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RESEARCH ARTICLE

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Sustainable intensification with irrigation raises farm profit despite climate emergency

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Societal Impact Statement

Despite comprising a small proportion of global agricultural land use, irrigated agriculture is enormously important to the global agricultural economy. Burgeoning food demand driven by population growth—together with reduced food supply caused by the climate crisis—is polarising the existing tension between water used for agricultural production versus that required for environmental conservation. We show that sustainable intensification via more diverse crop rotations, more efficient water application infrastructure and greater farm area under irrigation is conducive to greater farm business profitability under future climates.

Summary

- Research aimed at improving crop productivity often does not account for the complexity of real farms underpinned by land-use changes in space and time.
- Here, we demonstrate how a new framework—*WaterCan Profit*—can be used to elicit such complexity using an irrigated case study farm with four whole-farm adaptation scenarios (*Baseline*, *Diversified*, *Intensified* and *Simplified*) with four types of irrigated infrastructure (*Gravity*, *Pipe & Riser*, *Pivot* and *Drip*).
- Without adaptation, the climate crisis detrimentally impacted on farm profitability due to the combination of increased evaporative demand and increased drought frequency. Whole-farm intensification—via greater irrigated land use, incorporation of rice, cotton and maize and increased nitrogen fertiliser application—was the only adaptation capable of raising farm productivity under future climates. *Diversification* through incorporation of grain legumes into crop rotations significantly improved profitability under historical climates; however, profitability of

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this adaptation declined under future climates. *Simplified* systems reduced economic risk but also had lower long-term economic returns.

- We conclude with four key insights: (1) When assessing whole-farm profit, metrics matter: *Diversified* systems generally had higher profitability than *Intensified* systems per unit water, but not per unit land area; (2) gravity-based irrigation infrastructure required the most water, followed by sprinkler systems, whereas *Drip* irrigation used the least water; (3) whole-farm agronomic adaptation through management and crop genotype had greater impact on productivity compared with changes in irrigation infrastructure; and (4) only whole-farm intensification was able to raise profitability under future climates.

KEYWORDS

adaptation, climate crisis, climate emergency, food economic security, grain, infrastructure, irrigation, water

1 | INTRODUCTION

Irrigated agriculture is enormously important to the global agricultural economy (D'Odorico et al., 2020). In Australia, irrigated croplands produce over 25% of agricultural gross value from less than 5% of arable land area and use 60% of freshwater withdrawals (ABS, 2020a; Tariq et al., 2020). Increasing global food demand will increase Australia's grain crop production by an additional 35% between 2020 and 2030 (Kingwell, 2019); such growth will be partly underpinned by a 20%–30% increase in Australian agricultural water use (Burek et al., 2016). Increasing demand for water will likely increase tension between agricultural production and environmental conservation (Fleming et al., 2022), and this uncertainty will deepen as extreme weather events such as drought become more frequent with climate change (Feng et al., 2019; Harrison, 2021, 2021; Hobday & Lough, 2011; Silberstein et al., 2012). As well, global and local inflationary factors are exacerbating the 'cost–price squeeze' in irrigated farming systems (Chang-Fung-Martel et al., 2017; Harrison et al., 2012a, 2012b, 2017). Together, these changes are resulting in reduced stream flow and lake storage (Hobday & Lough, 2011; Silberstein et al., 2012; Walker et al., 2021). High water prices in conjunction with the rising prices for fertilisers, agrochemicals and energy relative to crop commodity prices borne by COVID-19 and the Ukraine war are key drivers of recent declines in profitability of irrigated farm businesses (FAO, 2022; Hughes et al., 2019; Snow et al., 2021). Collectively, these factors underscore a clear and urgent need for integrated social, economic and environmental solutions that carefully and strategically plan sustainable pathways for future profitable irrigated land use (Harrison et al., 2021; Shahpari et al., 2021).

Past work on agronomic adaptation to climate change has primarily focused on field-scale interventions such as changes to management and/or genotype/crop type combinations to improve yield (Ibrahim et al., 2019; Langworthy et al., 2018; Liu et al., 2021; Liu, Harrison, Hunt, et al., 2020) such as that aimed at closing yield gaps (Angella et al., 2016; Bryan et al., 2014; Liu et al., 2015, 2022; Muleke, Harrison, de Voil, et al., 2022; Pradhan et al., 2015). However, higher crop yields do not necessarily translate to higher crop profitability, because above a certain level of inputs, the rate of return from increased inputs diminishes (Ibrahim et al., 2018). Indeed, economic approaches that account for whole-farm productivity together with associated economic factors (input costs and prices) have received much less attention (Ara et al., 2021; Monjardino et al., 2022). Even though efficient irrigation technologies are known to represent crucial transformational adaptation to climate change, few studies have directly compared farm-scale economic performance of irrigation infrastructure in terms of yield and profitability (Ash et al., 2017; Maraseni et al., 2012; Mupaso et al., 2014; Mushtaq et al., 2013). Collectively, these observations suggest a clear need for frameworks that integrate and allow scenario testing of productivity and profitability at the whole-farm level.

At the farm scale, irrigated crop growers are faced with multiple and competing tactical (short-term) and strategic (longer term) decisions (Harrison et al., 2020; Liu, Harrison, Ibrahim, et al., 2020; Liu, Harrison, Shabala, et al., 2020), and often, forethought and planning of strategic decisions on irrigation infrastructure can be overlooked (Ara et al., 2021). An example of such strategic decision is the investment worth of a flood-based system compared with an overhead lateral or pivot system. Economic assessments of optimal irrigation infrastructure options are often fraught with uncertainty as they are at the nexus of many agronomic, climatic, financial and social factors that are changing dynamically over time (Harrison et al., 2016; Ho et al., 2014). Appropriate economic decision support system frameworks and digital tools that account for these factors may help farmers disentangle and navigate the solution space for strategic analyses through computation of long-term profit (i.e., net present value [NPV], return on assets and investment worth) over the life of the investment (e.g., 20 years). Currently however, few whole-farm economic decision support system tools are available for irrigation farmers to facilitate making such strategic economic decisions (Ara et al., 2021).

In an attempt to fill this gap, we developed '*WaterCan Profit*' (WCP)—a decision support tool designed and refined through iterative participative people-centric methods (e.g., farmer surveys, focus group discussions and semi-structured interviews) with eight farmer groups spread across the entire Australian Murray-Darling Basin, from South Australia, to northern Victoria and southern Queensland (Harrison et al., 2020). *WaterCan Profit* comprises a mathematical Optimiser Application ("Optimiser App") that allows users to contrast multiple tactical factors, including crop choice, cropping areas, water price, water use, expected crop yields, seasonal climatic conditions and historical farm management (e.g., crop rotation) (Muleke, Harrison, Eisner, et al., 2022). *WaterCan Profit* also includes an *Investment Application* ("*Investment App*") that allows strategic analyses through computation of long-term profit (NPV, return on assets and investment worth) over the life of the investment (Harrison et al., 2020). This work was conducted in response to a demand-driven need for whole-farm economic decision support system tools. Specifically, our aims here were to (1) illustrate the *Investment App* in *WaterCan Profit* using a case study and (2) examine the adaptation potential of whole-farm adaptation and alternative irrigation infrastructure on profitability under future climates.

2 | MATERIALS AND METHODS

2.1 | Overview

We examined holistic agronomic systems intervention (via intensification, simplification and diversification) and alternative irrigation infrastructure under historical (1985–2004) and future (2070–2089) climates. We used a case study farm in the Coleambally region of New South Wales (NSW) (Figure 1) to examine a factorial combination of the four agronomic interventions (*Baseline*, *Diversified*, *Intensified* and *Simplified*) crossed with four irrigation infrastructure interventions (*Gravity*, *Pipe & Riser*, *Pivot* and *Drip*), resulting in the 16 adaptation scenarios shown in Tables 1, S1 and S2. Biophysical input data for *WaterCan Profit* (WCP) were obtained (1) using the farming systems model APSIM Version 7.10 (Holzworth et al., 2014; Keating et al., 2003) and (2) using data from existing literature on experimental trials, for example, ABARES (2021), ABS (2021b), DPI (2018), GRDC (2020b) and Poole, Straight, and Jones (2020). Economic data were drawn from Monjardino et al. (2022).

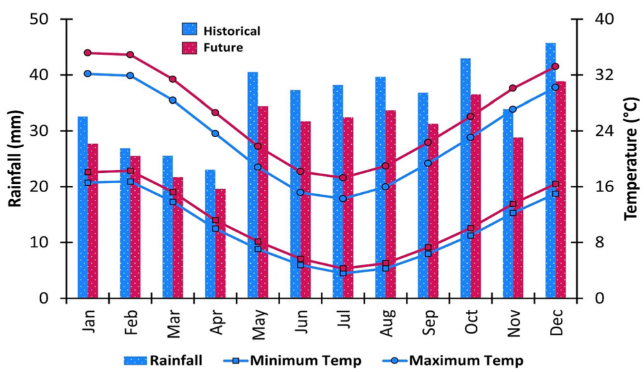

FIGURE 1 Historical (1985–2004) and future (2070–2089) climates for a case study farm situated in the Riverina of New South Wales (NSW), Australia

TABLE 1 Description of four holistic systems adaptations (*Baseline*, *Diversified*, *Intensified* and *Simplified*) in terms of crop choice, allocation of irrigation water, area of farm under irrigation and level of inputs and costs

Adaptation	Description
Baseline	The current farm system with gravity irrigation as the *historical Baseline* (described under Section 2.2). The *Baseline* scenario represents the current farm situation in terms of agronomy and irrigation.
Diversified	Diversification of the *Baseline* system using a grain legume (faba beans; *Vicia faba*). This adaptation has similar average water usage and irrigated farm area as the *Baseline*, a greater variety of winter crops grown within the year—i.e., wheat, canola and a grain legume—but similar inputs and costs.
Intensified	This was designed to be a high-input, high-output adaptation. Relative to the *Baseline*, the *Intensified* scenario applies higher amounts of water per unit area and per year and assumes a larger portion of the farm area is irrigated (i.e., less unirrigated fallow), higher inputs per unit area and year (e.g., N and herbicides).
Simplified	This was designed as a low-input, low-output adaptation. Relative to the *Baseline*, the *Simplified* scenario was designed to require less irrigation water per unit area and year, has more rainfed crops and reduced inputs per unit area (e.g., N and herbicides).

2.2 | Case study farm baseline

An irrigated broadacre farm situated near the Coleambally township in the Riverina region of NSW, Australia (−34.8016°S, 145.8904°E), was used as a case study (Figure 1). The region accounts for over 456,000 ha of irrigated farmland (CICL, 2019; Shi & Elmahdi, 2010) within the Murray-Darling Basin, Australia's largest irrigation zone. The warm temperate to semi-arid climate with hot summers, mild winters and trend towards drier spring conditions (Harrison et al., 2017; Harrison, Cullen, & Rawnsley, 2016) mean that use of irrigation is often necessary to reduce crop water deficit in the Riverina. Soil types include self-mulching sandy clay loam, red-brown earths and transitional red-brown earths with bulk density of 1600 kg/m^3 (0–0.3 m) and soil water holding capacity of 200 mm to 1.5 m. For the baseline, we adopted the average broadacre farm size of the region (approximately 1000 ha; DPI, 2018), with 750 ha of irrigated winter crops (e.g., canola–wheat–wheat) in rotation with summer fallow. Surface water supply is diverted from the Murrumbidgee River, ensuring that most farms have access to a minimum daily flow rate of 14 Ml/day (CICL, 2021). Most broadacre irrigators in the Riverina use surface/gravity irrigation methods, including lasered contour bays, bed/furrow and some border check; gravity irrigation was assumed as the baseline in the present study.

2.3 | Historical and future climate data

Historical climate data for daily maximum and minimum temperature, rainfall and solar radiation from 1 January 1985 to 31 December 2004 were sourced from meteorological archives (Jeffrey et al., 2001). Historical annual rainfall of the case study location was 423 mm, with 235 mm precipitating in winter and 188 mm in summer (Jeffrey et al., 2001); precipitation in the region is projected to decrease by 14% by 2070–2080 (see below). Historical average maximum and minimum daily temperatures were 23°C and 9.9°C, respectively, with projections suggesting an increase of 13% under future climatic conditions (see text below and Figure 1). All baseline simulations were conducted using an atmospheric CO_2 concentration of 380 ppm. We focused on the more extreme end of potential climate change projections, noting that near-term climate change estimates are likely to be less severe than those occurring towards the end of the 21st century. In adopting a 2080 climate horizon, we were afforded insight into which adaptations were likely to have greater economic and productivity efficacy when temperature changes were greater, and distributions of seasonal rainfall more variable. Future climate scenarios for each site were developed from 1 January 2070 to 31 December 2089 (median time horizon of 2080) using Representative Concentration Pathways 8.5 (RCP8.5) (IPCC, 2014; Schwalm et al., 2020), with the numeral representing a radiative forcing of 8.5 W/m^2 by the end of the century. We adopted RCP8.5 because this scenario most closely aligns with the existential climate (Bell et al., 2013; Chang-Fung-Martel et al., 2017; Phelan et al., 2015; Schwalm et al., 2020). Historical climate data were used to generate future climate data using monthly 'change factors' (CFs) prescribed from global circulation models (CCIA, 2021) to elicit average monthly changes in temperature and rainfall between the historical and future periods. Methods described in Harrison, Cullen, and Rawnsley (2016) were used to increase the frequencies of drought, heat waves and extreme rainfall events while preserving monthly average changes in climate. Atmospheric CO_2 concentration of all future climate scenarios was set to 850 ppm following Collier et al. (2011).

2.4 | Crop growth and irrigation infrastructure

We used the Agricultural Production Systems SIMulator (APSIM) v7.10 (Holzworth et al., 2014; Keating et al., 2003) to simulate growth and development of wheat (Brown et al., 2014; Wang et al., 2003), canola (Robertson et al., 1999), faba bean (Turpin et al., 2003), maize (Harrison et al., 2014), rice (Bouman et al., 2001) and cotton (Hearn, 1994). Following assessments outlined in Muleke, Harrison, de Voil, et al. (2022), irrigated crops were sown on fixed dates (mid-May for winter crops and mid-November for summer crops) and dryland crops were sown when sufficient autumnal rainfall opportunities occurred (i.e., 25 mm over 4 days), as shown in Table 2. Soil details were adopted from the APSoil database (Dalgliesh et al., 2012). Plant available soil water at sowing and application of irrigation water and nitrogen (N) fertiliser for the whole-farm adaptations (*Baseline*, *Diversified*, *Intensified* and *Simplified*) were set following Monjardino et al. (2022) (further details are shown below and in Tables 1 and S1). We adopted four levels of irrigation efficiency (0.7, 0.8, 0.9 and 1; Brouwer et al., 1985; Maraseni et al., 2012; Monjardino et al., 2022; Thompson, 2019) for the four irrigation infrastructure types (*Gravity*, *Pipe & Riser*, *Pivot* and *Drip*, respectively). Further details of irrigation infrastructure are shown in Table S1. To estimate maximum yield, we used optimal flowering periods (OFPs), defined here as the window that minimises long-term risk of abiotic stress exposure. The OFPs were computed as the flowering dates corresponding to ⩾95% of the maximum 15-day running average frost–heat yield according to Liu, Harrison, Hunt, et al. (2020) and Liu et al. (2021). The OFPs and average yield modelled in this study (Table 3) are close to results reported in field and simulation studies conducted adjacent to the case study region. Our simulated yields align closely with data reported by Monjardino et al. (2022), Muleke, Harrison, Eisner et al. (2022) and Muleke, Harrison, de Voil et al. (2022). Experimental field trials conducted at the Finley Irrigated Research Centre (−35.619083°S, 145.584803°E) in southern NSW found yields of irrigated winter crops (faba beans, canola and wheat) (Poole, Morris, et al., 2020) and maize (Poole, Straight, & Jones, 2020) that were within one standard deviation of that modelled in the present study (Table 4). Collectively, alignment of our results with those in the aforementioned studies lends confidence to the simulated data reported here.

2.5 | Whole-farm systems adaptations

The 16 adaptation scenarios were developed using a factorial combination of four whole-farm adaptations (*Baseline*, *Diversified*, *Intensified* and *Simplified*) and four types of irrigation infrastructure (*Gravity*, *Pipe & Riser*, *Pivot* and *Drip*) (Tables 1, 2 and S1, adapted from Monjardino et al., 2022). *Baseline* scenarios assumed 750 ha of irrigated canola–wheat–wheat in serial rotation, with which each winter crop followed by a summer fallow (Table 2 and Figure S1). Summer fallows stored water and nitrogen, incurring weed control costs (0–4 herbicide spray events). *Diversified* scenarios included a canola–wheat–faba bean rotation, with each winter crop followed by a summer fallow (750 ha). Relative to *Baseline*, *Simplified* scenarios were allocated lower irrigation rate and irrigated farm (only 50% of wheat area; 375 ha); dryland canola was sown on 750 ha of the farm area (Table 2 and Figure S1). *Intensified* scenarios were irrigated at higher rates (Ml/ha), assuming 750 ha for the winter crops (canola and wheat) and 25% of the farm area (188 ha) for summer crops (maize, cotton and rice), with the remaining 75% of farm area fallowed in summer. Nitrogen fertiliser rates for each crop type in the *Baseline* scenario were obtained from the case study farmer. We then matched these fertiliser rates for corresponding crops in the *Diversified* and *Simplified* scenarios. We assumed 50–100 kg N/ha greater application

TABLE 2 Details of crop type, sowing date, irrigated farm area and level of nitrogen fertiliser input for 16 scenarios combining four whole-farm adaptations (*Baseline*, *Diversified*, *Intensified* and *Simplified*) and four irrigation infrastructure types (*Gravity*, *Pipe & Riser*, *Pivot* and *Drip*) (adapted from Monjardino et al., 2022, and Muleke, Harrison, de Voil, et al., 2022)

Whole-farm adaptations	Irrigation infrastructure	Crop	Sowing date	Irrigated area (ha)	N applied (kg N/ha/year)
Baseline	Gravity	Canola	17 May	750	100
		Wheat	7 Jun	750	150
	Pipe & Riser	Canola	17 May	750	100
		Wheat	7 Jun	750	150
	Pivot	Canola	17 May	750	100
		Wheat	7 Jun	750	150
	Drip	Canola	17 May	750	100
		Wheat	7 Jun	750	150
Diversified	Gravity	Canola	17 May	750	100
		Wheat	7 Jun	750	150
		Faba bean	29 Mar	750	50
	Pipe & Riser	Canola	17 May	750	100
		Wheat	7 Jun	750	150
		Faba bean	29 Mar	750	50
	Pivot	Canola	17 May	750	100
		Wheat	7 Jun	750	150
		Faba bean	29 Mar	750	50
	Drip	Canola	17 May	750	100
		Wheat	7 Jun	750	150
		Faba bean	29 Mar	750	50
Intensified	Gravity	Canola	17 May	750	150
		Maize	29 Dec	188	400
		Wheat	7 Jun	750	250
		Cotton	1 Oct	188	300
		Rice	15 Nov	188	500
	Pipe & Riser	Canola	17 May	750	150
		Maize	29 Dec	188	400
		Wheat	7 Jun	750	250
		Cotton	1 Oct	188	300
		Rice	15 Nov	188	500
	Pivot	Canola	17 May	750	150
		Maize	29 Dec	188	400
		Wheat	7 Jun	750	250
		Cotton	1 Oct	188	300
		Rice	15 Nov	188	500
	Drip	Canola	17 May	750	150
		Maize	29 Dec	188	400
		Wheat	7 Jun	750	250
		Cotton	1 Oct	188	300
		Rice	15 Nov	188	500
Simplified	Gravity	Canola (dry)	10 May	750	100
		Wheat	7 Jun	375	150
	Pipe & Riser	Canola (dry)	10 May	750	100
		Wheat	7 Jun	375	150
	Pivot	Canola (dry)	10 May	750	100
		Wheat	7 Jun	375	150
	Drip	Canola (dry)	10 May	750	100
		Wheat	7 Jun	375	150

rates for each crop in the *Intensified* scenario, as our aim for this adaptation was to examine the effect of intensification through greater N application (Table 2). The aim of this work was not to examine crop responses to N application per se but rather to compare whole-farm intensification through both increased N application per unit area and increased farm area under irrigation with that of the *Baseline* scenario.

TABLE 3 Average prices ($/t and $/bale) for crops across a range of Australian irrigated cropping regions. Price ranges are from ABARES (2021) and ABS (2021b).

Crop	Low	Median	High
Canola	560	708	1086
Cotton seed[a]	290	329	695
Cotton lint[a]	201	448	619
Faba bean	311	484	677
Maize	273	418	528
Rice	272	425	815
Wheat	332	448	596

[a]Price for cotton seed is given in $/t and cotton lint in $/bale.

Readers are directed to other works (Bilotto et al., 2021; Mielenz et al., 2016; Rathnappriya et al., 2022; Robertson & Lilley, 2016) for sensitivity effects of nitrogen on crop growth.

2.6 | Prices and costs

Commodity prices in Table 3 were drawn from ABARES (2021), GRDC (2021) and ABS (2021a, 2021b) for the historical period. Historical real prices were adjusted for inflation using the consumer price index (CPI).

Capital and overhead costs for irrigation infrastructure in Table S3 were based on data sourced from a broad range of existing literature, including Hogan et al. (2006), Khan et al. (2009), Petheram et al. (2016), Roth et al. (2005) and Thompson (2016). Capital costs associated with irrigation infrastructure comprised installation purchases for pumps, electrical works, earthworks and storage. Other upfront costs included machinery for new irrigated crops and motor vehicles (or workshops) attributable to irrigation. A key assumption here was that capital costs were incurred in the first year and all irrigation infrastructure were considered brand-new investments. Overhead (fixed) annual costs included outgoing payments related to irrigation operation and maintenance such as power consumption for pumping, repair and maintenance (R&M) of irrigation systems, vehicle running costs and additional labour. Overhead costs were assumed constant throughout the analysis for each scenario under historical and future climatic periods, as shown in Table S3. Annual variable costs were sourced from ABARES (2021), GRDC (2020a), Ash et al. (2017), Harrison et al. (2020), McKellar et al. (2013), NRE (2021), PIRSA (2021) and DPI (2021). Variable costs included expenses associated with sowing, seed, fertiliser, chemicals (herbicides and fungicides), field operations (i.e., cultivation, fallow management, spraying, casual labour, fuel and repairs), irrigation water use, harvesting (i.e., stripping, windrowing, packaging and freight) and other selling expenses (i.e., crop insurance and levies). Water prices were derived from ABS (2020b), BoM (2021) and Westwood et al. (2021) based on a 30-year historical distribution. Irrigation water costs ($/Ml) were computed as the product of the average real price of water and application rates of irrigation water (Ml/ha) derived from APSIM simulation. Nitrogen fertiliser rates were adopted from Muleke, Harrison, Yanotti, et al. (2022); N fertiliser costs were estimated as the N rate per crop by N fertiliser price (Table S3). In the present study, we examine only the impact of (and potential adaptations to) the climate crisis, rather than simultaneously assessing effects of changes in both future climates and markets, as the latter would add significant uncertainty to our analysis. As such, we depict only variability associated with seasonal and inter-annual changes in climate in our results.

2.7 | Modelling whole-farm economic returns using *WaterCan Profit*

We input crop yields and water use generated from APSIM together with economic inputs into the *Investment App* of *WaterCan Profit* (https://watercanprofit.com.au/; Figures S2 and S3). This framework allowed computation of NPV, investment worth, internal rate of return (IRR) and payback period for the historical and future climate periods. The *Investment App* includes the following:

- *Scenarios*: productive life of the investment, discount rate, capital costs of investment, overhead costs and water costs (Table S3).
- *Crops*: crop rotation and area sown (Table 2 and Figure S1); variable costs, crop price, irrigation water application rates and crop yields at OFP (Tables 3, 4 and S4).
- *Calculation*: the *Investment App* computes a discounted cash flow analysis based on simulated crop yield, costs, grain price, productive life of investment and discount rate under historical and future climates.

Irrigation investments with NPV larger than the present value of costs (i.e., NPV > 0) were deemed viable. To examine the value of adaptation across irrigation scenarios and climatic periods, we computed the net benefit of adaptation as the difference between the NPV of historical *Baseline* (gravity-based irrigation) and the NPV of each adaptation scenario (e.g., Table 5). System profit do gap for the whole-farm adaptations and irrigation infrastructure was determined as the difference between the largest net value of all scenarios considered in this study and the *Baseline* under historical and future climatic conditions.

3 | RESULTS

3.1 | Crop yields and water use under historical climates

Across irrigation infrastructure and crop types, average long-term yields and water use were highest for the *Intensified* adaptation (8.8 t/ha and 6.1 Ml/ha, respectively) and lowest for the *Simplified* adaptation (4.2 t/ha and 1.8 Ml/ha, respectively; Table 4 and Figure 2). The *Diversified* adaptation had higher mean yields and water

TABLE 4 Simulated average crop yield, irrigation water use and fertiliser N rate for the 16 scenarios comprising four whole-farm adaptations and four types of irrigation infrastructure under historical (H; 1985–2004) and future (F; 2070–2089) climates

Whole-farm adaptation	Irrigation infrastructure	Crop	Crop yield (t/ha or bale/ha)		Water use (Ml/ha/year)		Total irrigation applied (Ml/year)		N rate applied (kg N/ha/year)
			H	F	H	F	H	F	
Baseline	Gravity	Canola	2.7	2.5	1.5	2.6	1159	1971	100
		Wheat	6.9	6.2	4.0	4.7	2974	3501	150
	Pivot	Canola	2.7	2.5	1.2	2.0	901	1533	100
		Wheat	6.9	6.2	3.1	3.6	2313	2723	150
	Drip	Canola	2.7	2.5	1.1	1.8	811	1380	100
		Wheat	6.9	6.2	2.8	3.3	2082	2451	150
	Pipe & Riser	Canola	2.7	2.5	1.4	2.3	1014	1725	100
		Wheat	6.9	6.2	3.5	4.1	2602	3063	150
Diversified	Gravity	Canola	4.5	4.4	3.2	4.2	2379	3143	100
		Faba bean	11.3	10.5	4.0	4.9	2998	3647	50
		Wheat	7.3	6.5	3.5	4.4	2653	3284	150
	Pivot	Canola	4.5	4.3	2.5	3.3	1851	2444	100
		Faba bean	11.3	10.5	3.1	3.8	2331	2837	50
		Wheat	7.3	6.5	2.8	3.4	2063	2554	150
	Drip	Canola	4.5	4.3	2.2	2.9	1666	2200	100
		Faba bean	11.3	10.5	2.8	3.4	2098	2553	50
		Wheat	7.3	6.5	2.5	3.1	1857	2298	150
	Pipe & Riser	Canola	4.5	4.3	2.8	3.7	2082	2750	100
		Faba bean	11.3	10.5	3.5	4.3	2623	3191	50
		Wheat	7.3	6.5	3.1	3.8	2321	2873	150
Intensified	Gravity	Canola	5.1	5.3	2.0	2.8	1537	2103	150
		Corn	21.0	24.0	12.4	14.0	2339	2628	400
		Cotton[a]	4.1; 10.7	5.7; 13	7.3	10.5	1379	1974	300
		Rice	14.0	13.2	18.1	21.5	3408	4043	500
		Wheat	5.0	4.4	1.9	2.2	1424	1670	250
	Pivot	Canola	5.1	5.3	1.6	2.3	1218	1688	150
		Corn	20.9	23.6	9.6	10.7	1804	2011	400
		Cotton[a]	4.1; 10.7	6.0; 13.0	5.5	7.7	1037	1457	300
		Rice	14.0	13.2	14.3	17.0	2692	3187	500
		Wheat	5.0	4.4	1.5	1.8	1156	1313	250
	Drip	Canola	5.1	5.3	1.6	2.1	1181	1538	150
		Corn	20.5	23.9	8.4	9.6	1589	1808	400
		Cotton[a]	4.1; 10.7	5.9; 12.4	4.9	7.0	924	1323	300
		Rice	14.0	13.2	13.2	15.3	2476	2871	500
		Wheat	5.0	4.4	1.4	1.6	1018	1177	250
	Pipe & Riser	Canola	5.1	5.3	1.8	2.5	1345	1855	150
		Corn	20.1	23.9	10.7	12.1	2015	2270	400
		Cotton[a]	4.0; 10.5	6.1; 13.6	6.4	9.0	1196	1687	300
		Rice	14.0	13.2	16.3	18.9	3064	3552	500
		Wheat	5.0	4.4	1.7	1.9	1275	1437	250
Simplified	Gravity	Canola (dry)	1.7	1.8	0.0	0.0	0	0	50
		Wheat	5.6	5.5	3.3	4.5	1706	2365	100
	Pivot	Canola (dry)	1.7	1.5	0.0	0.0	0	0	50
		Wheat	5.6	5.4	2.5	3.5	1327	1840	100

(Continues)

TABLE 4 (Continued)

Whole-farm adaptation	Irrigation infrastructure	Crop	Crop yield (t/ha or bale/ha) H	F	Water use (Ml/ha/year) H	F	Total irrigation applied (Ml/year) H	F	N rate applied (kg N/ha/year)
	Drip	Canola (dry)	1.7	1.5	0.0	0.0	0	0	50
		Wheat	5.6	5.4	2.3	3.2	1194	1656	100
	Pipe & Riser	Canola (dry)	1.7	1.5	0.0	0.0	0	0	50
		Wheat	5.6	5.4	2.8	3.9	1493	2070	100

[a]Cotton is split into cotton seed (t/ha) and cotton lint (bale/ha).

use (7.5 t/ha and 3.0 Ml/ha) than the *Baseline* (5.4 t/ha and 2.6 Ml/ha, respectively). Relative to the *Baseline*, long-term yield gains were attained for the *Intensified* (mean 68%) and *Diversified* (mean 36%) scenarios. *Simplified* scenarios yielded less on average than the *Baseline* (mean −14%; Figure S4). In contrast, average long-term yields were similar between irrigation infrastructure in each agronomic adaptation (Figure 2). *Intensified Gravity* and *Intensified Pipe & Riser* scenarios had the highest mean water use (7.3 and 6.4 Ml/ha) whereas the *Simplified Drip* had the lowest water use of all scenarios examined (1.5 Ml/ha; Figure 2). The high yield attained by irrigated maize was the main driver of profitability in *Intensified* (Table 4 and Figure 3).

3.2 | Crop yields and water use under future climates

For all adaptations, future climates reduced mean yields across whole-farm adaptations except for the *Intensified* scenario. Average water use across adaptation scenarios increased by 1.4 Ml/ha relative to the historical period (Table 4 and Figure S5). *Intensified* scenarios had the largest increases in irrigation water application (mean 2.7 Ml/ha); high water use and fertiliser N rates in these scenarios more than counter-balanced detrimental impacts of climate change, resulting in large yield gains (mean +1.2 t/ha), as shown in Figure 2. Whereas surface irrigation methods (*Gravity* and *Pipe & Riser*) of the *Intensified* scenario resulted in higher water application rates under future climates, mean yield gains were relatively invariant across irrigation infrastructure (Figure S5), demonstrating that whole-farm adaptation had greater impact on biophysical and economic indicators compared with irrigation infrastructure per se.

3.3 | Profitability under historical climates

Across whole-farm adaptations and irrigation infrastructure, mean profitability and investment worth were highest per unit of land for *Intensified* and largest per unit of water for the *Diversified* scenario (Table 5 and Figures 4–6 and S6). The *Simplified* scenario was generally less profitable than the *Baseline*. Due to the combination of low capital irrigation infrastructure combined with modest irrigation efficiency, *Pipe & Riser* irrigation infrastructure systems were typically more profitable per unit land, whereas the highly water-efficient infrastructure (e.g., *Drip*) was more profitable per unit water. The least water-efficient *Gravity* system attained lowest mean profitability per unit land and water across adaptation scenarios.

In general, positive NPV for all scenarios indicated that the irrigation investments were profitable (Table 5). Driven by differences in yield, crop type and irrigation use, NPV varied substantially across the scenarios, from \$2.3 M for the *Simplified Gravity* scenario to \$24.4 M for the *Intensified Pipe & Riser*. The *Baseline Gravity* system had mean profitability of \$5.0 M. The net value of adaptation per unit land ranged from −\$115/ha/year for the *Simplified Gravity* system to \$972/ha/year for the *Intensified Pipe & Riser* (Figure 5). Annualised equivalent benefit per unit water varied from −\$55/Ml/year (*Simplified Gravity*) to \$342/Ml/year (*Diversified Drip*). The annual equivalent benefit per unit area aligned with annualised equivalent benefit per unit water for all scenarios expect for the *Intensified* adaptations (Figure 6), suggesting that intensification would be more suited to farmers targeting area-based returns, whereas diversification is best suited for farmers with limited water and/or higher water prices.

IRR on investment was highest for the *Intensified Gravity* scenario at 55% with a lower payback period of 2 years, whereas the *Simplified Pivot* scenario had the lowest IRR at 4% and the highest payback period of 13 years (Table 5), suggesting that investing in high-cost irrigation infrastructure (e.g., *Pivot*) would not be viable for low input systems. Overall, the *Intensified* scenarios accrued higher benefits per unit of land from large gross margin gains per unit of area; this consistently offset high production costs (e.g., water costs), whereas *Diversified* scenarios had higher return per unit of water due to the more diverse income sources, mitigated economic risk (Table 5).

3.4 | Profitability under future climates

Across irrigation adaptations and infrastructure, future climates reduced average profitability and investment worth per unit water (−37% and −52%, respectively; Table 5 and Figures 4–7, S6 and S7) than per unit land (−17% and −39%). The *Baseline* system had the highest revenue reductions on an area and water basis and was most negatively impacted by future climatic conditions, suggesting that the cost of no adaptation to climate change would be greatest. Relative to historical climates, *Intensified* scenarios increased returns and

TABLE 5 *WaterCan Profit* analysis of 16 adaptation scenarios combining whole-farm adaptation and irrigation infrastructure for a case study farm in the Riverina region of New South Wales (NSW), Australia, under historical (blue rows) and future (yellow rows) climates

Agronomic adaptation	Irrigation infrastructure	Net present value ($M)	NPV per year		Net value of adaptation[a]		Investment worth		Internal rate of return (%)	Payback period (years)	Gross margin ($/ha)	Net cash flow ($/ha)
			($/ha/year)	($/Ml/year)	($/ha/year)	($/Ml/year)	($/ha/year)	($/Ml/year)				
Baseline	Gravity	5.0	331	106	0	0	206	66	15	7	755	406
	Pivot	6.4	426	176	95	39	201	83	10	9	857	522
	Drip	6.5	435	199	103	47	160	73	7	11	897	534
	Pipe & Riser	7.0	468	172	137	50	293	107	15	7	810	574
Diversified	Gravity	16.2	1083	305	752	212	958	270	53	2	1678	1329
	Pivot	17.9	1113	432	861	312	968	351	32	3	1798	1463
	Drip	17.7	1130	475	849	342	905	365	26	4	1812	1449
	Pipe & Riser	18.2	1214	391	883	284	1039	335	42	2	1724	1488
Intensified	Gravity	22.2	1185	162	854	117	1060	145	55	2	1803	1454
	Pivot	22.9	1219	214	888	156	994	175	31	3	1833	1498
	Drip	23.9	1271	247	940	183	996	194	27	4	1925	1562
	Pipe & Riser	24.4	1303	202	972	151	1128	175	43	3	1837	1601
Simplified	Gravity	2.3	216	92	−115	−55	91	43	8	10	616	267
	Pivot	2.9	276	139	−55	−33	51	31	4	13	676	341
	Drip	3.4	325	172	−6	−4	50	34	14	4	764	401
	Pipe & Riser	4.5	396	137	95	51	151	82	14	7	759	523
Baseline	Gravity	2.4	157	39	−174	−43	32	8	1	12	544	195
	Pivot	3.6	242	77	−89	−28	17	5	2	14	632	297
	Drip	4.7	311	109	−20	−7	36	13	3	14	744	381
	Pipe & Riser	5.0	332	94	1	0	157	44	10	9	642	406
Diversified	Gravity	12.5	837	186	505	113	712	158	41	3	1377	1028
	Pivot	14.2	945	271	614	176	720	206	26	4	1495	1160
	Drip	14.1	940	299	609	194	665	211	20	5	1516	1153
	Pipe & Riser	14.7	982	250	651	166	807	205	35	3	1440	1204
Intensified	Gravity	24.5	1308	147	977	110	1183	133	57	2	1958	1609
	Pivot	25.6	1363	198	1032	150	1138	165	34	3	2011	1676
	Drip	24.8	1324	213	993	160	1049	169	28	4	1987	1624
	Pipe & Riser	27.5	1465	189	1134	146	1290	167	47	3	2036	1800
Simplified	Gravity	1.6	155	49	−176	−56	30	10	1	12	541	192
	Pivot	2.5	238	97	−93	−38	13	5	2	14	629	294
	Drip	3.0	290	131	−41	−19	15	7	2	15	720	357
	Pipe & Riser	3.2	302	109	−29	−10	68	24	8	10	606	370

[a]Net value of adaptation relative to the *Baseline Gravity* system.

investment value per unit area by +11%, whereas *Diversified* scenarios resulted in the highest mean profitability and investment worth per unit water ($401 and $330/Ml/year, respectively) but were also accompanied by larger reductions (−37% and −41%; Figures 4 and 5). These results suggest that *Intensification* would be most climate resilient per unit land owing to larger gains in profit that counterbalance higher production costs, whereas *Diversification* will be most profitable per unit water, but highly vulnerable to climate change. *Gravity* systems had the highest reduction in mean profitability per unit land and water (−23% and −41%, respectively; Figure 4), whereas *Drip* systems attained the lowest declines (−13% and −34%) under future climates, indicating that returns for less water-use-efficient infrastructure (e.g., *Gravity*) would result in greater economic impact under climate change compared with more water-efficient infrastructure. *Intensified Pipe & Riser* systems generated the highest annualised net value gains per area of irrigated land (343%; Table 5 and Figures 3 and 5), whereas *Diversified Drip* systems achieved superior performance in terms of value gains per unit water (182%) under future climates.

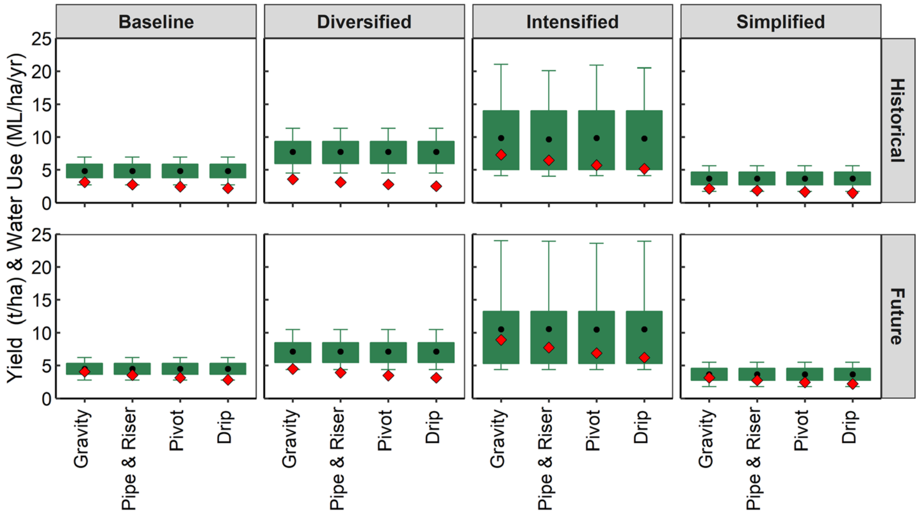

FIGURE 2 Effect of whole-farm adaptation and irrigation infrastructure on crop yield and water use under historical and future climates. Boxplots represent long-term crop yield. Black circles represent means for crop yield (averaged across irrigation infrastructure and crop types). Red diamonds represent average annual irrigation water use.

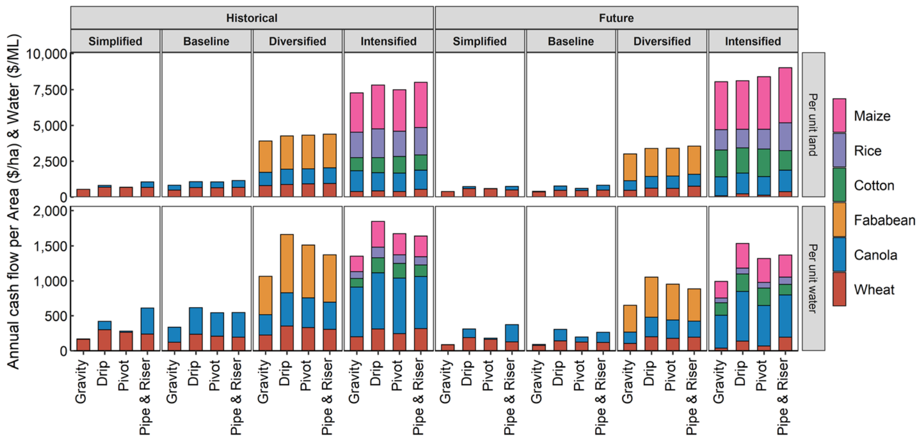

FIGURE 3 Average annual cash flow of each crop on area and water bases for historical and future climatic periods. Stacked columns represent cumulative crop cash flow per unit area and water for each of the 16 adaptation scenarios. The annualised cash flow is computed in the *Investment App* of *WaterCan Profit* and excludes capital cost for irrigation infrastructure.

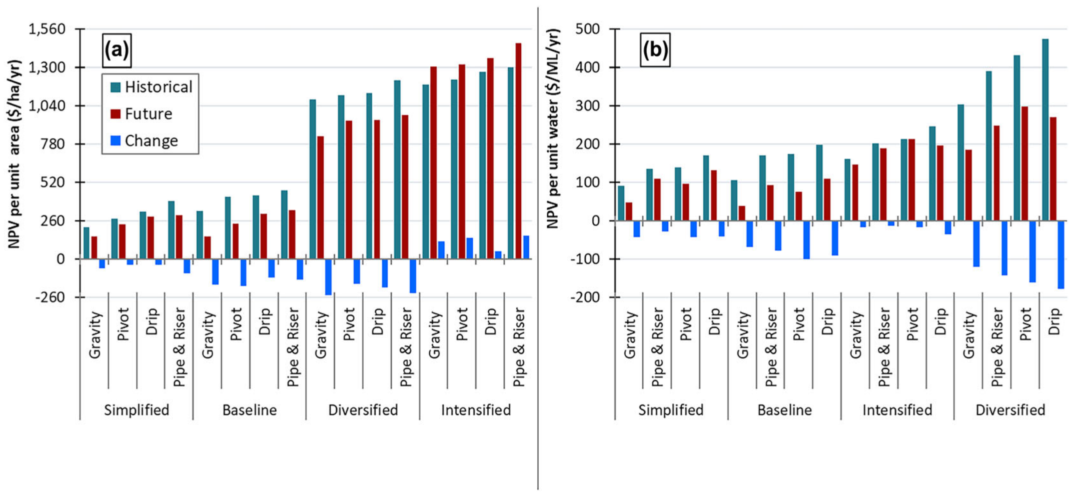

FIGURE 4 Impact of climate change on net present value (NPV) per unit area (a) and per unit water (b) for a range of whole-farm and irrigation infrastructure adaptation scenarios. Green and red columns represent mean NPV under historical climates and future climates, respectively; blue columns depict change in NPV between historical and future climates. Scenarios are ranked in ascending order from left to right in each panel.

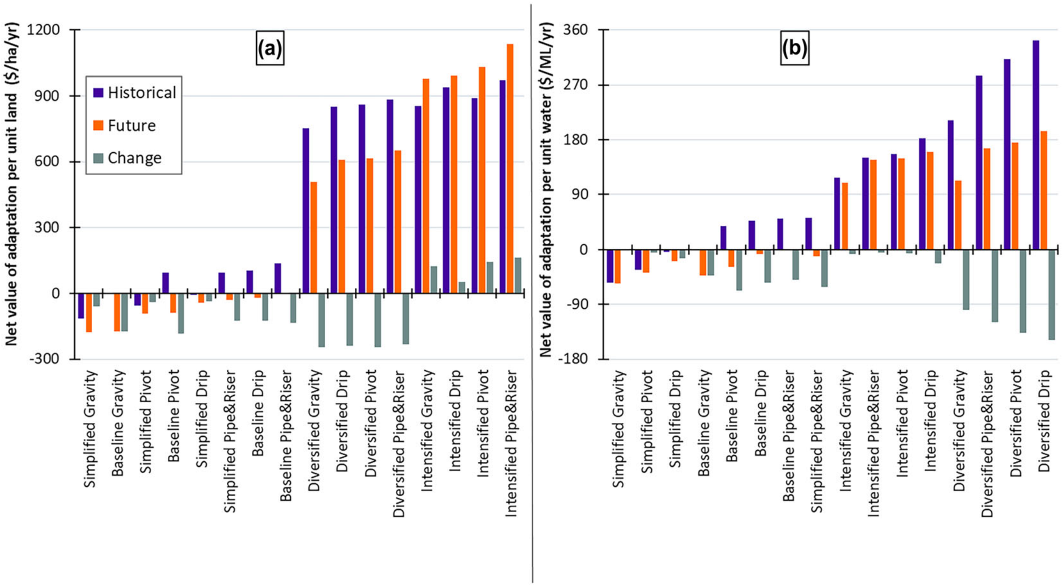

FIGURE 5 Impact of climate change on annualised equivalent benefit per unit area (a) and per unit water (b) for a range of whole-farm and irrigation infrastructure adaptation scenarios. Purple and orange columns represent mean net value of adaptation under historical climates and future climates, respectively. Grey columns show the change in average net value of adaptation between historical and future climates. Scenarios are ranked by mean net value of adaptation under future and historical periods for graphs (a) and (b), respectively.

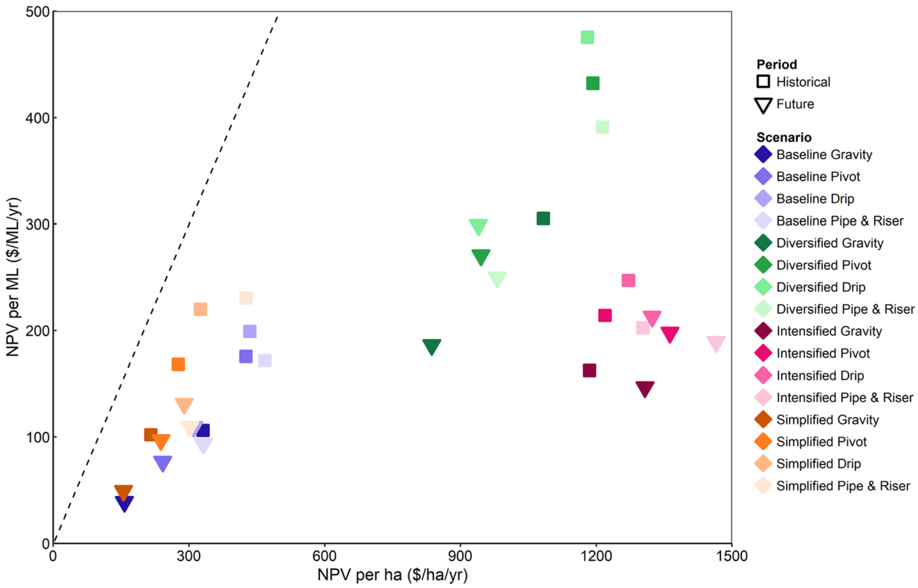

FIGURE 6 Net present value (NPV) per unit area and per unit water for 16 adaptation scenarios under historical and future climates. Squares depict the historical period, whereas triangles indicate future climates. The dashed line indicates equal profitability per hectare and per megalitre of water.

Intensified systems had the highest net value per unit land, which surpassed *historical Intensified* scenarios by +36%, whereas *Diversified* systems had the largest average return per megalitre of water but were significantly lower than *historical Diversified* scenarios (−118% decline).

3.5 | System profit gap under historical and future climates

Our probabilistic analysis showed that the magnitude of profit gap on an area basis increased under future climates by 29%, from $19.5 M to $25 M for *Intensified Pipe & Riser*, whereas water-based profit gap decreased by −30% from $5.5 M to $3.9 M (Table 5). The main drivers of high profitability per unit area and water for *Intensified* scenarios were maize and canola, respectively, whereas inclusion of faba bean in *Diversified* scenarios increased returns per unit area and water relative to *Baseline* and *Simplified* scenarios for both climatic periods (Figure 3).

4 | DISCUSSION

The aim of this study was to illustrate the capability of *WaterCan Profit* by exploring how whole-farm intensification/simplification/

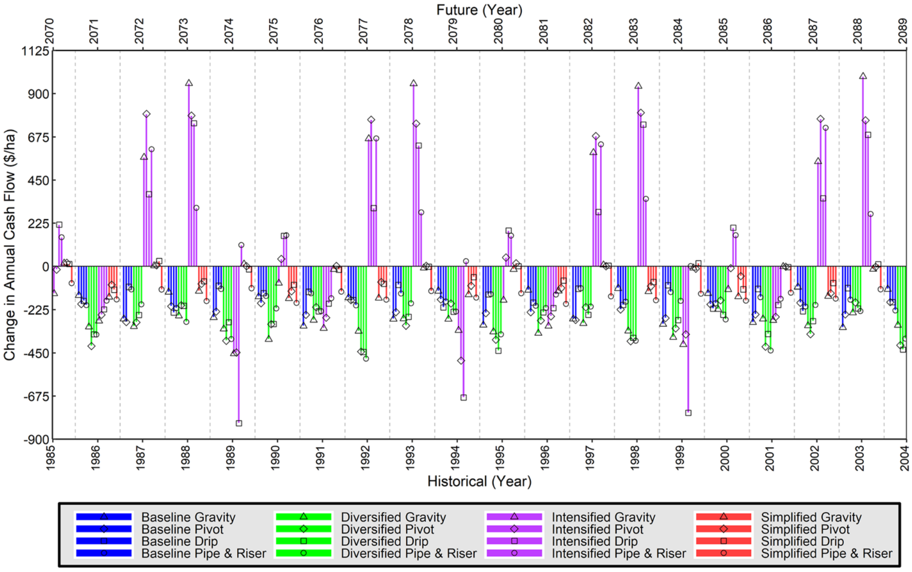

FIGURE 7 Change in area-based annualised cash flow caused by climate change across adaptation scenarios. Colours represent adaptations: blue = *Baseline*, green = *Diversified*, purple = *Intensified* and red = *Simplified*. Points represent irrigation infrastructure: triangles = *Gravity*, diamonds = *Pivot*, squares = *Drip* and circles = *Pipe & Riser*.

diversification and alternative irrigation infrastructure impacted on profitability under future climates. We showed that the *Baseline* had the highest revenue losses on an area and water basis (−38% and −53%, respectively; Table 5 and Figure 4), demonstrating that farmers with gravity-based irrigation and relatively simple crop rotations will likely incur the greatest economic impacts of the climate emergency in the absence of adaptation. Even for most adaptations, productivity and profitability declined under future climates due to (1) higher evaporative demand consuming more water, (2) faster crop lifecycles due to greater growing degree-day accumulation, (3) lower mean rainfall and (4) more frequent drought periods. This suggests that careful agronomic and economic management will be needed to overcome the detrimental impacts of existential climate crisis in the region.

The *Intensification* scenario was the only adaptation that improved average yields and profit declined under future climatic conditions. This result was attributed to higher proportion of farm area under irrigation and higher rates of irrigation, higher N usage and a more intense cropping system rotation that included high yielding maize and rice (Figures 3–5). This suggests that whole-farm intensification can be used to overcome the impacts of climate change. *Intensification* increased average returns and investment worth per unit area under future climates by up to 11% under future climates irrespective of irrigation infrastructure, whereas the *Diversified* scenario was most profitable per unit water but characterised by precipitous declines under future climates (−41%; Figures 3–7 and S6). The *Simplified* was the least profitable adaptation under future climates. The *Intensified* system offset high input costs including additional water use to generate higher returns per area of irrigated farm, whereas *Diversification* was superior in mitigating economic risk due to higher returns per megalitre but was a poor climate change adaptation. For a study of climate change adaptation of dairy systems, Harrison et al. (2017) similarly found that the *Intensification* option was least impacted under the 2040 climate change trajectories (−0.08% change in profitability) across three sites in South Australia. It is however worth noting that our scenarios were modelled at the farm scale: If numerous farms applied *Intensification* at the regional scale, it is possible that nitrogen leaching into ground water and regional irrigation requirements would increase, suggesting a need for more regional studies that take into account interactions between farms at the landscape scale (e.g., Shahpari et al., 2021).

We also found that in comparing the relative profitability across adaptations, metrics matter. We found greater climate-induced economic losses per megalitre of irrigation water (−37%) than per area of irrigated farm (−17%) under all adaptation scenarios. This indicates that farm returns per unit water are more vulnerable to the detrimental impacts of climate change relative to income per unit land. Under future climates, water application rates increase (e.g., by +1.4 Ml/ha; Figure 4) to compensate for high soil moisture deficit at increased temperature (+13%; Figure 1) and decreased rainfall (−14%). The high application rates increase water costs and the resulting variable costs (Table S2). Such high input costs relative to income (i.e., decline in terms of trade with inflation) are the key drivers for the substantial whole-farm profit losses per megalitre of water. As part of this, we showed that whereas large gains in returns per hectare are achievable, economic returns per unit water saturate beyond a certain point (Figure 6), suggesting that under future climates, it may be more difficult to make a profit in cases where water (rather than land area) is limiting.

In contrast to whole-farm adaptation, changes in irrigation infrastructure had relatively little effect on productivity of profitability. Across adaptations, surface irrigation (*Gravity*) attained the highest net losses per unit land and water (−23% and −41%, respectively; Figure 5) in future climates, whereas the pressurised *Drip* infrastructure had the lowest declines (−13% and −34%) under future climates. These results align with those of Narayanamoorthy et al. (2018), who found that drip irrigation was more profitable (+54%), water saving (+40%) and cost-effective than conventional gravity/flood irrigation. Maraseni et al. (2012) assessed the economic trade-offs associated with adoption of more water-efficient and energy-intensive irrigation technologies in Australia using an integrated assessment framework and suggested that conversion to water-efficient pressurised infrastructure (e.g., drip) generated highest profitability per unit area ($9065/ha/year) and water savings ($4613/Ml) in addition to reduction of greenhouse gas (GHG) emissions. Together, these observations suggest that water-use-efficient irrigation infrastructure such as pressurised *Drip* would likely be more economically feasible compared with less water-efficient irrigation infrastructure (e.g., *Gravity*) under climate change. Indeed, other empirical studies (e.g., Fader et al., 2016; Frisvold & Deva, 2013; Mushtaq & Maraseni, 2011) view investment in highly efficient irrigation infrastructure as a fundamental adaptation to climate change. However, farm-level financial constraints associated with high initial capital investment costs (e.g., in Table 5) are often critical barriers for growers to invest in such improved efficiency irrigation infrastructure.

The majority of previous studies have focused either on reducing yield gaps (i.e., the difference between actual and potential yields; Bell et al., 2015; Hatfield & Beres, 2019; Hochman et al., 2012; Khan et al., 2021; Lobell et al., 2009; Pasuquin et al., 2014; Rattalino Edreira et al., 2021), even though eternal increases in grain yield do not necessarily result in higher whole-farm profitability. To overcome this limitation, we quantified both productivity and profitability. Under future climates, the system-level profit gap increased on an area basis by 29% for *Intensified Pipe & Riser* scenario and decreased by −30% on a water basis for *Diversified Drip* (Table 5). These results again demonstrate that it may be more difficult to make a profit in contexts with limited irrigation water or when water price is higher. More broadly, these observations indicate that plausible pathways for farmers to close the area-based profit gap under future climates would be to intensify the irrigated systems in tandem with investing in low capital cost irrigation infrastructure, whereas crop rotation diversification combined with high-efficiency infrastructure, cost-effective subsidies and other farmer-tailored risk aversion strategies (e.g., appropriate crop mix) would potentially help narrow profit gaps associated with water use or use efficiency.

The strong financial performance per unit area and water for *Intensified* scenarios in the present study was driven by the high net revenue gains of maize and canola, respectively (see Figure 3). Incorporation of faba bean in *Diversified* scenarios increased returns per unit area and water relative to *Baseline* and *Simplified* scenarios. The economic viability of *Intensified* and *Diversified* scenarios, indicated by the higher IRRs and shorter payback periods, was in part attributed to profitability of crop mix in the rotations, as shown in Figure 3. Under future climates, inclusion of profitable water-intensive crops such as rice, cotton and maize would increase returns per unit farm area for *Intensified* rotations; however, the high water requirements will likely predispose the profitability to climate-induced penalties if climate change reduced regional water allocated to individual farms. The relatively low water requirement crops such as faba bean and canola have the potential to sustain high return per unit of irrigated water in both *Diversified* and *Intensified* rotations. A promising risk aversion strategy for irrigators here would be to increase climate-smart profitable crop options, for example, mung beans or chickpeas, in the sequence of diversified and intensified crop rotations.

Although the focus of this study was primarily on biophysical and economic aspects, assessments of other variables may change the key conclusions drawn (viz., Harrison et al., 2019). For example, although we showed that *Intensified* adaptations were most promising in an economic sense, pressurised irrigation infrastructure systems (e.g., centre pivot sprinklers) can be more energy intensive, and greater nitrogenous fertiliser use can lead to higher nitrous oxide emissions (Bilotto et al., 2021; Christie et al., 2018; Christie et al., 2020; Rawnsley et al., 2019), which is a potent GHG. Alternatively, greater irrigation use (e.g., in the *Intensified* system) could lead to improved carbon sequestration and storage (Farina et al., 2021; Henry et al., 2022; Sándor et al., 2020), reducing farm-level emissions if irrigation was maintained over the longer term (Ara et al., 2021; Phelan et al., 2018; Taylor et al., 2016). Although cross-disciplinary assessments are often more holistic, they require greater resources to elicit and, as such, were beyond the scope of the present study. Indeed, the next step in the present research programme is to investigate how the holistic systems adaptations modelled here impact on carbon storage and net GHG emissions.

The modelling framework used here cannot distinguish between intensification due to fertiliser or irrigation, because we modelled bundled holistic adaptations that intensified existing systems by changing both fertiliser and irrigation use. Mueller et al. (2012) demonstrated that globally, intensification can considerably close yield gaps (the difference between actual and potential yields in a given region) with appropriate, contextualised changes in fertiliser use and irrigation. Mueller et al. (2012) contended that global production could be increased by 45%–70% for most major crops, particularly in Eastern Europe and Sub-Saharan Africa, with East and South Asia also having substantial intensification opportunities owing to their vast arable land areas and geographic variability in yields and yield gaps. Mueller et al. (2012) found that regions with high fertiliser application rates are concentrated in high-income and some low- and middle-income countries, whereas irrigation zones were mainly concentrated in South Asia, East Asia and parts of the United States, with spatial variability in management explaining 60%–80% of global yield variability for most major crop types. Given these findings, plus the fact that purchasing fertiliser and/or irrigation infrastructure requires significant financial outlay (Ara et al., 2021; Monjardino et al., 2022), practitioners may be forced to choose between either fertiliser or infrastructure (or other investment; Snow et al., 2021), rather than simultaneously investing in all the interventions in the *Intensified* scenario.

5 | CONCLUSIONS

We invoke the digital framework *WaterCan Profit* to examine impacts of climate change on profitability and productivity for several holistic adaptations and irrigation infrastructure scenarios. Our results indicate that climate change induced greater economic losses per unit water (approximately −37%) compared with per land area (approximately −17%). We also showed that low-cost and moderate to high-efficiency irrigation infrastructure types would be best suited to farmers targeting area-based income; high-efficiency and high-cost infrastructure would be preferable for farmers focused on revenue per unit water. We conclude that in the context of global climate change, (1) intensification of irrigated systems with greater farm areas under irrigation, more diverse crop types and greater N use was more beneficial in terms of productivity and profitability; (2) whole-farm adaptation had much greater effect than changes in irrigation infrastructure; (3) when assessing farm profit, metrics matter: *Diversified* systems generally had higher profitability than *Intensified* systems on a per unit water basis, but not a per unit land area basis; and (4) gravity-based (surface) irrigation systems were generally the highest users of irrigation water, followed by *Pipe & Riser* and *Pivot* (sprinkler) systems, with *Drip* irrigation having the lowest use of irrigation water. Perhaps most importantly, the cost of no adaptation to climate change will be greatest, suggesting that proactive farmers who adapt now will benefit financially in the decades to come.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

M.T.H. conceived and designed the study. A.M. contributed to the conception of the study and performed the experiments with support from M.T.H., R.E., P.V. and M.Y. All authors (M.T.H., A.M., R.E., P.V., M.Y., K.L., M.M., X.Y., W.W., J.N., C.F., J.Z., F.Z., S.F., N.S., F.P., Y.Z., D.F., R.Y., Z.Q., W.F., X.G., J.M. and N.L.) contributed to the writing and revision of the manuscript. M.T.H. was awarded the funding to conduct the study.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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