Transformative and systemic climate change adaptations in mixed crop-livestock farming systems

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Abstract

Mixed crop-livestock farming systems provide food for more than half of the world's population. These agricultural systems are predicted to be vulnerable to climate change and therefore require transformative adaptations. In collaboration with farmers in the wheatbelt of Western Australia (WA), a range of systemic and transformative adaptation options, e.g. land use change, were designed for the modelled climate change projected to occur in 2030 (0.4-1.4° increase in mean temperature). The effectiveness of the adaptation options was evaluated using coupled crop and livestock biophysical models within an economic and environmental framework at both the enterprise and farm scales. The relative changes in economic return and environmental variables in 2030 are presented in comparison with a baseline period (1970–2010). The analysis was performed on representative farm systems across a rainfall transect. Under the impact of projected climate change, the economic returns of the current farms without adaptation declined by between 2- 47%, with a few exceptions where profit increased by up to 4%. When the adaptations were applied for 2030, profit increased at the high rainfall site in the range between 78-81% through a 25% increase in the size of livestock enterprise and adjustment in sowing dates, but such profit increases were associated with 6-10% increase in greenhouse gas (GHG) emissions. At the medium rainfall site, a 100% increase in stocking rate resulted in 5% growth in profit but with a 61-71% increase in GHG emissions and the increased likelihood of soil degradation. At the relatively low rainfall site, a 75% increase in livestock when associated with changes in crop management resulted in greater profitability and a smaller risk of soil erosion. This research identified that a shift toward a greater livestock enterprises (stocking rate and pasture area) could be a profitable and low-risk approach and may have most relevance in years with extremely low rainfall. If transformative adaptations are adopted then there will be an increased requirement for an emissions control policy due to livestock GHG emissions, while there would be also need for soil conservation strategies to be implemented during dry periods. The adoption rate analysis with producers suggests there would be a greater adoption rate for less intensified adaptations even if they are transformative. Overall the current systems would be more resilient with the adaptations, but there may be challenges in terms of environmental sustainability and in particular with soil conservation.

Keywords: climate change; adaptation; mitigation; integration; modelling; GHG; land use change

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1. Introduction

Mixed crop-livestock enterprises dominate agricultural systems in many parts of the world and provide food for more than half of the world's population (Herrero et al., 2010). In Australia, mixed crop-livestock farms are also major agricultural systems across low rainfall regions (Bell et al., 2014) and are important for their economic and social contribution to rural communities. The projected adverse impact of climate change might result in a significant decline in grain, wool, and meat productivity of Western Australian mixed-farming systems (Ghahramani and Moore, 2016), while adaptations which may offset this decline are a hypothesis worth testing. Australia's primary industries have always performed in a highly variable climate with significant related challenges, e.g. soil water management and soil erosion, and this has required innovative climate risk management practices to be developed. Climate change brings with it some new variations on these challenges not yet accounted for by Australian primary producers, e.g. greater frequency of years with extremely low rainfall (Crimp et al., 2016) and a decrease in water use efficiencies (Ghahramani et al., 2015). Previous research (e.g. Ghahramani and Moore, 2013, 2016; Lobell et al., 2008; Lesk et al., 2016; Vermeulen et al., 2013) has suggested that incremental adaptation strategies may not be sufficient to offset the impact of climate change on agricultural productivity, thus requiring primary industries to adopt more systemic or transformative adaptations (Ghahramani and Moore, 2015). These include changes in the function or structure of current systems to sustain productivity and profitability under changing climate (Rickards and Howden 2012; Marshall et al., 2016). There is a likelihood that climate change impacts and adaptations may be different in mixed systems from non-mixed systems due to a wider variety of enterprises being present. Currently, there is limited previous research on this topic (e.g. Rigolot et al., 2017 for Africa) that considers climate change impacts and adaptations on integrated crop-livestock systems while also considering economic and environmental health.

The interactions between crops and livestock can be managed to contribute to sustainable production and risk management, but there is a severe knowledge gap on these interactions under climate change (Thornton and Herrero, 2014). There is also a need for an analysis of the impact of localised climate change on agricultural systems for a better understanding of their possible evolution in an integrated framework. This integration should consider different dimensions of sustainability e.g. environment, economic (Thornton and Herrero, 2014; Thornton and Herrero, 2015).

Western Australia, with about 7 million ha of land used for grain production, is a major contributor to the Australian agrifood sector and, as a result, the Australian economy (The Department of Agriculture and Food, 2014). Pastures in this state play a significant role in agricultural enterprises and contribute over $3 billion annually through animal production, improvements to crop rotations and conserved fodder (The Department of Agriculture and Food, 2014). In addition to the practical importance of understanding climate change effects in the region, Western Australian mixed farming systems have characteristics that make them useful as a case study for a wider understanding of the impact of climate change on agriculture (Ghahramani and Moore, 2016). There is clear evidence of an overall decline in winter rainfall and increased temperatures in southern regions of the state over past decades (Bureau of Meteorology, 2016; Delworth and Zeng, 2014), and the issue of changing rainfall is particularly salient and well known to farmers (discussed in stakeholder workshops and has been personally experienced by the second author). In addition, as most of the agricultural commodities produced in Western Australia, i.e. wheat, barley, canola, wool, and meat are for international export, we can, therefore, assume that their market is sensitive to global socioeconomic factors (Ghahramani and Moore, 2016) which are fed into AR5 emissions scenarios that have been used here (Stocker et al., 2013).

In the first of this series (Ghahramani and Moore, 2015), the impact of climate change in Western Australia mixed crop-livestock systems was evaluated. In this paper, the effectiveness of a range of systemic and transformative adaptation options have been identified and evaluated with producers and their advisors who were already familiar with climate-related issues, e.g. climate variability. This paper evaluates economic and environmental resilience and adaptive capacity of the current farms (Rivington et al., 2007) under climate change by application of adaptation options. All evaluations were reported for 2030, relative to a historical baseline of 1970-2010 (to be consistent with the 5th report of Intergovernmental Panel on Climate Change, i.e. Clarke et al., 2014) across a high to low rainfall climate transect. This paper considers the effectiveness of adaptation options at multiple level (enterprise and farm) and against various criteria (profit, risk, environmental impacts, and GHG emissions). This provides key insights into the challenges associated with managing land use change resulting from climate change while evaluating a range of systematic adaptation options in sustaining productivity and profitability under such changes.

2. Methods

2.1 Study sites

Three representative mixed farming systems were selected across a historical rainfall gradient of 308-431 mm (growing season rainfall during Apr-Oct, 1970-2010) (Fig 1). Three sites were chosen to represent farming systems of relatively high rainfall (Katanning), medium rainfall (Cunderdin), and relatively low rainfall systems (Merredin). These sites represent complex agroecosystems, each with different soil, management, and input intensities (Table 1). These sites are those used in Ghahramani and Moore (2016) which were selected and identified through workshops with a range of related stakeholders including extension and research officers from Department of Agriculture and Food Western Australia, farmers, representatives of farmer groups, and consultants.

2.2 Modelling & representative farming systems

Modelling approach

Mixed crop-livestock farms are complex systems which include interactions between climate and weather, surface and sub-surface soil, vadose zone, crops, pasture, animal production and human management with economic components. The climate, through weather and the timing of weather patterns, is one of the main factors because rainfall and temperature drive the productivity, profitability and environmental health of the system. Integrated models of crop-livestock systems were constructed by linking the APSIM 7.7 soil water, soil nutrient cycling, crop and surface residue modelling components (Holzworth et al., 2014) to the GRAZPLAN pasture and ruminant simulation models (Donnelly et al., 2002; Moore et al., 1997) using the AusFarm modelling software (version 1.4.7). AusFarm is an agroecosystem modelling environment that couples APSIM and GRAZPLAN to model dynamic interactions between climate, soil, plants, and animals (Ghahramani and Moore, 2016).

Crop-livestock system

Components of the cropping and livestock enterprises were characterised through consulting both farmers and extension officers in producer workshops. Five main crops: wheat, barley, canola, lupin, and field pea were included in the models, and field pea was used as a green fertiliser/manure plant for the purpose of the modelling. Each representative site had several soil types, and rotation systems were allocated to each soil type (Table 1). Sowing of crops was simulated upon receipt of a rainfall threshold, i.e. when 5-day (Cunderdin and Katanning) or 3-day (Merredin) total rainfall exceeded 10 mm. Following Ghahramani and Moore (2016), for the purpose of modelling stationary systems, the humus and microbial biomass in the soil were reset to their initial levels once per rotation cycle, this also prevented the effect on plants from soil carbon build-up on productivity over a long-term period. Pasture and livestock management rules and systems inputs were decided in consultation with producers and extension officers, mostly in stakeholder workshops. A sheep enterprise of self-replacing ewes was included in the models using a Medium Wool Merino genotype. Management systems were described using flexible rules that allocated land to the different crop-pasture sequences and these were managed through the sowing and removal of the various crops and forage, nitrogen fertiliser (N) applications, the annual cycle of sheep reproduction, buying and selling of livestock, supplementary feeding and grazing management.

Soil

The majority of soils in WA, including those at the representative sites of this paper, have topsoils that are relatively low in clay and soil organic matter and are often constrained by sub-soil acidity. A range of representative soil profiles was identified for each site using the APSoil database (Dalgliesh et al., 2006). It takes a few years to stabilise model prediction of yields if extractable soil water is not reset each year when commencing with arbitrary initial conditions (Ghahramani et al., 2015). Therefore, simulations were conducted for 1965-2010 and the initial five years before 1970 were removed to allow equilibration of soil water. In this paper, the carbon-nitrogen flow was coupled by modelling the organic matter cycle among plants, soil, and animals. Livestock could be placed in cropping paddocks to graze growing crops, the stubble residues and spilt grain after harvest using the same logic as for grasslands, while livestock excreta could return to the soil surface as part of the model's internal dynamics.

Elevated CO_2 concentration

Elevated atmospheric carbon dioxide (eCO_2) concentrations in 2030 are expected to affect plant growth rates. Therefore, in this paper following Ghahramani and Moore (2016), all projections of production and profit for 2030 were modelled including the effects of elevated CO_2. Both APSIM and GRAZPLAN simulate crop and pasture growth via radiation-use efficiency, transpiration efficiency and the critical nitrogen concentration, which are modified by atmospheric CO_2 concentration using leaf-level mechanistic equations (Reyenga et al., 1999). In APSIM, yield has a linear response to eCO_2 as a consequence of a collection of assumptions which are consistent with the results from FACE experiments undertaken with the moderate elevation of the atmospheric CO_2 (e.g. Olesen and Bindi, 2002). The APSIM response functions have been reported to satisfactorily reproduce the effect of eCO_2 in FACE experiments for moderately elevated CO_2 (e.g. Asseng et al., 2004; Tubiello et al., 2007). Ghahramani et al. (2015) indicated that the modeled fertilisation effects of eCO_2 for 2030 across the Australian wheat belt are in agreement with experimental results, e.g. Tubiello et al. (2002) that have shown the positive response of wheat yield when water is a limiting factor (Chaudhuri et al., 1990; Kimball et al., 1995).

Agroecosystem health and GHG emission

A range of metrics was simulated to evaluate the effectiveness of adaptations on environmental health, and these included net primary productivity, ground cover, the frequency of low ground cover (days in a year that cover is < 0.7), and crop water use efficiency.

Crimp et al. (2016) reported that under climate and management scenarios assessed across this transect, pre-farm emissions remained unchanged, while on-farm emissions of $N_2O$and CH_4 increased. In this paper emission of N_2O from soil and CH_4 from animals were simulated as the primary sources of GHG emission by using the current APSIM and GRAZPLAN models, respectively. Emissions of CH_4 and N_2O were converted to CO_2-equivalents using 100-year global warming potentials of 28 and 265, respectively (IPCC, 2014). As soils of the Western Australian wheatbelt are limited in soil organic materials (Murphy et al., 2011), losses or gains of soil carbon were not considered for on-farm GHG emissions.

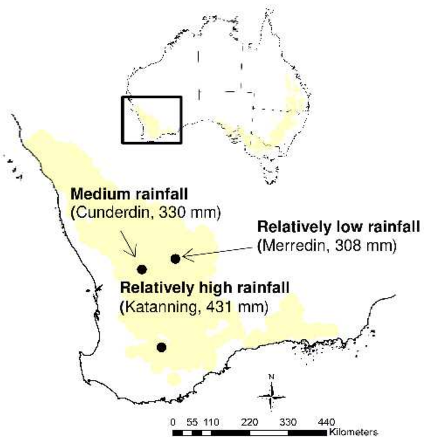

Fig 1 Representative mixed farms. Numbers in brackets are average rainfall during 1970-2010.

Table 1. Summary of the adaptations used for assessment. A: annual pasture, W: wheat, B: barley, C: canola, L: lupin, P: field pea, F: long fallow, DSE: dry sheep equivalent. Rotations are equally distributed over the different soils types.

Site	Management	Baseline	Impact	Alteration of the crop-	Low in risk and return	Medium in risk and return	High in risk and return
High rainfall	cropping: fallow: pasture	0.60:0.00:0.40	baseline	0.60:0.00:0.40	0.60:0.00:0.40	0.53:0.08:0.40	0.72:0.00:0.28
	Rotation system	AWCB, ACWB, AAAWC, AWCB, AAB	baseline	AWCB, ACWB, AAAWC, AAWCB, AAB	AWCB, ACWB, AAAWC, AAWCB, AAB	AWCB, AFWB, AAAWC, AAWCB, AAB	AWCB, ACWB, AWAWC, ABWCB, AWB
	Farm area (ha)	3000	baseline	No change	No change	No change	No change
	Crop grazing	Wheat, dse_days:1200.0	baseline	No change	No change	No change	No change
	Fallow policy (long)	No Long fallow	baseline	No change	No change	Long fallow	No change
	Stocking rate (DSE/ ha)	1.2	baseline	1.5	1.2	1.8	2.0
	Minimum stubble cover	0.6	baseline	No change	No change	No change	No change
	Maximum days on stubble	150*	baseline	No change	No change	No change	No change
	N (kg/ha), top dress	W:50, B:40, C:60	baseline	W:50, B:40, C:60	W:45, B:36, C:52	W:60, B:48, C:72	W:50, B:40, C:60
	Cultivar	Wheat: Mace, Canola: Stingray	baseline	Wheat: Axe, Canola: Crusher	Wheat: Axe, Canola: Crusher,	Wheat: Mace, Canola: Stingray	Wheat: Mace,Canola: Stingray
	Start of sowing window#	Wheat:105, Canola:105	baseline	Wheat:90, Canola:90	Wheat:90, Canola:90	Wheat:105, Canola:105	Wheat:105, Canola:105
	Pasture termination	No	baseline	No	Annul legumes, August/Sept	Annul legumes, August	Annul legumes, August
Medium rainfall	cropping: fallow: pasture	0.84:0.00:0.16	baseline	0.68:0.00:0.32	0.64:0.04:0.32	0.78:0.16:0.06	0.92:0.00:0.08
	Rotation system	AAACW, WLWCB, WPWCB, ABWLW	baseline	AAAAW, WAWCB, WAWCB, ABWLW	AAAAW, WAWCB, WAWCB, ABWFW	AAACW, WLWCB, WFWCB, ABWLW	AWACW, WLWCB, WPWCB, WBWLW
	Farm area (ha)	4000	baseline	No change	No change	No change	No change
	Crop grazing	Wheat & Barley	baseline	No change	No change	No change	No change
	Fallow policy (long)	No Long fallow	baseline	No change	Long fallow	Long fallow	No change
	Stocking rate (DSE/ ha)	0.5	baseline	1.0	0.5	1.0	1.0
	Minimum stubble cover	0.6	baseline	No change	No change	No change	No change
	Maximum days on stubble	150*	baseline	No change	No change	No change	No change
	N (kg/ha), top dress	W:40, B:30, C:60	baseline	W:40, B:30, C:60	W:36, B:30, C:52	W:48, B:36, C:72	W:40, B:30, C:60
	Cultivar	Wheat: Mace, Canola: Crusher	baseline	Wheat: Axe, Canola: Hyola42	Wheat: Axe, Canola: Hyola42	Wheat: Mace, Canola: Crusher	Wheat: Mace, Canola: Crusher
	Start of sowing window	Wheat:105, Canola:105	baseline	Wheat:90, Canola:90	Wheat:90, Canola:90	Wheat:105, Canola:105	Wheat:105, Canola:105
	Pasture termination	No	baseline	No	Annul legumes, August	Annul legumes, August	Annul legumes, August
Relatively low rainfall	cropping: fallow: pasture	0.90:0.00:0.10	baseline	0.78:0.00:0.22	0.70:0.08:0.22	0.82:0.08:0.10	0.90:0.00:0.10
	Rotation system	AAW, WWWCB, WWCWWP, WWCWWL, WBWBB, WWWC	baseline	AAA, WWWCB, WWCWWA, WWCWWL, WBWBB	AAA, WWWCB, WWCWWA, WWCWWF, WBWBF, WWWA	AAW, WWWCB, WWCWWP, WWCWWF, WBWBF, WWWC	AAW, WWWCB, WWCWWP, WWCWWL, WBWBB, WWWC
	Farm area (ha)	5000	baseline	No change	No change	No change	No change
	Crop grazing	N/a	baseline	No change	No change	No change	No change
	Fallow policy (long)	No Long fallow	baseline	No change	Long fallow	Long fallow	No change
	Stocking rate (DSE/ ha)	0.4	baseline	0.7	0.7	0.4	1.0
	Minimum stubble cover	0.6	baseline	No change	No change	No change	No change
	Maximum days on stubble	150*	baseline	No change	No change	No change	No change
	N (kg/ha) and timing	W:40 sowing, B:20 top dress, C:40 top dress	baseline	W:40 sowing, B:20 top dress, C:40 top dress	W:36 sowing, B:18 top dress, C:36 top dress	W:44 sowing, B:22 top dress, C:44 top dress	W:40 sowing, B:20 top dress, C:40 top dress
	Cultivar	Wheat: Mace, Canola: Stingray	baseline	Wheat: Axe, Canola: Crusher	Wheat: Mace, Canola: Stingray	Wheat: Mace, Canola: Stingray	Wheat: Mace, Canola: Stingray
	Start of sowing window	Wheat:105, Canola:105	baseline	Wheat:90, Canola:90	Wheat:105, Canola:105	Wheat:105, Canola:105	Wheat:105, Canola:105
	Pasture termination	No	baseline	No	Annul legumes, August	Annul legumes, August	Annul legumes, August

Soils: High rainfall: Deep loamy duplex, shallow sandy duplex (alkaline sub soils), grey sandy duplex, saline wet soils; Medium rainfall: Gravelly sand, deep sandy, duplex, deep loamy duplex, acid yellow sand, Relatively low rainfall : Yellow deep sand, yellow & brown sandy earths, shallow loamy duplex/alkaline subsoils (loamy brown), gravely duplex.

*is maximum, decreases with decline in quality of stubble with growing season rainfall. # Start of sowing window is number Julian days after January 1

2.3
Simulations

For this analysis, a simulation platform was developed to undertake large factorial simulations by using the Condor cycle-harvesting software (Department of Computer Science, University of Madison–Wisconsin; HTTP:// research.cs.wisc.edu/htcondor).

2.4 Financial calculations

The adaptations presented here involve changes in land use and/or livestock numbers which altered the capital position of the farm business, and therefore whole-farm profit was calculated for each financial year of the simulations. Following the methodology outlined in Ghahramani and Moore (2016), farm gross margin was calculated for each year of the simulation by subtracting farm operating costs from farm income. A whole-farm profit for each year was then calculated by subtracting the costs of labour, depreciation, interest and business tax from the gross margin. Farm income was computed by summing the product of the simulated sales of each product (grain, wool, young livestock, cull stock and fodder) using annually-varying prices. Indices of prices received by farmers for annual crops, wool, lamb and mutton and prices paid for N fertiliser were obtained from ABARES (ABARES, 2014). Operating costs for managing pastures and winter fallows were assumed to be fixed. Location-specific price and cost time series (per unit area) were converted to 2014–2015 dollars using the Consumer Price Index (Ghahramani and Moore, 2016). The total capital required by each simulated farm was calculated by summing the capital value of land, machinery and other infrastructure, and livestock. The average amount of capital invested in machinery and infrastructure was used to calculate the total capital invested, i.e. a constant rate of replacement in dollar terms was assumed. The capital value of sheep (expressed on a per- dry sheep equivalent basis) was calculated from the average sale price of livestock and an estimated dry sheep equivalent value for adult stock (Crimp et al., 2016).

2.5 Validations

Simulated crop yields and livestock production were validated through producer workshops and a regional database for the period of 1996-2013 (Ghahramani and Moore, 2016). This database is constructed through a biannual survey completed by growers about their planted areas and yields and the results averaged across each shire. The performance of the models of representative sites (current practice and under historical climate) in this paper against the observed data for crops is presented in Ghahramani and Moore (2016) which is the first paper of these series focused on the impact of climate change in Western Australia. The GRAZPLAN pasture simulation model is widely employed in Australia for research purposes (e.g. Alcock and Hegarty, 2011) and for supporting producer decisions (e.g. Donnelly et al., 2002). Pasture and livestock simulation results were discussed and model performance evaluated in producer workshops.

2.6 Climate projections

Following Ghahramani and Moore (2016), three plausible future climate scenarios were considered, based on the clustering of projections from 23 Global Circulation Models (Burgess et al., 2012). Two Representative Concentration Pathways (RCP) 4.5 and 8.5 (van Vuuren et al., 2011) of high and low sensitivity (to allow sampling across the more likely range of possible future climates) were applied with three global climate models: HADGEM2-AO (Pope et al., 2000), GFDL CM3 (Delworth et al., 2006), and MIROC5 (Burgess et al., 2012). The three possible climate scenarios of 2030 included a ‘hot and dry’ based on the RCP 8.5 x high sensitivity x GFDL CM3; a ‘hot and moderate changes in rainfall’ based on RCP 8.5 x high sensitivity x MIROC5; and a RCP 4.5 x low sensitivity x HADGEM2-AO considered a ‘warm with least changes in rainfall’. The projections of global climate models used at each case study location were statistically downscaled using the quantile matching method which produces daily weather data sequences (Burgess et al. 2012). Atmospheric CO_2 concentrations of 435 ppm for 2030 under the RCP 4.5 and 449 ppm under RCP 8.5 scenarios were assumed. For the baseline, monthly atmospheric CO_2 concentration measured at Cape Grim station were used and values ranged between 335.7 ppm and 366.5 ppm (CSIRO and Bureau of Meteorology, 2014).

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2.7 Adaptation options

Using a stakeholder-driven approach (Mastrandrea et al., 2010), facilitated stakeholder workshops were conducted during the life of the project to identify adaptation options to future climate conditions and to gather the information required to benchmark the baseline models. The ADOPT (Adoption and Diffusion Outcome Prediction Tool) decision support tool (Kuehne et al. 2014) was used with stakeholders to identify a suite of adaptation options and to examine the feasibility of each option based on a series of agreed metrics. The focus of the workshops was on identification and design of systemic-to-transformational adaptations including changes in land use, enterprise change, or the adoption of combinations of incremental and transformative adaptation options that together build a systemic change (Ghahramani and Moore, 2015). The systemic combinations of incremental adaptation options were grouped into four packages. Within these packages, three management types were considered: cropping as principal farm business i.e. “cropping centred”; livestock as primary farm business i.e. “livestock centred and diversifying a cropping only systems i.e. “diverse cropping”.

Currently an increase in the livestock enterprise (pasture area and/or stocking rate) is seen as a less risky strategy compared to the cropping for managing climate variability (Kingwell et al., 2013), and is demonstrated to stay a risk-avoiding enterprise under changing climate as well (Ghahramani and Moore, 2016). Therefore increased land allocated to cropping is considered as a risky strategy that can result in a high financial return only in years when adequate rainfall occurs. Therefore adaptations which result in a greater cropping area are considered a risky reconfiguration. All the designed adaptation packages are considered systemic, while changes in land use and the shift between cropping and pasture can be transformative because they require significant changes in current systems. However, according to the terminology of Smit and Wandel (2006), most of the designed adaptation packages in this paper may be considered as transformative as they result in significant changes in the composition of the farming system and are a response to opportunities.

In broad terms, the four adaptation packages developed can be described as below:

1. Alteration of the crop-livestock balance: This was to increase the livestock component of the system by an increase in the proportion of pasture in the relative areas of existing crop-pasture sequences, and/or an increase in stocking rate. Shorter season grain varieties (more suited to later sowing) were included to allow grazing of cropping paddocks prior to seeding.
2. Low risk and low return farming options: This package of choices also increases the area used for livestock, either by changing the relative areas of existing crop-pasture sequences or the relative length of the crop/pasture phases, but the package also included long-fallows (a single year), lower inputs and the adoption of more drought-tolerant crops.
3. Medium risk and medium return farming options: This package of choices included maintaining the cropping and livestock mix at levels close to the baseline, but increasing the rate of inputs above the current baseline values. This included slightly riskier crops, running livestock at slightly higher rates with greater utilisation of pasture and short fallows introduced into the rotation.
4. High risk and high return farming options: This package of choices included increasing the area used for cropping well above that of the baseline (or equal to baseline in the low rainfall environment), the selection of higher production but less climate resilient crops and greater rates of fertiliser use. This package also includes much higher stocking rates as well as utilisation rates, with the use of short fallows and full chemical weed control to minimise soil water losses.

3. Results

The results of climate change impact and adaptations are presented along a rainfall gradient of relatively high growing season rainfall (Katanning 431mm), medium rainfall (Cunderdin 330mm) to relatively low rainfall (Merredin 308mm) locations. While the rainfall differences between Cunderdin and Merredin appear small there is usually a later onset to seeding rains and earlier onset of the growing season finish for Merredin. This results in later germination opportunities and greater moisture stress during grain filling and spring growth of pasture. The results have also been divided into production and profitability, environmental health and greenhouse gas emission sections.

3.1 Projected changes in climate relative to the baseline

The 'hot and dry' climate change scenario (the most severe projected climate for 2030) had an increase in mean temperature in the range between 1.0 °C and 1.2 °C across the transect, with the least increase at the relatively high rainfall site (Table 2). The 'warm with least changes in rainfall' scenario is still predicted to result in a 0.5 °C increase in temperature across sites. Overall, there were projections for a warmer spring and autumn at all sites across the transect. There was an increase in spring and mid-summer rainfall projected for most site × climate scenarios, but reductions occurred in autumn and winter rainfall. However, in most cases, increases in monthly rainfall were also associated with increases in temperature (also explored by Ghahramani and Moore, 2016) and hence potentially greater evaporation.

3.2 Effectiveness of adaptation on production and profit

The effect of the adaptation packages varied between representative sites for different climate scenarios in 2030. As was expected, under the baseline whole farm profit decreased from the high rainfall site toward the relatively low rainfall site, and this was in a range between \$117 and \$80 per hectare (Table 3). Without any adaptation options being implemented, this profit declined under the impact of climate change by 2% at the high rainfall site, 22% at the medium rainfall site, and 47% at the relatively low rainfall site. These declines in profit were also associated with the decreased ground cover. However adaptation packages were often able to offset the negative impact of climate change, but each adaptation package that was financially effective over a long-term period has different financial risk management and environmental consequences. Details for each site have been presented below.

3.2.1 High rainfall site

Wheat yield increased (2% to 24%) under all climate scenarios for 2030 if adaptation packages were used, except for the adaptation package 1: 'alteration of the crop-livestock balance' (Table 3). Application of this adaptation resulted in a predicted decline in wheat yields across all future climates, but an increase in canola yields (Fig 2, Table 3). This suggests that the current sowing rules and fertiliser usage for crop production will be still profitable under changed climate conditions in a relatively high rainfall region. The 'medium risk and return' adaptation package, resulted in the largest increase in wheat yields but was not the most profitable adaptation package (Table 3) due to greater fertiliser costs, lower canola yields and removal of land from production for fallow.

There was an opportunity to increase stocking rate at this site without pressure on the pasture sustainability. A 10% increase in stocking rate was able to be sustained (without pressure on the ground cover) by the additional pasture forage produced as a result of the changes in climate, and the use of supplementary feeding of wheat crops during the autumn feed gap.

The whole-farm profitability had almost no change (between -2% and +1%) across all three potential climate scenarios for 2030 if the current practices remained unchanged (Fig 2, Table 3). The majority of the adaptation packages were financially effective, but the most effective option was number 1: 'altering the crop-livestock balance' which increased profitability by an average of nearly 80%. Gross margins of both livestock and cropping enterprises increased with this adaptation package by up to 50% and 21% respectively (Fig 2, Table 3). For cropping, this was largely related to improvements in management without adding costs, i.e. modification of sowing dates and cultivar choice. Overall, the adaptation packages served to increase whole-farm profitability under future climates, 'but the high risk and return' package was the worst performing financially (Fig 2, Table 3).

3.2.2 Medium rainfall

The impact of climate change on the current farm systems decreased the production of wheat and canola (Fig 2, Table 3). The effectiveness of adaptations for wheat yield varied among the future climate scenarios between -11% and 16% (Table 3). Wheat production decreased with the implementation of 'crop-livestock alteration' package under all possible future climates despite optimising cultivar and sowing date and changes in the rotation systems (Table 3, Fig 2). The 'medium risk and return' and 'high risk and return' adaptation packages increased wheat yields through planting longer season varieties and increasing the *N* input rate (Table 1, 2). In the WA wheatbelt, barley is known to be less sensitive to lower rainfall (Stakeholder workshops), and it continued to be productive under climate change scenarios (Table 3). Although barley has exhibited a negative yield response to changes in temperature (Ghahramani and Moore, 2016), by continuing the current practice in the future climates barley yield increased between 7% and 9% (Table 3). This can be related to increased CO_2 levels and tolerance to winter drought.

The livestock sale weight of the baseline systems declined under climate change in the range of between 1% and 7%. (Table 3). All the adaptations packages were able to increase the sale weight in the range between 8% and 117%, with 'Alteration of the crop-livestock balance' proving to be the most effective (Fig 2, Table 3).

Climate change reduced the gross margin of the current practice for both cropping and livestock by up to 13% and 7%, respectively (Fig 2, Table 3). Overall, the evaluated adaptations were more successful in increasing gross margin of livestock enterprises compared to the cropping, and in particular when there was a 50% increase in stocking rate and pasture area (Table 3). The 'low and medium risk and return' adaptations were the most efficient options for improving gross margins of the cropping over a long-term but only under the least change in climate scenario (Table 3). The profitability of current practice changed in the range between -22% and 4% under the range of possible future climates (Fig 2, Table 3). Under both the severe and moderate climate scenarios, the adaptation packages were able to increase profitability between 5% and 20% of years (Figure 3). Overall, alteration of the crop-livestock balance had the greatest positive effect on whole-farm profitability (Table 3).

Table 2. Summary of the climate changes at 2030 projected under three climate change scenarios. See the text for a description of the three climate projections. GSR: Growing season rainfall.

Site	Site	Baseline 1970-2010	Climate Scenarios - changes in 2030 relative to the baseline		
			Hot and dry (severe climate change)	Hot and moderate changes in rainfall (moderate climate change)	Warm with least changes in rainfall (least climate change)
High rainfall (Katanning)	Min T	9.4 (°c)	0.9	1	0.4
	Max T	22.2 (°c)	1.2	1.2	0.5
	MeanT	15.8 (°c)	1	1.1	0.5
	GSRRainfall	456.2 (mm)	-11%	-9%	-3%
Medium rainfall (Cunderdin)	Min T	11.2 (°c)	1	1.3	0.5
	Max T	25.3 (°c)	1.3	1.4	0.5
	MeanT	18.3 (°c)	1.2	1.4	0.5
	GSRRainfall	351.0 (mm)	-12%	-10%	-3%
Relatively low rainfall (Merredin)	Min T	11.3 (°c)	1.1	1.2	0.5
	Max T	25.0 (°c)	1.4	1.4	0.5
	MeanT	18.1 (°c)	1.2	1.3	0.5
	GSRRainfall	326.3 (mm)	-12%	-8%	-3%

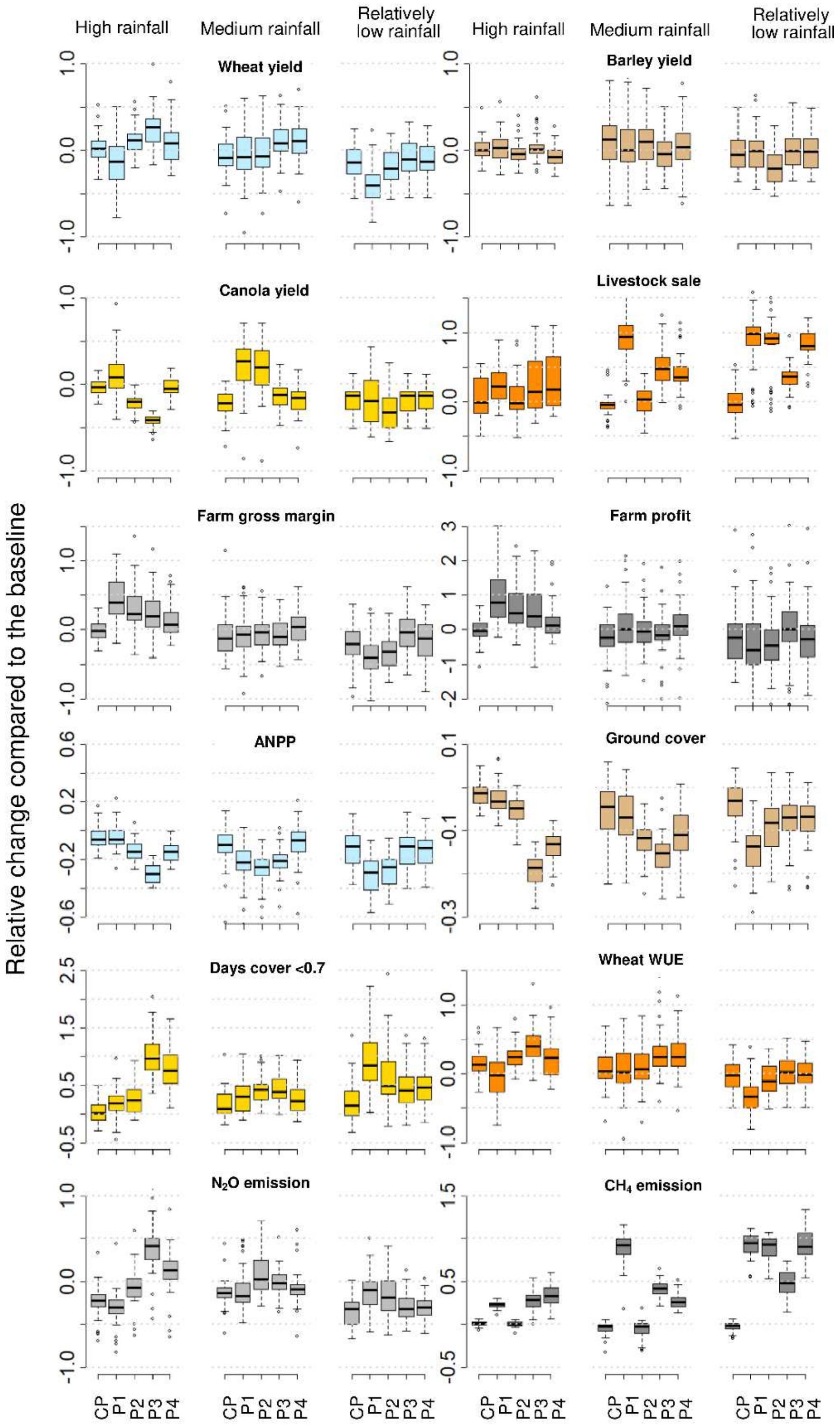

Fig 2 Relative change in production and profit, environmental health, water use efficiency (WUE), and primary GHG emission under "Hot and dry" climate scenario of 2030 (RCP 8.5 x high sensitivity x GFDL CM3) compared to the baseline (1970-2010). CP: current practice. P1: Alteration of the crop-livestock balance, P2: Low risk and low return, P3: Medium risk and medium return, P4: High risk and high return. ANPP: annual net primary productivity.

3.2.3 Relatively low rainfall

The impact of climate change on the current system resulted in a decline in wheat yields in the range between 4% and 13% (Table 3). The most profitable adaptation package was the ‘medium in risk and return’ (associated with 10% increase in N fertiliser), but none of the adaptation packages could offset the negative impact of climate change on wheat yield (Table 3, Fig 2). The barley yield of current systems declined by 2% under the ‘hot and dry’ potential climate of 2030 while an increase of between 4% and 6% was simulated under the least and moderate changes in climate respectively (Table 3). The adaptation packages that included changes in rotation systems, alternative management of other crops, and/or long fallows could increase barley yield under all climate scenarios projected for 2030 (Fig 2, Table 3).

Changes in climate had only a little impact on animal sale weights in the current systems (Fig 2, Table 3). All the adaptation options made a significant increase in livestock sale weight of between 29 and 99% (Fig 2, Table 3).

The livestock gross margin for current practice declined by 15% under the ‘hot and dry’ climate of 2030 (Table 3), by 6% under moderate changes in climate and no changes under least changes in climate. The adaptation option of ‘high in risk and return’ which was associated with an increase in stocking rate (but not increase in the area of annual pasture) was effective in increasing the gross margin of the livestock enterprise up to 39% (Table 3). The profitability of the whole farm under the current practice declined between 9% and 47% under the three climate scenarios (Table 3). Only two adaptation packages were effective in improving farm profitability under the ‘moderate’ and ‘least’ changes in climate (Table 3, Fig 2, 3). The ‘medium and high’ in risk and return adaptations were the most effective with profitability increases of up to 33% under least changes in climate (Table 3). The relative change of farm production compared to the current practice varied seasonally among adaptation packages over the analysis period of 1970-2010 (Fig 2). Under the severe climate change projected for 2030, long-term average wheat yield declined more significantly than barley (Table 3) with greater interannual variability (Fig 2). The implementation of low in risk and return adaptation (i.e. an increase in stocking rate and pasture area), not only improved long-term average animal sale weights compared to the baseline (Table 3) but also resulted in the smallest inter-annual variability of profitability compared to the other adaptations (Fig 2). At the relatively low rainfall site, the adaptation package of ‘high in risk and return’ was able to offset some of the negative impacts of climate change on profitability and provide potential opportunities for the majority of individual years if climate change was least (Fig 3), but was still over $170,000 less profitable per farm under the more severe climate change scenario. It was neither the most effective over the long-term (Table 3) nor in years with high profit (Fig 3), as the ‘medium in risk and return’ was more effective in high-profit individual years (Fig 3). The adaptation packages were able to create opportunities to produce a greater profit compared to the baseline if the climate change was least, and could offset part of the negative impact under severe and moderate changes in climate, but only in years with adequate rainfall (Fig 3).

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Table 3. Performance of adaptations for climate scenarios in 2030. The historical values are average over 1970-2010 and the rest are relative changes in 2030 compared to the historical. CP: Current practice. P1: Alteration of the crop-livestock area, P2: Low in risk and return, P3: Medium in risk and return, P4: High in risk and return. All farm area is considered for the calculation of livestock gross margin per unit area as livestock feeding is also depended on cropping lands, e.g. crop grazing, stubble grazing.

		Historical	Hot and dry (severe climate change)					Hot and moderate changes in rainfall (moderate climate change)					Warm with least changes in rainfall (least climate change)				
	Metrics	CP	CP	P1	P2	P3	P4	CP	P1	P2	P3	P4	CP	P1	P2	P3	P4
igh rainfall	Wheat yield (tonne/ha)	2.3	0.01	-0.18	0.02	0.24	0.06	0.04	-0.21	0.01	0.24	0.06	-0.01	-0.22	0.00	0.19	0.02
	Barley yield (tonne/ha)	2.4	0.01	0.03	-0.06	0.02	-0.07	-0.04	0.02	-0.09	0.01	-0.10	0.01	0.04	-0.05	0.00	-0.10
	Canola yield (tonne/ha)	1.2	-0.03	0.12	-0.23	-0.43	-0.04	-0.02	0.13	-0.23	-0.43	-0.04	-0.01	0.15	-0.23	-0.42	-0.02
	Sold animal weight (tonne/ farm)	157	-0.17	0.02	-0.23	-0.17	-0.13	-0.18	0.04	-0.29	-0.17	-0.14	-0.06	0.08	-0.14	-0.19	-0.17
	Net primary productivity (tonne DM/ farm)	19867	-0.05	-0.05	-0.15	-0.3	-0.15	-0.05	-0.06	-0.16	-0.31	-0.17	-0.01	-0.01	-0.12	-0.32	-0.16
	Ground cover (farm average)	0.81	-0.01	-0.03	-0.04	-0.19	-0.14	-0.02	-0.03	-0.05	-0.20	-0.15	0.00	-0.01	-0.04	-0.19	-0.14
	Pasture cover	0.90	-0.01	-0.03	-0.06	-0.25	-0.20	-0.02	-0.03	-0.07	-0.26	-0.21	0.00	-0.01	-0.05	-0.25	-0.20
	Crop cover	0.75	-0.02	-0.03	-0.03	-0.14	-0.08	-0.02	-0.03	-0.04	-0.15	-0.09	0.00	-0.02	-0.03	-0.15	-0.08
	Water use efficiency-wheat (kg/ha.mm)	5.2	0.12	-0.09	0.14	0.39	0.17	0.13	-0.14	0.11	0.36	0.15	0.02	-0.2	0.03	0.23	0.04
	Water use efficiency-barley (kg/ha.mm)	5.6	0.14	0.16	0.06	0.15	0.05	0.05	0.12	0.00	0.11	0.00	0.05	0.08	-0.02	0.03	-0.07
	N_2O (t CO2-eq/farm)	227	-0.21	-0.27	-0.05	0.41	0.15	-0.13	-0.20	0.01	0.51	0.24	-0.07	-0.14	0.03	0.45	0.21
	CH_4 (t CO2-eq/farm)	452	0.01	0.23	-0.16	0.28	0.33	0.02	0.23	-0.15	0.27	0.32	0.01	0.22	-0.16	0.26	0.30
	Total N_2O & CH_4 (t CO2-eq/farm)	679	-0.06	0.06	-0.12	0.32	0.27	-0.03	0.09	-0.10	0.35	0.29	-0.02	0.10	-0.10	0.32	0.27
	Crop gross margin ($/ farm)	$553,463	-0.03	0.50	0.30	0.22	0.09	-0.01	0.48	0.28	0.21	0.08	-0.01	0.5	0.3	0.22	0.06
	Crop gross margin ($/ ha)	$307	-0.03	0.50	0.34	0.39	-0.09	-0.01	0.48	0.31	0.37	-0.10	-0.01	0.50	0.31	0.38	-0.11
	Livestock gross margin ($/ farm)	$304,738	0.03	0.18	-0.19	0.04	0.05	0.04	0.20	-0.20	0.03	0.04	0.01	0.21	-0.20	-0.01	-0.01
	Livestock gross margin ($/ ha)	$102	0.03	0.18	-0.03	0.04	0.05	0.04	0.20	-0.03	0.03	0.04	0.01	0.21	-0.02	-0.01	-0.01
	Profit ($/ farm)	$349,586	-0.02	0.80	0.33	0.39	0.14	0.01	0.78	0.30	0.37	0.11	0.00	0.81	0.32	0.35	0.06
	Profit ($/ ha)	$117	-0.02	0.80	0.47	0.39	0.14	0.01	0.78	0.41	0.37	0.11	0.00	0.81	0.45	0.35	0.06
edium rainfall	Wheat yield (tonne/ha)	2.1	-0.06	-0.11	-0.06	0.13	0.10	-0.04	-0.09	-0.05	0.14	0.12	0.00	-0.01	0.02	0.16	0.16
	Barley yield (tonne/ha)	2.2	0.09	0.05	0.08	-0.04	0.04	0.08	0.06	0.09	-0.06	0.02	0.07	0.13	0.11	-0.14	-0.01
	Canola yield (tonne/ha)	1.2	-0.20	0.17	0.16	-0.13	-0.17	-0.17	0.21	0.18	-0.09	-0.14	-0.03	0.33	0.27	0.04	0.00
	Sold animal weight (tonne/ farm)	60	-0.07	0.82	0.09	0.37	0.31	-0.04	0.81	0.08	0.36	0.30	-0.01	1.17	0.16	0.41	0.31
	Net primary productivity (tonne DM/ farm)	24780	-0.11	-0.23	-0.27	-0.21	-0.08	-0.09	-0.22	-0.26	-0.20	-0.07	-0.01	-0.13	-0.20	-0.16	-0.01
	Ground cover (farm average.)	0.71	-0.06	-0.07	-0.13	-0.16	-0.11	-0.06	-0.07	-0.11	-0.16	-0.10	-0.01	0.00	-0.06	-0.12	-0.06
	Pasture cover	0.69	-0.02	-0.01	-0.17	-0.34	-0.19	-0.04	-0.03	-0.36	-0.20	-1.00	0.01	0.05	-0.11	-0.33	-0.15
	Crop cover	0.71	-0.07	-0.09	-0.10	-0.13	-0.11	-0.06	-0.08	-0.13	-0.10	-1.00	-0.02	-0.02	-0.03	-0.09	-0.05
	Water use efficiency-wheat (kg/ha.mm)	6.3	0.04	0.00	0.06	0.27	0.24	0.05	0.01	0.06	0.27	0.24	0.03	0.04	0.07	0.22	0.21
	Water use efficiency-barley (kg/ha.mm)	6.7	0.21	0.16	0.21	0.06	0.14	0.17	0.15	0.20	0.01	0.10	0.10	0.16	0.15	-0.12	0.02
	N_2O (t CO2-eq/farm)	69	-0.10	-0.12	0.09	0.03	-0.04	-0.03	-0.06	0.08	0.01	-1.00	-0.02	-0.01	0.17	0.09	0.00
	CH_4 (t CO2-eq/farm)	180	-0.04	0.89	-0.05	0.42	0.28	-0.04	0.91	0.41	0.26	-1.00	-0.02	0.99	-0.02	0.44	0.27
	Total N_2O & CH_4 (t CO2-eq/farm)	249	-0.06	0.61	-0.01	0.31	0.19	-0.04	0.64	0.32	0.19	-1.00	-0.02	0.71	0.03	0.34	0.20
	Crop gross margin ($/ farm)	$787,274	-0.13	-0.17	0.01	-0.06	0.04	-0.09	-0.14	0.04	-0.03	0.07	0.03	0.04	0.20	0.04	0.18
	Crop gross margin ($/ ha)	$234	-0.13	0.04	0.32	0.02	-0.05	-0.09	0.06	-0.09	0.04	-0.02	0.03	0.29	0.57	0.12	0.08
	Livestock gross margin ($/ farm)	$171,578	-0.07	0.57	-0.23	0.03	0.15	-0.06	0.57	-0.22	0.01	0.13	-0.03	0.86	-0.20	0.03	0.12
	Livestock gross margin ($/ ha)	$43	-0.07	0.58	-0.23	0.03	0.15	-0.06	0.57	-0.06	0.01	0.13	-0.03	0.86	-0.20	0.03	0.12
	Profit ($/ farm)	$359,268	-0.22	0.05	-0.06	-0.08	0.12	-0.15	0.10	-0.01	-0.05	0.16	0.04	0.48	0.24	0.07	0.33
	Profit ($/ ha)	$90	-0.22	0.07	-0.06	-0.08	0.12	-0.15	0.10	-0.15	-0.05	0.16	0.04	0.48	0.24	0.07	0.33
elatively low rainfall	Wheat yield (tonne/ha)	2	-0.13	-0.42	-0.19	-0.09	-0.11	-0.06	-0.38	-0.14	-0.03	-0.05	-0.04	-0.38	-0.14	0.00	-0.04
	Barley yield (tonne/ha)	2.2	-0.02	0.01	-0.20	0.00	-0.01	0.06	0.08	-0.19	0.06	0.05	0.04	0.10	-0.16	0.07	0.04
	Canola yield (tonne/ha)	1.2	-0.17	-0.15	-0.28	-0.17	-0.17	-0.08	-0.08	-0.20	-0.10	-0.11	-0.02	0.04	-0.09	-0.01	-0.02
	Sold animal weight (tonne/ farm)	58	0.00	0.88	0.84	0.29	0.69	-0.01	0.96	0.99	0.31	0.73	0.05	0.90	0.93	0.33	0.72
	Net primary productivity (tonne DM/ farm)	33690	-0.13	-0.3	-0.27	-0.13	-0.15	-0.06	-0.25	-0.22	-0.07	-0.09	-0.01	-0.18	-0.16	-0.02	-0.04
	Ground cover (farm average.)	0.79	-0.04	-0.15	-0.09	-0.08	-0.08	-0.02	-0.12	-0.08	-0.06	-0.06	0.00	-0.09	-0.03	-0.04	-0.05
	Pasture cover	0.85	-0.02	-0.11	-0.10	-0.22	-0.28	-0.01	-0.06	-0.06	-0.23	-0.28	0.00	-0.01	-0.01	-0.24	-0.31
	Crop cover	0.79	-0.05	-0.17	-0.10	-0.06	-0.05	-0.02	-0.15	-0.10	-0.04	-0.03	-0.01	-0.12	-0.05	-0.02	-0.01
	Water use efficiency-wheat (kg/ha.mm)	6.2	-0.03	-0.35	-0.10	0.01	0.00	-0.01	-0.34	-0.07	0.05	0.02	-0.01	-0.36	-0.11	0.03	0.00
	Water use efficiency-barley (kg/ha.mm)	6.9	0.08	0.11	-0.11	0.11	0.10	0.12	0.15	-0.14	0.14	0.13	0.06	0.12	-0.14	0.10	0.07
	N_2O (t CO2-eq/farm)	56	-0.31	-0.12	-0.14	-0.27	-0.28	-0.14	0.01	0.07	-0.11	-0.12	-0.08	0.03	0.14	-0.03	-0.04
	CH_4 (t CO2-eq/farm)	128	-0.02	0.92	0.90	0.47	0.94	-0.01	0.98	0.95	0.50	0.98	0.00	1.04	1.01	0.52	0.96
	Total N_2O & CH_4 (t CO2-eq/farm)	184	-0.11	0.60	0.58	0.24	0.57	-0.05	0.68	0.68	0.31	0.65	-0.02	0.73	0.75	0.35	0.66
	Crop gross margin ($/ farm)	$1,103,996	-0.21	-0.51	-0.43	-0.02	-0.18	-0.07	-0.43	-0.37	0.10	-0.07	-0.04	-0.39	-0.34	0.16	-0.03
	Crop gross margin ($/ ha)	$245	-0.21	-0.43	-0.27	0.07	-0.18	-0.07	-0.34	-0.18	0.21	-0.07	-0.04	-0.29	-0.15	0.27	-0.03
	Livestock gross margin ($/ farm)	$116.996	-0.15	0.86	0.79	-0.08	0.19	-0.06	0.94	0.88	0.00	0.28	0.00	1.07	1.03	0.07	0.39
	Livestock gross margin ($/ ha)	$23	-0.15	0.86	0.79	-0.08	0.19	-0.06	0.94	0.88	0.00	0.28	0.00	1.07	1.03	0.07	0.39
	Profit ($/ farm)	$400,248	-0.47	-0.73	-0.60	-0.07	-0.34	-0.15	-0.56	-0.44	0.20	-0.08	-0.09	-0.44	-0.35	0.33	0.03
	Profit ($/ ha)	$80	-0.47	-0.73	-0.60	-0.07	-0.34	-0.15	-0.56	-0.44	0.20	-0.08	-0.09	-0.44	-0.35	0.33	0.03

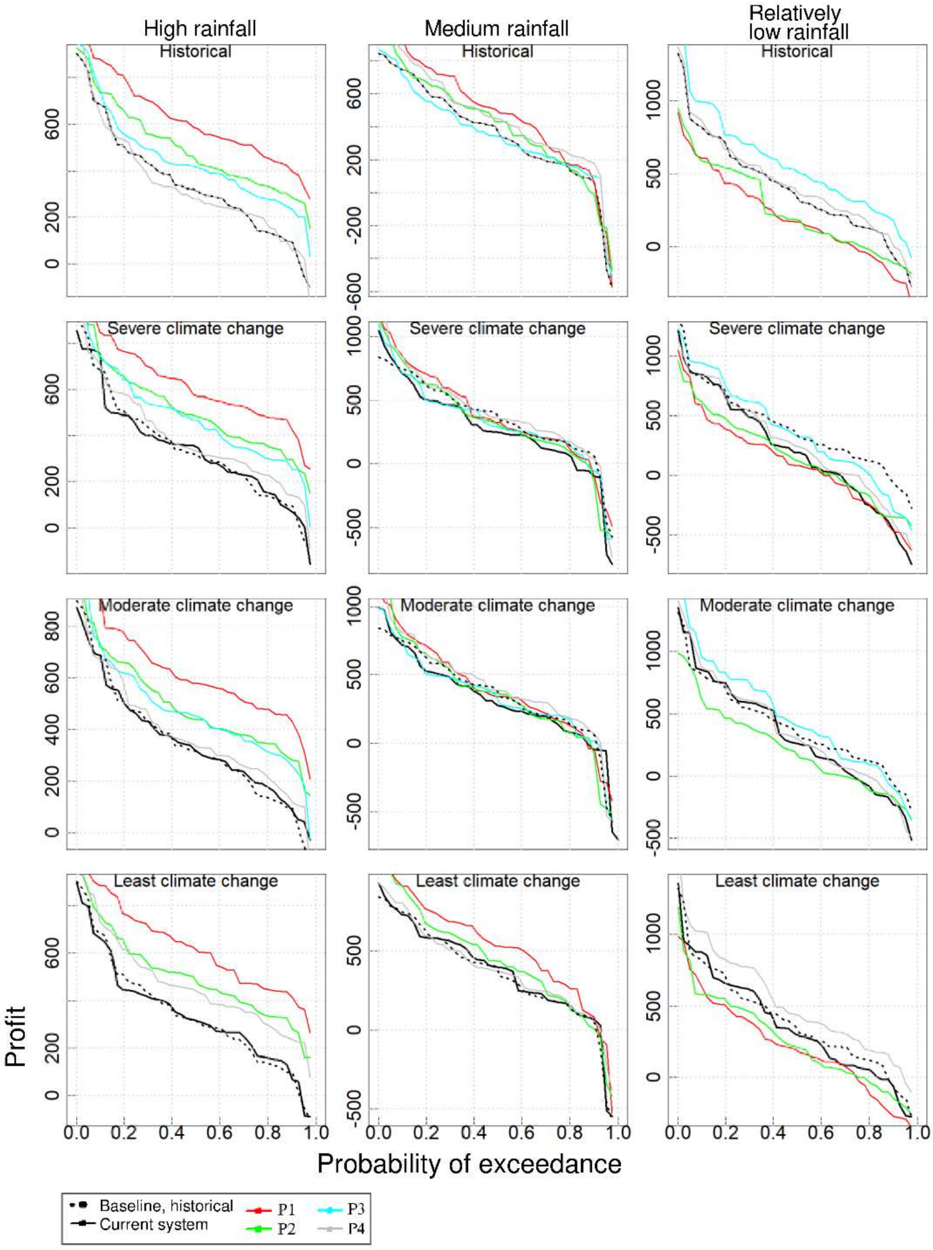

Figure 3 Empirical probability of exceedance for whole farm profit, across transect and under historical and projected climates for 2030 and the baseline and adaptation packages. P1: Alteration of the crop-livestock balance, P2: Low risk and low return, P3: Medium risk and medium return, P4: High risk and high return. The black line is the baseline model under projected climates. The dotted black line is the baseline model of historical climate. The baseline case under historical climate is plotted in all figures to compare projected profitability with the baseline.

3.3 Environmental health

3.3.1 High rainfall

The net primary productivity declined under all projected climates for 2030 and all adaptation packages in the range of between 1% and 32% with the smallest decline through alteration of the crop-livestock balance (Table 3, Fig 2). For the baseline simulation, the average ground cover was 0.81, considered a “healthy condition” (Lang and McCaffrey, 1984), but under future climates, ground cover dropped to 0.7 considered as “transitional state” particularly under ‘medium and high in risk’ and return adaptations. The ‘medium and high in risk’ and return adaptations had the greatest negative impact on total productivity and ground cover of pasture and cropping systems (Table 3). Water use efficiency increased under these adaptation packages and climate scenarios because the decline in yield is not proportional to decline in rainfall as genetic improvements are introduced through more water-efficient varieties.

3.3.2 Medium rainfall

The ‘high in risk and return’ adaptation package had the greatest effect in offsetting the negative impact of climate change on net primary productivity (Fig 2, Table 3). The adaptations were not able to offset the changes in ground cover under severe and moderate changes in climate (Table 3). According to the simulation results, soil erosion would be a heightened risk in the medium rainfall region as all adaptation packages resulted in ground cover losses well below the required threshold (Table 3). The frequency of low ground cover was increased by use of the ‘low and medium in risk and return’ adaptation packages (Fig 2). Overall water use efficiency varied between adaptations and increased compared to the baseline (Table 3), and is consistent with Ghahramani et al. (2015).

3.3.3 Relatively low rainfall

The net primary productivity of the whole farm declined under all adaptation packages and potential climates for 2030 in the range between 3% and 27% (Table 3, Fig 2). Similarly ground cover decreased by 3% to 15% depending on the climate scenario and the adaptation package (Table 3). Under the ‘medium and high in risk and return’ adaptation packages the modelled pasture ground cover would have fallen to 0.6 (Table 3), which would result in a major risk of soil erosion. The adaptation packages of ‘altering crop-livestock balance’ and ‘low in risk and return’ resulted in changes in ground cover that could be acceptable only under the moderate and least climate change scenarios. Under the impact of climate change on existing systems, water use efficiency of wheat declined in the range between 1% and 3%, and ‘alteration of the crop-livestock balance’ and ‘low in risk and return’ adaptation packages exacerbated this decline in the range of between 7% and 36% (Table 3). The water use efficiency of barley in existing systems increased under the impact of climate change in a range of between 6% and 12% (Table 3). The ‘low in risk and return’ adaptation was associated with a 10% decrease in N fertiliser rate and a decreased water use efficiency for barley up to 14%, while under ‘alteration of the crop-livestock balance’ water use efficiency increased by up to 15% (Table 3). This suggests a requirement for N fertiliser to prevent any further decline in water use efficiency for at least barley and wheat.

3.4 Groundcover

There was a significant linear correlation between ground cover and the frequency of days in the year in which ground cover was less than 0.7 (Fig 4a). Thus long-term average ground cover can also represent the frequency of low ground cover. It is important to make the linkage between profitability and ground cover (long-term average and frequency of low days) to evaluate the likely risk of soil erosion (Fig 4b). Profit had a positive and linear correlation with the ground cover, particularly in medium and relatively low rainfall sites (Fig 4b).

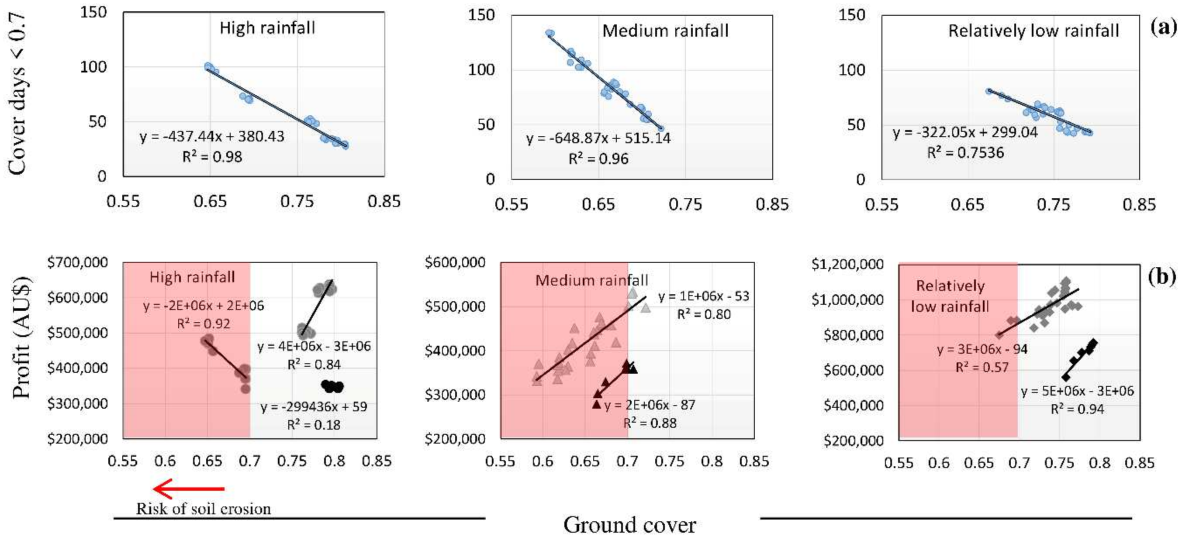

Fig 4 Relationship between ground cover and profitability (a) a linear relationship between farm frequency of low cover days and ground cover. (b) the relationship between long-term average farm profitability and ground cover, black marks represent historical climate and grey marks to the projections for 2030.

3.5 GHG emission

N_2O emission

Under the impact of climate change on existing farm systems with current practice, modelled nitrous oxide (N_2O) emissions declined in all site x potential climate scenario combinations by 21%, 10%, and 31% at high rainfall, medium rainfall and relatively low rainfall sites respectively (Table 3), while annual variability differed among sites (Fig 2 for severe climate change). At the high rainfall site the 'medium and high in risk and return' adaptation packages, which were associated with an increase in the N input rate and in the cropping area, resulted in an increase in N_2O emission in the range of between 15% and 51% compared to the baseline (Table 3, Fig 2). At the medium rainfall site, N_2O emission increased (by up to 17%) under the 'low and medium in risk and return' adaptation packages (Table 3), and these adaptations were associated with increases in N input rate and replacement of legumes with annual pasture or fallow. At the relatively low rainfall site N_2O emissions declined as a result of adopting any of the four adaptation packages under potential climates, except for the 'alteration of the crop-livestock balance' and 'low in risk and return' packages and the least climate change scenario for 2030 (Table 3). These changes can be related to the interactions between projected climate, changes in rotation systems, and sowing date. In general, the current N_2O emissions from soils in Western Australian farming systems are low (Barton et al., 2008), but the N_2O emissions were predicted to increase as a consequence of some of the adaptation packages, e.g. up to 51% at the high rainfall site (Table 3).

CH_4 Emission

Changes in the modelled ruminant CH_4 emissions varied between -4% at the medium rainfall site and +1% at the relatively high rainfall site under the impact of climate change on the existing farm systems (Table 3). These changes related to the pasture production and shorter growing seasons and consequent effects on animal growth and sale date. Yearly variability of ruminant CH_4 emissions was smallest at the highest rainfall site (Fig 2). CH_4 emissions varied as a consequence of the adoption of different adaptation packages, and as was expected those with an increase in stocking rate resulted in greater CH_4 emissions in comparison with the baseline (Table 3). Ruminant CH_4 emissions depend on the livestock numbers and with the changes in the size of livestock enterprises, ruminant CH_4 emissions were predicted to increase significantly across site x potential climate combinations (Table 3).

3.6 Adoption by producers

A range of adaptation pathways was investigated in the stakeholder workshop to quantify the adoption rate of new management (adaptations). The level of the adoption of new management under a changing climate was investigated by applying mathematical principles (using ADOPT, Kuehne et al., 2014) in stakeholder workshop to quantify the degree of adoption. To remove locality effects and decrease the likely bias (because each mixed crop-livestock farm is a unique system with details varying between the farms), the investigation was conducted at three higher levels - cropping centred, livestock centred, and diverse cropping. The maximum adoption levels of the climate change adaptations were quantified and time to adoption was estimated (Fig 4c). Maximum adoption levels were 93%, 70%, and 33% for cropping centred, livestock centred, and diverse cropping, respectively. Time to peak adoption was estimated as about four years for cropping centred, six years for livestock centred, and six years for diverse cropping (Fig 4c).

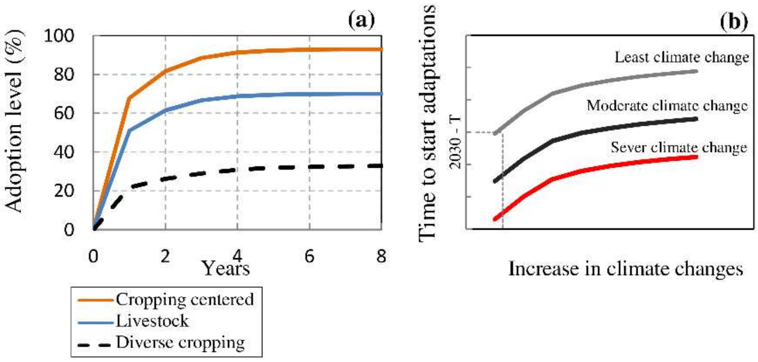

Fig 5 Stakeholder response to adaptation (a) Modelled stakeholder response in this project for adaptability of changes in the current systems. Cropping centred: focus on cropping with a decline in livestock, Livestock: emphasis on livestock enterprises with an increase in pasture area and a decrease in cropping, diverse cropping: intensification in cropping systems. (b) Schematic illustration for the minimum required time to start adaptations (after Vermeulen et al., 2013).

4. Discussion

4.1 Selection of adaptation options

The long-term average profitability of adaptation packages declined from 'land use change' and 'low risk and return' toward 'high risk and return' at the high rainfall site while this pattern was reversed for the relatively low rainfall site (Fig 2). This was due to an increased frequency of years with extremely low rainfall, particularly at the relatively low rainfall site. In the years since 2000, there has been a major increase in the percentage of farms being cropped across the low rainfall sites of the WA wheat belt, and this has coincided with six very dry years in 15 years with growing season rainfall in the bottom 20% of the historical record. It would appear that farmers have already identified the 'medium risk and return' and 'high risk and return' strategies as the appropriate response to increased drying, but only so long as adequate credit is available from banks or government to plant and harvest future crops after drought years.

Across the examined transect, the projected change in crop yield under current practice was in the range between -20% (canola, medium rainfall site) and +9% (wheat, medium rainfall site) for a 1-degree increase in temperature (Table 3). While these values are different to the 5% decrease predicted for global production (Challinor et al., 2014), the negative yield values of wheat and canola under low rainfall and the more extreme climate change indicate cause for concern. On average, globally adapted crop yield is reported to be 7% greater than non-adapted crops (Challinor et al., 2014). In Western Australia, the range of adaptation effects on crop production reported here varied substantially between sites x crops x management (Table 3).

The effectiveness of adaptations must be decided not only on the profitability of the systems but also on a broad range of effects on agroecosystem health and GHG emissions (e.g. Table 3). For a sustainable production, the preferred adaptations should be those that produce the smallest GHG emissions while making farm systems resilient by protecting the natural capital of the system.

Overall, in a high rainfall site, a 25% increase in stocking rate when complemented by adjustment of the sowing window for wheat and canola and cultivar choice, could result in the most profitable system in the longer term (Fig 2, Table 3). Although this option had a significant interannual variability of profit (Fig 2), annual profit from this option was greater than the baseline in any individual year projected for 2030 (no single year with negative gain) (Fig 3). This profitable option had little effect in increasing on-farm GHG emissions (N_2O and CH_4) compared to an existing farm under historical climate (Table 3).

At the medium rainfall site, a 100% increase in stocking rate with an increase in the area of annual pasture could result in a greater profit (Table 3 and Fig 2) but the significant increase in GHG emissions and decreases in ground cover (and consequently the risk of soil erosion) make this adaptation less attractive. A greater emphasis on cropping would be a more sustainable management option although with less long-term profit.

At the relatively low rainfall site, the adaptation packages of “medium in risk and return” and “high in risk and return” are the most profitable packages with small GHG emissions, but they might be expected to cause an unacceptably low ground cover level in the pasture (Table 3). Use of the “alteration of the crop-livestock” and “low in risk and return” packages could maintain the ground cover of pasture at an acceptable level but they were not financially effective (Table 3). An increase in pasture area was not an effective adaptation under any potential climate of the future. A ‘medium in risk and return’ package appears most favourable for severe changes in climate, while a ‘high in risk and return’ appears best for the least change in the climate scenario. Both these adaptation packages were associated with an increase in stocking rate while maintaining the ground cover at an acceptable level, but they resulted in significant increases in GHG emissions (Table 3).

Overall, the implementation of adaptation packages was profitable if they were associated with an increase in cropping area and an increase in stocking rate. Application of the adaptations also resulted in lower inter-annual variability across most of the simulated metrics.

It is important to understand the impact of technological change when considering the choice of adaptations. Farmers in WA in the cropping sector rapidly change technology through variety choice, seeding system, fertiliser choice, soil amendment, guidance systems and pesticide choice. Future technological improvements which complement the transformative packages outlined here may make for even more resilient systems under climate change. The modelling packages used to develop this paper offer an innovative way to test these improvements prior to field evaluation but will require updating with validated field data if meaningful results are to be obtained. This presents a challenge to the strategic planners who seek to minimise the current and future impacts of climate change, as it requires a long-term vision to create a research environment in which to test the new technologies, many of which are imported into Australia.

4.2 Mitigation

Mitigation policies may affect the use of adaptations evaluated in this paper, and the implementation of the profitable adaptations can ‘‘buy time’’ until an effective mitigation response can be identified using adaptation analyses for the design of future mitigation practices (Howden et al., 2007). Trade-offs between economic (profitability), environment, GHG reduction, and social effect need to be considered to identify appropriate adaptation options (Thornton and Herrero, 2014). However, in a real world, farmers undertake adaptation options if they are motivated by profit. They may not be strongly motivated toward environmental action unless they are either well informed or restricted by law.

Maximizing farming community resilience to future climate risk will likely involve a mix of both mitigation and adaptation; the percentage contribution of each strategy will depend on economic cost/benefit analyses. It is likely that adaptation which leads to smaller on-farm GHG emissions will be implemented if there are enough financial benefits to encourage farmers to undertake this course of action, but this will depend on the availability and ease of use of an emissions market. Currently, the adjustment of profitability and consideration of emission costs is uncertain and depends on future food, energy, and emission market prices, and government policy initiatives.

4.3 Adoption by producers; Adoption capacity and time horizon

The predicted negative impact of climate change in Western Australia suggests that changes to current systems are required to ensure their resilience in the near future. The required changes can be transformations that include changes in function or structure (Fig 2, 3) (Marshall et al., 2016). Adaptations used in this paper are expected to have a high adoption rate with a shorter time horizon because they are well known to the producers. Adoption of a systemic combination of incremental options is predicted to be low if associated with intensification (Fig 5a). This was evidenced through stakeholder workshops where significant intensification became less attractive to producers, who they preferred to undertake the transformation in the farming system, e.g. shift toward either more cropping or livestock (Fig 5a). The evaluated adaptations required a relatively short time horizon to reach the peak point of the adoption (Fig 5a). It, therefore, seems likely that there will be sufficient time to verify the adaptations in the field prior to farmers making necessary modifications (Fig 5b), and a key focus for research funding bodies and the government should be the discovery and testing of new adaptations in for farming systems. From the research reported here, it was evident that lack of motivation for adaptation in system management is not limited to transformative changes. Any systemic adaptation to focus on livestock or cropping may have a lower adoption rate if adaptation is associated with intensification.

4.5 Likely economic barriers

In the context of Australian agriculture, when farmers move from incremental to transformational adaptation options, it is likely that decisions will be made based on the outcome of the business structure, portfolio management, off-farm investments and geographical diversification (Robertson and Murray-Prior, 2016). This suggests a requirement for exploring localised on-farm business and economics as applied in this paper. The biophysical barriers due to climate change, e.g. water stress, increased temperature reduce production, and profitability (Fig 2), and a small reduction in production can have a significant negative effect on the profitability of the system (Thamo et al., 2017). This was particularly obvious with the relatively low rainfall site where under the most severe climate change whole farm profit dropped significantly as the cropping system production dropped. Because farm business models usually is different between mixed crop and livestock systems, the financial barriers to climate change adaptations are also likely to be unique to each farming system. A progressive reduction in whole farm profit (e.g. due to climate change impact) may cause a decline in land value, return on investment, and over time lower farm equity. While at an industry level, the reduction in profit can be offset through merging farms (those who cannot adopt leave – less intensification) to make a larger farm (purchase or lease), the short-term need to increase farm size is associated with an additional cost that may not be an attractive option for all farmers. Per-hectare gross margins, unlike whole-farm margins, are reported to be generally and relatively insensitive to farm size (Ghahramani and Moore, 2016). The effects of changes in farm size on whole farm profit are not always apparent, as both positive and negative effects of this change on return and on investment have been reported (Nossal et al., 2009; Sheng et al., 2015). In general, farmers in Western Australia are prepared to accept higher levels of risk to achieve a profit. Farmers who make changes towards increasing cropping intensity (Fig 5a) may not be able to do it all at once due to the costs of machinery or other production inputs, particularly if they delay until the implication of adaptations are identified, or if they have insufficient access to credit with which to fund the change.

4.6 Uncertainty

Technical uncertainty related to the model's capability is the most commonly expected uncertainty in modelling climate change impact and adaptation (Vermeulen et al., 2013). To reduce this uncertainty, this paper has used models that have had their performance under moderately elevated atmospheric CO_2 and limited water availability tested and proven to be consistent with the results from the FACE experiments (Ghahramani et al., 2015; Asseng et al., 2004). Uncertainties related to the social complexities of the systems were managed by using a capacity approach with stakeholders (e.g. Vermeulen et al., 2013) to design and evaluate adaptation options. Stakeholders in Western Australia are always managing their farms under highly variable climate and weather, and adaptations which are exclusively developed by stakeholders can be game changers, or in some cases lead to maladaptation (Grothmann and Patt, 2005). Thus, the impact of climate change was also considered in the design of adaptations packages to reduce likely bias, e.g. converting negatively affected crops to the annual pasture if livestock was more profitable under climate change.

As in Ghahramani and Moore (2016), modelling analysis in this paper was designed to investigate how specific farming systems which are representative of good present-day practice would respond to adaptations under future climates. Here a “stationary” analysis was carried out (Ghahramani and Moore, 2013; Williams et al., 2015; Ghahramani and Moore, 2016), in which trends in slowly changing variables of average prices and costs were removed. There are assumptions to be made about changes in prices in a coming decade. Although the Fifth Assessment Report of the Intergovernmental Panel on Climate Change indicates the sensitivity of the crop market to climate change, the global crop price for 2030 is projected to show little increase (Porter et al., 2014). The World Bank (2017) has predicted a moderate decline in the current global price of wheat and N fertiliser, which results in the ratio of N fertiliser cost to wheat price remaining almost stable. In the adaptation packages evaluated here, the only increase in input was N fertiliser, and in Australian agriculture, there is little effect from variations in N fertiliser cost because the trend in the ratio of N fertiliser cost to grain price has been stable (Angus, 2001). On the other hand, The World Bank (2017) has predicted an increase in meat price in 2030 compared to 2017. Considering the expected increase in global demand for meat (e.g. Godfray et al., 2010), and a greater unit price in comparison to grains, an increase in land allocation to livestock systems could be a viable adaptation. Based on the projected commodity prices, and acknowledging that there is uncertainty, we do not expect the results in this paper to be significantly impacted by changes in the global market conditions for agricultural commodities during the next decade and possibly up to 2030.

5. Conclusion

The economic returns to farmers as a consequence of projected climate changes in 2030 were variable across all the examined case study sites and enterprises and were often lower in comparison with current practice. At the relatively low rainfall site, the ‘medium risk/ medium return’ type adaptation resulted in better economic returns compared to the historical baseline with smaller year-to-year variabilities and could provide a better economic return averaged over a long period (20 years). The ‘alteration of the crop/livestock balance’ and ‘low risk/ low return’ adaptation options had a better financial performance in relatively high rainfall sites. The results indicated that under projected climates for 2030, an increase in the stocking rate when associated with no additional cost to cropping management could have the greatest profitability in a relatively high rainfall site. The adaptation package which includes an increase in livestock and pasture appears to be the better option to manage financial risks in this environment and may be most useful in years with extremely low rainfall. In the relatively low rainfall site, only an increase in stocking rate would have such an effect. Greenhouse gas emissions were, for the most part, higher under all the future scenarios considered and across all farming systems regardless of adaptation options employed. Therefore, consideration of an emission intensity control policy may be one measure for reducing GHGs under future agricultural systems. Quantifying the likelihood of adoption by producers indicated that there is time available for adopting new farm systems for the target year of 2030. Adoption will be higher if reconfiguration of the current system is associated with less intensification regardless of whether the adaptations are transformative or systemic.

According to the research presented here, there is the potential to sustain current productivity and profitability, but the most profitable adaptation may not be the most environmentally sustainable, particularly as soil ground cover is susceptible to loss under some adaptation packages. This work suggests that an integrated approach which includes economic and climate analysis, technology research, environmental management, and GHG emission management is an ongoing requirement in the design of adaptation of mixed farming system options.

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