584	1%
Sprinkler/pressurised									
Microspray	10,718	22,004	28,181	13,896	4979	2033	3008	84,820	5%
Portable irrigators	22,696	14,816	24,767	1372	1217	16,297	19	81,185	4%
Hose irrigators	36,919	19,752	118,634	7434	356	30,442	68	213,604	12%
Large mobile machines	52,027	42,733	62,310	59,710	6161	29,469	631	253,041	14%
Solid set	4240	17,361	16,084	6841	4251	2001	21	50,800	3%
Other	28,961	19,551	22,292	11,548	4382	7955	357	95,047	5%

Table 7
Indicative capital set-up and annual operating costs of irrigation infrastructure (Redfern and Twine, 2020).

Irrigation type	Capital set up cost ($/ha)	Annual operating costs $/ha/annum)
Siphon	$1500/ha	$150 -$175/ha/annum
Automated smart siphons	$800 – $1100/ha	–
Bankless channels	$1500 – $2500/ha	$20/ha/annum
Lateral move	$6000/ha	$240/ha/annum
Drip	$9000/ha	$250/ha/annum

efficiency. Under future conditions expected for Australia including longer droughts and higher water prices, transitioning to more effective and efficient pressurised forms of irrigation may represent a transformational adaptation.

Few studies have concurrently assessed WUE and profitability for irrigation infrastructure, though there are some studies on the effect of infrastructure on cotton yields. Gall (2018) examined Gross Production Water Use Index (GPWUI) for cotton from 2010 to 2018 at Moree (NSW, Australia) and showed that the lateral move infrastructure produced the highest average GPWUI (gross yield per unit volume of water input) of 1.30 bales/ML and yield of 13 bales/ha. The lateral move technology was also reported to have a high flexibility to water multiple crops in the same season, which was an added feature of management flexibility not offered by the other irrigation technologies. While Gall (2018) did not find that any one technology consistently outperformed the others, the high GPWUI variation between seasons (0.44 bales/ML) compared to the low GPWUI variation between technologies (1.1 bales/ML), suggests that optimising the irrigation technology and management for the seasonal conditions is a prospective pathway for enhancing WUE and profitability of irrigated grain systems.

Automation of irrigation infrastructure may help optimise irrigation technologies and management, leading to improved WUE, yield and profitability. Automation is increasingly being used to address labour shortages, reduce labour costs and manage large operations, as well as to help improve irrigation efficiencies (Roth and Day, 2018). In Australia, there is increasing farmer interest in automating surface irrigation technologies (siphon and bankless). Gall (2018) reported that automated smart siphons with improved irrigation application uniformity had a cotton yield of 14.90 bales/ha compared with 12.20 bales/ha achieved with manual siphons. Automation of irrigation technologies is still in its infancy (Koech and Langat, 2018), with widespread adoption limited by costs associated with installation, availability of systems that provide flexibility to fit into the range of irrigation designs, available DSS and the telecommunication networks to support automation (Uddin et al., 2018).

Owing to the complex nature of irrigation cropping systems, many DSS have been developed to assist users explore multiple options without the risk of on-farm trial and error (Ara et al., 2021; Herold et al., 2018; Phelan et al., 2018). Planning and risk management DSS tools such as *CropARM* and Yield Prophet® provide cost-effective mechanisms for climatic risk management (Phelan et al., 2018). DSS designed to support decision making on irrigation water management include *WaterTrack Rapid*™, *WaterSched Pro Apps* and *IrriSAT*. *WaterTrack Rapid*™ is a commercial whole farm DSS tool that provides a simple web-based approach to calculating seasonal farm water balance.[2] *WaterSched-Pro Apps* consist of *CropWaterUse* tool which helps to assess the total water demand of irrigated crops, and the *WaterSched* tool used to manage irrigation scheduling decisions on farms across Australia.[3] While such tools are useful for determining water balances or irrigation scheduling, few DSS support end-users in making both tactical and strategic decisions that improve biophysical and economic outcomes. Recent work suggests that economic metrics associated with alternative irrigation infrastructure may be useful, given the relatively large initial capital investment required in such infrastructure and the practical constraints associated with alternative infrastructure. For example, Monjardino et al. (2022) show that whole farm intensification (with greater areas of the farm under irrigation, greater nitrogen use and more diverse crop rotations) generally had much greater impact on whole farm profit compared with effects of irrigation infrastructure per se. Monjardino et al. (2022) also demonstrate that analysis of multiple biophysical and economic metrics is necessary to identify trade-offs between alternative forms of irrigation investment. For example, drip irrigation tended to have the lowest annual water use but also lowest rate of return on investment, while flood (gravity) irrigation had the greatest water use and highest overall rate of return. Ara et al. (2021) conducted a comprehensive review of the application, adoption and opportunities for improving decision support systems in irrigated agriculture. Ara et al. (2021) reveal that past DSS have tended to be developed as a result of a technology push rather than end-user pull. This included a lack of documented end-user feedback on DSS and a general tendency to develop DSS for a particular region or site, with fewer developers opting to build on the past work of others. Ara et al. (2021) compiled a comprehensive table of various DSS that included strengths and weaknesses, the latter including a lack of inclusion of uncertainty in DSS outputs and few options for exploring both short and long term decisions (tactical and strategic). Ara et al. (2021) conclude that reasons for 'disadoption' (use followed by jettisoning of DSS) may indicate that heuristics promulgated may have been successfully learnt, obviating the need for future use of the DSS. From this, we suggest that more work on the use and disuse of DSS in irrigated agriculture is required, including the extent to which DSS outputs lead to changes in end-user decisions.

[2] The WaterTrack Rapid™ tool is available online at http://www.watertrack.com.au/

[3] The WaterSched-Pro Apps can be accessed at https://waterschedpro.net.au/

10. Conclusions

This review aimed to (1) quantify longitudinal changes in Australian irrigated grains yield gains, (2) illustrate biophysical and economic impacts of climate change and extreme weather events on yields and (3), elicit holistic systems adaptations that have potential for simultaneously improving profitability and water-use efficiency under hotter, drier and more variable climates. In addressing these aims, we uncovered many insights:

(1) Yield gains of Australian irrigated grain crops have progressed little over the last two decades. In fact, yield gains of rainfed grain crops have been greater than those of irrigated crops. These trends suggest that abiotic stresses, climate change and factors governing water use (mainly water price, availability, policy and infrastructure availability) have exerted a greater negative impact on the historical trends enterprise scale production and economic performance compared with the positive contributions realised with the advancement and adoption of new technology, skills, agronomy, genotypes and policy;
(2) Long-term temporal variability in national grain yield of irrigated grain crops is greater that the variability in the area of irrigated grain sown. This suggests that variability in national irrigated grain yields over time is driven by factors other than total area sown;
(3) Despite theoretically having alleviated drought stress and water deficit, irrigated crops are still impacted by climate change through indirect linkages between the impacts of rainfall on regional water supply and irrigation demand, as well as water price;
(4) The profitability of irrigated crops is susceptible to more factors than the profitability associated with rainfed crops;
(5) Higher productivity (grain weight per unit area) does not necessarily translate to higher profitability (gross margin per unit area);
(6) Further work is needed to determine the extent to which optimal flowering periods (OFP) of irrigated crops differ from those or rainfed crops, as well as the management levers (sowing time, crop type, genotype choice) needed to ensure that OFPs are achieved;
(7) Further work is needed to determine the extent to which OFPs have changed associated with globally warming, including the extent of change predicted under future emissions scenarios;
(8) There is an urgent need to raise the profitability of irrigated cropping systems. A prospective adaptation may be one that addresses key drivers as part of a whole farm system, entailing biophysical, engineering, genotypic and agronomic aspects. Investing in alternative irrigation infrastructure may be a transformational adaptation for improving profitability and WUE, although a comprehensive analysis of irrigation infrastructure remains to be conducted.
(9) Few whole farm DSS are available for irrigation farmers to facilitate contrasting of and insights into both tactical and strategic (longer-term) strategic economic decisions, as well as the reasons for adoption and dis-adoption of DSS.

Credit authorship contribution statement

MTH conceived the study. All authors contributed to the writing and revision of the manuscript.

Declaration of Competing Interest

The authors have declared no conflicts of interest for this article.

Data availability

Data will be made available on request.

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