Impact of climate changes on existing crop-livestock farming systems

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Abstract

The state of Western Australia is a major producer and exporter of crops and livestock. Mixed farming systems are typical agricultural enterprises in the Western Australian wheatbelt where climate drives the productivity and profitability of these farms and therefore the effects of likely climate change on their performance need to be understood. Here the effects of climate change projected at 2030 were evaluated compared to a baseline period (1980-1999) on mixed farming systems at paddock, enterprise and whole farm scales using the coupled APSIM and GRAZPLAN biophysical simulation models. The yield of different crops, livestock production and gross margins were assessed under current and projected climates using current farming technology and management practices. Representative mixed-farm systems were selected along a climate transect. Modelling analysis suggests that current production levels and gross margins of mixed farm systems in Western Australia will not be sustained in 2030 climate conditions except in areas of moderately

high-rainfall. Whole farm gross margin declined at all site x potential climate scenarios between 1% and 22% except in moderately high rainfall where gross margin increased by up to 4% under a 'hot and moderate change in rainfall' climate. Projected crop yields declined for most of the crop x site x potential climate combinations, with greatest declines under a hot and dry climate (at driest margin of transect) in which wheat, barley, canola, and lupin yield declined up to 16%, 15%, 21%, and 27%, respectively. Increase in yield was predicted for wheat and barley at some of the site x potential climate s. Wheat yield increased only under moderately high rainfall region by 6% while barley increased by 1%. Simulated cropping gross margin was also shown to decline by between >1% and 23%, except for the moderately high-rainfall site where cropping gross margins were projected to increase by up to 3%. Changes in simulated livestock production were smaller and less variable than for crop production. The change in weight of livestock sold across sites x potential climate combinations ranged between -3% and +3%. Livestock gross margin varied between -11% and +6%. Modelling results indicated a greater fertilisation effect of the elevated CO₂ on pasture production than on crop yield and biomass particularly in drier sites. But however, this could not offset negative impact of climate change under hot potential climates. The main negative environmental impacts from the projected climate change were declines in annual net primary production (ANPP), ground cover and water use efficiency mostly at drier sites. Whole farm N₂O emission declined significantly for the majority of site x potential climate combinations, while smaller decreases in ruminant CH₄ emission were predicted. In 2030, returns from livestock enterprises are predicted to be smaller, but less variable than from cropping and with increasing probability of success in drier regions. Reduced variability in financial return is important from the perspective of whole farm risk management. Shifts in enterprise mix in dryland mixed-farming systems towards increased livestock may be a helpful strategy in adapting to climate change and managing the associated financial risks.

Key words: mixed farm systems, complex system, modelling, APSIM, GRAZPLAN, AusFarm, CO₂

1. Introduction

Climate change projections suggest that the scale and rate of change driven by increases in concentration of greenhouse gases in the atmosphere is unprecedented in human history, and will significantly – and in many cases dramatically – alter the accessibility and quality of natural resources (IPCC, 2014). Changes in key climatic variables such as temperature and rainfall will act to push agro-ecosystems towards their thresholds of change, in some cases threatening the future of agricultural industries and communities (Lenton, 2011; Wilbanks, 2003). Primary enterprises and industries, which include the sectors of agriculture, are highly vulnerable to climate change because of their dependency on climate-sensitive natural resources for their prosperity and sustainability (Zamani et al., 2006). Specifically, primary enterprises are expected to contend with more frequent climate crises, environmental degradation and even climate-related regulatory change (IPCC, 2007). Climate related stressors occur against an existing backdrop of conventional drivers including economic, biophysical, institutional, cultural and political pressures (Howden et al., 2007; Marshall et al., 2012).

There is a good deal of literature on the potential impacts of climate change on single agricultural enterprises (e.g. Cullen et al., 2009, Ghahramani et al., 2015 and Ludwig & Asseng, 2006 in Australia; Butterworth et al., 2009 in the UK; Ducharne et al., 2007 in France; Ko et al., 2012 in the USA). Multiple-enterprise farms are central to agriculture in much of the world Herrero et al. (2013) estimate that 69% of global milk production and 61% of ruminant meat production is sourced from crop-livestock farms. Despite their economic and social importance, and the likelihood that both climate change impacts and the options for adapting to changed climate will be different when multiple enterprises are present, studies considering climate change impacts on integrated crop-livestock systems are uncommon. The only two examples we have found are Rodriguez et al. (2014), who analysed mixed-farming systems in southern Queensland, and Rigolot et al. (2016), who examined the impact of climate change on smallholder crop-livestock systems in Burkina Faso.

Broadacre farming contributes approximately AU\$33 billion (mean across the five years to 2011-12) to Australia's agricultural export earnings (ABARES, 2013) and provides a mean return of around AU\$83,000 per farm (mean across the 10 years to 2011-12). Broadacre farming is strategically important to the Australian economy because it ensures a reliable domestic and international supply of grain and meat products. In southern Australia (including the wheat belt of Western Australia), broadacre farming can be characterised predominantly by mixed cropping and livestock systems that include diverse enterprises where wool and sheep meat production are integrated with cereal, pulse and oilseed crops and where pastures are incorporated into the cropping sequence (Kirkegaard et al., 2010).

Australia's primary industries have historically operated in a highly variable climate. This has posed significant challenges to production, requiring sound and responsive risk management practices. Climate change has, and will, introduce even greater challenges. This means that there is a need to assess the impact of climate change in order to explore vulnerabilities and opportunities for farmers to improve how they respond to climate variability.

Western Australia (WA), with about 4 million ha of wheat-growing farms, is a major contributor to the Australian agrifood sector and economy. In the 2012/13 financial year the Western Australian cropping industries exported a total of \$3.9 billion with \$2.2 billion of wheat exports (8.5 million tonne) (Department of Agriculture and Food, 2013). Pastures in WA have a major role in agricultural enterprises and contribute over \$3 billion annually in Western Australia through animal production, improvements to crop rotations and conserved fodder (Department of Agriculture and Food, 2014). Livestock is an important part of agriculture in WA. In 2011/12, the WA livestock industries contributed 26% of the state's agriculture, fisheries and forestry production, worth approximately \$2 billion at the farm gate (Department of Agriculture and Food, 2012).

In addition to the practical importance of understanding climate change impacts in the region, WA mixed farming systems have features that make them useful as a case study contributing toward a wider understanding of climate change impacts on agriculture. First, there is clear evidence of an

overall decline in winter rainfall in southern WA over past decades (Delworth and Zeng, 2014), so that the issue of changing climate is particularly salient to WA farmers. Second, and in contrast to the environments studied by Rodriguez et al (2014) and Rigolot et al (2016), the climate in WA is Mediterranean and its agriculture therefore relies heavily on winter rainfall. Third, and again in contrast with southern Queensland, mixed farming systems in WA are typically integrated in space (Bell & Moore 2012); sequences of crops and pastures occupy the same land. Fourth, the WA wheatbelt has a high temporal variability of rainfall (Smith et al., 2000) that requires sound and responsive risk management practices. Fifth, WA can be a good place for examining impact of projected climate change scenarios on agriculture because main agricultural productions of WA i.e. wheat and livestock are for international export and thus can be assumed to be sensitive to global socioeconomic factors which are fed into AR5 emissions scenarios that we have used in here (Stocker et al., 2013).

In Australian crop-livestock systems, an emphasis on livestock is currently a less risky strategy compared to cropping for managing climate variability (Kingwell, 2013). Climate change has, and will, introduce even greater risk-related challenges. This means that there is a need to assess the impact of climate change in order to explore vulnerabilities and opportunities for farmers to improve how they respond to climate variability. Over the last 30 years crop yields in WA have increased by an average of 1.2% p.a., which has been related largely to the closing yield gap by improvement in agronomic technologies (Fischer et al. 2014). However, there is little prospect of increasing current crop yield with current technologies and in the near future (Fischer et al. 2014; Ghahramani et al., 2015). In Australian mixed farm systems, an emphasis on livestock is a less risky strategy compared to cropping for managing climate variability (Kingwell, 2013). From 1980 to 2000 there was a marked shift toward cropping on WA mixed farms (Bell & Moore, 2012) which appears to have been driven mainly by greater expected profitability of crops and by labour availability constraints associated with increasing farm sizes. Given that there is less prospect of further closing the yield gap for crops with current technologies and there are likely negative effects of changes in climate on cropping

systems, we can hypothesize that livestock might be still a viable and lower risk enterprise under changed climate conditions. There is a capacity for greater livestock production even under projected climate changes (Ghahramani and Moore, 2015) and a predicted increase in global demand for meat (Godfray et al., 2010). Thus, livestock might be a favourable enterprise in the near future.

This paper identifies the likely effect of climate change projected for 2030 on current mixed farm systems of Western Australia across a climate transect in terms of impacts on production, gross margin, and environmental consequences. Here, impact of climate change evaluated for projected climate scenarios in 2030 relative to a historical baseline of 1980-1999. This work presents modelling the complex interactions among climate, soil, crops, pasture, and animal within a whole mixed farm system. Evaluating the impacts of climate change in this way is a necessary first step toward designing climate adaptation strategies through assessing options such as shifts towards more intensive livestock systems and dual-purpose cropping. We will address the effectiveness of climate adaptation options in subsequent papers.

2. Methods

Our modelling analysis was designed to investigate how specific farming systems which are representative of good present-day practice would respond to current and future climates. It therefore does not consider future improvements in plant or animal genetics (as in Moore and Ghahramani, 2013); nor does it incorporate any anticipated adaptations to changing climate. We carried out a “stationary” analysis (Moore and Ghahramani et al., 2013; Williams et al., 2015), in which trends in slowly-changing variables such as soil organic matter content and average prices were removed. Each year of a given simulation should therefore be considered as a realisation of the

variable climate obtaining at a particular time (1990 in the historical simulations, 2030 in the future scenarios).

2.1 Study sites

We selected four representative mixed farming systems in Western Australia across a climate gradient of 241-369 mm growing season rainfall (April-October, 1980-1999 means; Fig 1a). These sites represent complex agro-ecosystems (Fig 1b) with different soil, crop and livestock management, and different levels of input intensity. Selection of sites and identification of cropping and livestock management systems were performed through facilitated workshops with stakeholders including farmers, representatives of farmer groups, consultants, and extension and research officers from the Department of Agriculture and Food, Western Australia. All details of mixed farms including soil type, landuse, pasture, cropping and livestock (Table 1) have been identified through these workshops together with available literature, including published and unpublished surveys (Anonymous, 2014; Co-operative Bulk Handling, 2013 unpublished; ABARES, 2014).

2.2 Climate change scenarios

Research has demonstrated that global CO₂ emissions, atmospheric CO₂ concentrations, sea-level rise and global temperatures are already tracking along the upper bounds of the previously-projected range (Peters et al., 2012). We therefore considered likely future climates with moderate and extreme changes in temperature and rainfall projected for 2030. In this paper, Coupled Model Intercomparison Project Phase 5 models were used (CMIP5; Taylor et al., 2012) for likely future climate scenarios of (i) hot and dry, (ii) hot and modest changes in rainfall, and (iii) warm with least changes in rainfall (Table 2). Two RCP 4.5 and RCP 8.5 scenarios were applied with high and low sensitivity that allowed us to sample across the more likely range of possible future climates in the focus year of 2030 using three global climate models (GCM): HADGEM2-AO (Pope et., 2000), GFDL

CM3 (Delworth et al., 2006), and MIROC5 (Burgess et al., 2012). These GCMs were statistically downscaled using the quantile matching (QM) method which produces daily weather data sequences (Burgess et al., 2012).

GCM output from above scenarios were statistically downscaled using a quantile matching (QM) method to produce daily weather data sequences (Burgess et al. 2012). QM model applies monthly change factors without reference to neighbouring months allowing for seasonal differences in changes of variance, thus can introduce some seasonal variability. The bulk of the changes in variability does come through the downscaling approach with the QM introducing heightened or reduced daily variability depending on the trends from the historical record (Kokic et al., 2013). However, should note that no method as yet addresses the full range of future change in variability.

2.3 Atmospheric CO₂ concentration

Elevated atmospheric carbon dioxide (eCO₂) concentrations in 2030 are expected to affect plant growth rates; in this paper, all projections for 2030 were therefore modelled including the effects of CO₂ unless otherwise indicated. 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 CO₂ concentration using leaf-level mechanistic equations (Reyenga et al., 1999). The APSIM response functions have been reported to satisfactorily reproduce the effect of elevated atmospheric CO₂ in FACE experiments (Asseng et al., 2004; Tubiello et al., 2007). In APSIM, yield has a linear response to elevated atmospheric CO₂ as a consequence of a collection of assumptions which is consistent with the FACE experiments (Olesen and Bindi, 2002) for moderate elevation of the atmospheric CO₂ (Ghahramani et al, 2015). GRAZPLAN and APSIM apply a similar method for the direct fertilisation effect of elevated CO₂ and its simulated pasture growth has been found to be consistent with experimental results (Moore & Ghahramani 2014). Atmospheric CO₂ concentrations of 435 ppm for 2030 under the RCP 4.5 and 449 ppm under RCP 8.5 scenarios were

assumed. For a baseline, monthly atmospheric CO₂ concentration measured in Cape Grim station were used for 1980-1999 values ranged between 335.7 ppm and 366.5 ppm (CSIRO & Bureau of Meteorology, 2014).

2.4 Building mixed farm models

Mixed agro-ecosystems are complex environments with interactions among climate, surface soil, vadose zone, crops, pasture, animal, and human management with economic components (Fig 1b). Climate becomes one of the main factors when such a system relies on rainfed because it drives the productivity, profitability and environment health of the system.

Biophysical simulation models of integrated crop-livestock systems were constructed by linking the APSIM (version 7.6) soil water, soil nutrient cycling, crop and surface residue simulation models (Holzworth et al., 2014) to the GRAZPLAN pasture and ruminant simulation models (Donnelly et al., 2002) using the AusFarm modelling software (version 1.4.7). AusFarm is a programmer-like agro-ecosystem modelling environment (Moore et al., 2014) that couples APSIM and GRAZPLAN to model dynamic daily interactions among climate, soil, plant, and animals. Our modelling is coupling carbon-nitrogen in a mixed farming system by modelling dynamics of the organic matter cycle among plants, soil, and animals. In particular livestock can be placed in cropping paddocks to graze residues and spilt grain (or growing crops), using the same logic as for grasslands, and livestock excreta are returned to the soil surface as part of the model's internal dynamics. In this study, APSIM's current formulation was extended with additional functions to account for frost and heat stress effects on crop yields (Farre, 2010; Bell et al., 2015; Lilley et al., 2015). The effects of frost and heat are expected to contribute to a direct decline in future yields (Porter et al., 2014).

Management systems were described using flexible rules (Moore et al., 2014) that coded to allocate land to the different crop-pasture sequences and then managed the sowing and removal of the various crop and forage species, nitrogen fertilizer (N) applications, the annual cycle of sheep reproduction, buy and sale, supplementary feeding and grazing management. This approach allowed

a mixture of both strategic policies and tactical management responses to be represented in the simulations. An example of the former is the balance between crop and pasture land uses, which changes only slowly at regional scale (Bell and Moore, 2012); examples of the latter are the policies governing crop sowing dates and livestock grazing management.

To parameterise the models, all farm management and input components related to cropping, pasture, and livestock were collected via producer workshop and communications with the Department of Agriculture and Food of Western Australia (DAFWA) and the other stakeholders (main parameters in Table 1).

A wide range of soils occurs in Western Australia's wheatbelt. These soils are often of low fertility, and many are deep sands, have coarse-textured topsoils, or are shallow, sandy duplex soils (Moore 2001). The majority of soils in WA, including at the representative sites, have topsoils that are relatively low in clay and soil organic matter and are often constrained by acidity. Some of WA's soils exhibit a high degree of weathering, widespread laterisation, low fertility, and coarse texture (Robson and Gilkes 1980; Anderson and Garlinge 2000). The representative soil profiles for each site were identified using the APSoil database (Dalglish et al., 2006). In keeping with our objective of modelling stationary farming systems, the humus and microbial biomass pools in the soil organic matter cycling submodel were reset to their initial levels once per rotation cycle, in order to avoid any effects of long-term trends in soil carbon stocks on productivity.

5 main crops (wheat, barley, canola, lupin, and field pea; Table 1) were included in the models; field pea was used only as a green manure. Each representative site had several soil type and rotation systems (Table 1). In the real world, the crop and pasture ratio is quite stable from year to year and changes slowly in response to price signals (Bell and Moore, 2012). Pasture species identified along the transect were annual ryegrass, subterranean clover, and *Biserrula* (Table 1). The baseline sowing

date window and reference wheat cultivar for each site were selected based on local conditions via producer workshops and the Planfarm Bankwest Benchmarks report (Anonymous, 2014). Sowing for all crops was simulated when 5-day (Cunderdin and Katanning) or 3-day (Mullewa & Merredin) total rainfall exceeded 10 mm.

Pasture and livestock management rules such as species, sowing, fertility class, threshold ground cover for grazing, joining date, replacement rules, shearing, grazing, sale policy, body condition, and supplementary feeding were decided in consultation with producers and extension officers (Table 1). A sheep enterprises (self-replacing ewe flock) was modelled at different locations using a Medium Merino genotype.

Environmental consequences of climate change evaluated by the modelling included changes in annual net primary productivity (ANPP), ground cover, deep drainage, N₂O emissions, and ruminant CH₄ emissions. Long-term transpiration efficiency of crops, pastures and the whole farm (TE, the ratio of ANPP to transpiration; Moore et al., 2011) was also calculated from model outputs for each site × climate combination to evaluate the response of water use efficiency to climate changes.

It takes a few years to stabilize model predictions of yields in an analysis such as this where extractable soil water is not reset each year (Ghahramani et al., 2015). Thus, simulations were conducted for 1975-1990 and the first 5 years (1975-79) were removed to avoid any effects of initial conditions.

2.5 Financial analysis

Partial budgeting is an appropriate financial approach for this climate change impact analysis; because the patterns of land use at each location have been held fixed, the requirements for capital items in the future climate scenarios will also be the same. A gross margin calculation was therefore carried out for each financial year of each modelled farming system (i.e. 20 years), taking into

account income from crops, wool and sales of livestock together with the costs of growing the crops, pastures and animals (as in Moore, 2014).

In keeping with our assumption of stationarity, detrended historical time series of major costs and prices were calculated for use in the gross margins. Indices of prices received by farmers for annual crops, wool, lamb and mutton and of prices paid for N fertilizer were obtained from ABARES (ABARES, 2014). The price and cost time series were converted to 2014-2015 dollars using the Consumer Price Index, the trend in each series of real prices was estimated using the LOESS algorithm, and a set of detrended price indices in real dollar terms was calculated. 5-year average real prices for each commodity were determined and combined with the price index time series to derive the final time series. The common free-on-board grain prices were then discounted by site- and crop-specific transport and handling costs (obtained from information published by grain marketing firms) in order to derive farm-gate prices for each site, crop and year. Other costs were taken from recent gross margin budgets prepared by State agencies. Because we carried out our analysis under stationary physical and financial conditions, valid summary statistics over the 20 years could be calculated for the calculated annual gross margins as well as for simulated crop yields and production of meat and wool. Conditional values-at-risk (CVaR, at 20%; see Moore, 2014) were calculated from the distributions of annual cropping, livestock, and farm total gross margins in order to evaluate likely changes in financial risk under changing climate.

2.6 Model evaluation

Simulated crop yields were checked for plausibility at producer workshops. Crop yields were also evaluated using the regional database of Co-operative Bulk Handling Pty Ltd (Anonymous, 2014 unpublished) for the period 1996-2013 (Fig 2). CBH's database is constructed through a biannual survey completed by growers about their planted areas and yields; the results are averaged across each shire. Our modelling does not consider the effects of disease, pest, and suboptimal management, and thus would be expected to overestimate observed productivity. Our use of

present-day best practices in this modelling analysis means that our results will also tend to overestimate productivity in the early years of the CBH database. 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 simulation results were discussed and model performance evaluated in producer workshops.

Since the early 1980s, the average operating size of farms in the WA has increased (Fischer et al. 2014) both positive and negative effects of this change on return on investment have been reported (Nossal et al. 2009; Sheng et al., 2015). Because the effects of changes in farm size are not clear, we did not consider any effect of changes in farm size. We note that per-hectare gross margins (unlike whole-farm economic analyses) are generally relatively insensitive to farm size.

3. Results

3.1 Projected changes in Climate

The HD potential climate scenario projected temperature increases between 1.0 °C and 1.4 °C across the transect, with least and greatest increase at Katanning and Mullewa, respectively (Table 3). The largest increases in temperature occurred under the HMCR future climate (Table 3). For the WLCR future temperature increases of between 0.5 °C and 0.7 °C were produced across sites (Table 3). Overall, there were projections for warmer spring and autumn for all sites across transect (Fig 1c). Annual rainfall declined for all sites x potential climate combinations (Table 3) but changes in rainfall varied across months and seasons (Fig 1c). Averaging over 20 years, there was an increase in spring and mid-summer (February) rainfall projected for most site x projected climate combinations, however most of these increases in monthly rainfall were also associated with increases in temperature (Fig 1c) and hence evaporative demand.

3.2 Farm production and gross margin (GM)

Averaged over 20 years and across all potential climates projected for 2030, projected yields declined for most of the crop × site combinations when compared to the baseline, ranging from a 27% decline for lupins at Mullewa to a 17% increase for barley at Cunderdin (Table 4 and Fig 3). For crop × site combinations, wheat yield changes ranged between -16% (Mullewa) and +6% (Katanning), changes in barley yields ranged between -15% (Mullewa) and +17% (Cunderdin), lupin yield changes ranged between -27% (Mullewa) and -1% (Merredin) and canola yield changes ranged between -21% (Mullewa) and -1% (Katanning). Wheat yield declined in all site x potential climate combinations under all potential climates, except at Katanning (Table 4). Barley declined in most site x potential climate combinations with a significant increase at Cunderdin (Table 4). Lupin and canola yield declined under all site x potential climate combinations (Table 4).

Simulated crop GMs changed between -23% at Mullewa (HD) and +3% at Katanning (HD). Crop GM increased only at Katanning, under the HD and HMCR projected climates (Table 4). Yearly crop GM was highly variable over time with the least and greatest variability at Merredin (HD) (Fig 3, 5) and Mullewa (HD).

Changes in simulated long term average livestock production were much more modest than for crop production, with the weight of livestock sold increasing by up to 3% under the WLCR potential climate (Table 4). Annual variability of livestock production was also smaller than that of cropping except for moderately higher rainfall site (Katanning) (Fig 3). Wool production changed with combinations of site x potential climate in a range between -6% at Cunderdin (HD) and +2% at Katanning (HMCR). Long term average livestock GM in combinations of site x potential climate changed between -11% (at Cunderdin in the HD potential future climate) and +6% (at Katanning in the WLCR scenario; Table 4). Despite a requirement for significant increase in supplementary feeding

to maintain the stocking rate (up to 54% at Merredin in the HD potential future climate), there was no significant increase in the cost of livestock enterprises compared to the baseline.

Changes in whole-farm GM at 2030 (Table 4), compared to the baseline, varied among sites between -23% at Mullewa (HD) and +4% at Katanning (HMCR). Katanning was the only site projected to have an increase in GM under the impacts of climate change without changing farm management (Table 4 and Fig 3).

When expressed as the coefficient of variation, long-term variability of the cropping gross margin increased in all farm systems except at Katanning under projected 2030 climates (Fig 5). Coefficients of variation were more stable for livestock gross margin (Fig 5).

3.3 Agro-ecosystem health and water use efficiency

Annual net primary productivity (ANPP) and ground cover (as key driver of soil erosion) declined in all site x potential climate except at Katanning (HMCR and WLCR) and Mullewa (WLCR) (Table 5 and Fig 4). Deep drainage declined significantly in all site x potential climate combinations. Pasture TE increased in all site x potential climate combinations while cropping TE decreased in almost all (Table 5). Whole farm TE (averaged over paddocks and soils) decreased up to 4% (at Mullewa under the HMCR climate; Table 5). Katanning was the only site where farm TE showed a substantial increase, of about 5% under all potential future climates (Table 5). This was related to the significant increase modelled in TE of pastures (Table 5).

Modelled N₂O emissions declined in all site x potential climate combinations (Table 5) but annual variability differed among sites x climates (Fig 4), being relatively smaller under the WLCR future (Fig 4). Modelled ruminant CH₄ emissions changed between -4% at Cunderdin and +1% at Katanning (Table 5; recall that stocking rates were held constant). Slight increases in ruminant CH₄ emissions

were related to increases in livestock production (Tables 4 and 5). Yearly variability of ruminant CH₄ emissions was smallest at Mullewa (Fig 4), which had a trading sheep enterprise (Table 1).

3.4 Sensitivity to changes in climate

Changes in wheat and barley production at different sites and years showed a mostly non-linear relation to changes in growing season (Apr-Oct) rainfall and particularly to the changes in extreme temperature projected for 2030 (Fig 6). Fig 6 shows that an increase in minimum temperature could improve wheat and barley yields under DH and HMCR climates for a small number of site x year combinations. Crops had different responses to changes in climate: in comparison with wheat, barley yield was less sensitive to rainfall while exhibiting a negative yield response to changes in temperature, particularly under the WLCR climate (Fig 6). Compared to wheat yield, changes in barley yields exhibited more of a non-linear response to changes in climate (Fig 6). Changes in wheat and barley yields declined with changes in minimum and maximum temperature in all site x year x potential climate combinations; sensitivity was least for the WLCR future (Fig 6). Under HMCR potential climate, barley yield increased with changes in minimum temperature up to 1.2 °C but declined after this point (Fig 6). Wheat yield declined progressively with increase in maximum temperature (Fig 6). Note that all of the above observations reflect the combined effects of changes in temperature, rainfall, and elevated atmospheric CO₂. Pasture and livestock production tended to be less responsive to changes in climate, except under the most extreme HD climate (Fig 6).

3.5 Changes in contribution of livestock and cropping in whole farm

There was a non-linear relationship between livestock production and GM with those of the cropping enterprises in all farm systems. The proportional contribution of livestock enterprises to whole-farm GM (the “livestock GM ratio”) at 2030 increased as whole-farm GM decreased in all site x potential climate combinations (Fig 7a). With the exception of Cunderdin (under HMCR and WLCR), the proportional contribution of livestock GM could be increasingly significant to the whole-farm GM

when there was a large decline in crop production. Overall, the livestock GM ratio was negatively related to whole-farm GM (Fig 7a) as cropping was the main source of the GM. However, at 2030, probabilities of exceedance for the livestock GM ratio increased along the climate gradient for all potential climates toward the drier margin of transect. At Cunderdin and Merredin (the two drier sites) an upward shift was projected for whole range of the probability of exceedance while a downward shift projected for Katanning (Fig 7b).

The Conditional values-at-risk (CVaR) of livestock GM was projected to be stable at Merredin under WLCR with slight decline under HMCR and HD potential climates, while it declined at Cunderdin under all potential future climates projected for 2030 (Fig 8). The CVaR of the both livestock and cropping GM increased at Katanning in comparison with the baseline. The CVaR of cropping GM and farm total GM declined for all sites x potential climates with exception in Katanning where CVaR of cropping GM increased progressively with more changes in climate (Fig 8).

4. Discussion

4.1 Potential impact of climate change

The responses of crop and livestock production and GM to changes in climate varied among enterprises and sites and the impact was variable over time and among representative sites (Fig 3). Averaging over 20 years, current production and profitability of mixed farm systems in Western Australia was projected not to be sustained under 2030 climate compared to the baseline except for wheat and barley production at the moderately high rainfall margin of the climate transect that was analysed. Wheat yield, barley yield and livestock production and GM increased at the moderately high rainfall margin, but canola and lupin yield declined (Fig 3 and Table 4). Under current farm management, cropping is the main contributor to farm GM and due to increases in water stress induced by the changes in rainfall and temperature (Williams et al., 2014) there were declines in production and GM of whole farm systems in the low rainfall margin of the transect (Table 4).

Livestock production and profit tended to be less responsive to changes in climate factors in comparison with cropping systems (Fig 4, 7). This is partly related to there being enough feed resources available for animal intake even under changing climate because farms currently have low stocking rates (Anonymous, 2014). Here the negative impact of climate change on pasture production is slightly smaller than that previously modelled by Moore and Ghahramani (2012), because they modelled financially optimised stocking rates in pastures isolated from cropping and C-N flow by crop-pasture rotation systems. Low stocking rates can make the livestock industry less vulnerable to changes in climate despite decline in pasture production in drier margins of the transect (Table 4). Declines in pasture production were compensated for by increased supplementary feeding but this did not cause significant increases in farm-scale costs of production. Climate change impacts on the trading livestock enterprise at Mullewa were negligible, most likely due to the very low stocking rate.

Farm ANPP and cover (average over year) declined in most site x potential climate combinations (Table 5), and this may increase risk of soil erosion particularly wind erosion which is common in Western Australia. Decline in TE of crops may make it difficult to increase water use efficiency despite the boost from eCO₂. Sandy soils of Western Australian are limited in soil organic matter levels (Murphy et al., 2011) and changes in climate would not improve this (Table 5). In general, N₂O emission is low in WA (Barton et al., 2008) and here N₂O emissions were predicted to decline in all site x potential climate combinations (Table 5). Ruminant CH₄ emission depends on the livestock numbers, because there were only small changes in the size of livestock enterprises, ruminant CH₄ emissions were not predicted to change significantly across site x potential climate combinations.

4.2 Likely effect of eCO₂

Moderately elevated atmospheric CO₂ projected for 2030, has a potentially positive effect on yield (Asseng, 2013) and GM of cropping systems. At the scale of Australian wheat belt the positive CO₂ effect may compensate for the effect of changes in rainfall and temperature (Ghahramani et al, 2015). Positive eCO₂ effects on wheat and barley yield at the locations with moderately high rainfall (relatively high in Western Australian) can be related to a greater increase in water use efficiency (Fig 4) (Kimball, 1983). This is an important part of the climate change response in water-limited environments i.e. the great majority of Australian production (Tubiello et al., 2007). In general, rain-fed cropping systems are reported to benefit from elevated eCO₂ (Porter, 2014), however there are local level effects of eCO₂ on cropping (Table 4). In the drier margin of the transect other controlling factors such as rainfall, temperature change (Hatfield et al., 2011) and water balance in different soil types could be the main reason (Fig 4) that CO₂ fertilisation could not compensate for the negative production impacts from changes in rainfall and temperature (Table 4). Here fertilisation effect of CO₂ on crops was predicted only for the moderately high rainfall margin of the transect (Table 4).

In the low rainfall regions of Western Australia, temperature and rainfall became the main drivers for productivity and GM of the cropping systems (Fig 6 and Table 4). It is likely that the greatest effect of rising temperatures is through higher vapour pressure deficit and its effect in lowering transpiration efficiency (Tanner and Endo, 1983, Table 4). Here, there was a relatively greater fertilisation effect of eCO₂ on pasture production compared to cropping in all sites with significant effect in increasing transpiration efficiency of pastures (Table 5). However, the eCO₂ fertilisation effect was not enough to counteract the negative effects from changes in rainfall and temperature at drier sites (Table 4 and Table 5; Moore & Ghahramani 2013).

Pasture response to climate change is more complex than for cropping systems because the direct climate drivers such as CO₂ concentration, temperature, and precipitation are overlain with indirect

interactions such as seasonal productivity and plant-animal interactions (Porter, 2014). eCO₂ is expected to increase water use efficiency (Moore and Ghahramani, 2013) and production in pasture and reduce pasture sensitivity to low rainfall (Table 4) and water stress with less positive effects in drier conditions (Ainsworth et al., 2008). Anderson et al. (2001) conducted an experiment along a CO₂ gradient from 200 to 550 ppm on a C₃ annual grass and reported a 37% increase in acclimated photosynthesis under the combined effects of changes in temperature, rainfall and CO₂. Campbell & Stafford Smith (2000) stated that doubling CO₂ stimulates grassland production by +17% on average in field experiments while Tubiello et al. (2007) concluded that observed increases in above-ground production of C₃ pasture grasses and legumes are of the order of +10% and +20%, respectively. Soussana and Lüscher (2007) reviewed the effects of climate change on grassland species and found that a doubling of CO₂ resulted in an increase in the rate of photosynthesis by 30-50% for C₃ species. Our modelling results showed an increase in pasture ANPP from the fertilisation effect of eCO₂ (combined effect with changes in temperature and rainfall) of 8%-11% under the HD future climate (Table 5). This effect was somewhat smaller (7-9%) under the WLCR climate. Given the 27% increase in CO₂ in our 2030 scenarios, our results seem to be consistent with the analysis of Tubiello et al. (2007).

4.3 Interactions between livestock and cropping

Many producers have reduced the numbers of livestock in their mixed farming systems since the 1990s with the rise in minimum-tillage cropping (ABARES, 2014) and livestock systems continue to decline in Western Australia (ABARES, 2014; Anonymous, 2014). It is known in the Australian mixed farm systems that emphasis on livestock system is a risk avoiding strategy compared to cropping (Kingwell, 2013). Our modelling results suggest the use of livestock as a risk avoiding strategy is likely to continue in future years since livestock income is expected to be less sensitive to changes in climate (Fig 8, 8). Cropping had greater variation in response to changes in rainfall and temperature compared to pasture and livestock systems (Fig 3 and 4). In drier regions, changes in livestock

production and GM had smaller inter-annual variability than cropping (Fig 3) making it more reliable (Fig 7b) for such regions.

Cropping system production in 2030 is predicted to be more variable (Fig 8, 5), increasing the risk to stability of whole farm financial outputs, especially if the current decline in the size of the livestock components of mixed-farming systems continue. Risk management is not only about the long term average financial outputs; what happens at the extremes (Nicholson, 2014) and variability over short time periods is also important. Greater emphasis on livestock with its more stable income in changing climate across the drier margin of the transect may be used to buffer against the greater probability of risk in cropping systems in 2030, particularly in seasons with great decline in crop yield (Fig 7b).

The CVaR (Conditional values-at-risk) of livestock GM in 2030 had smaller value in comparison with the baseline at drier sites, but, the CVaR of livestock GM and consequently financial risk of livestock was much less than those of cropping (and relatively stable) (Fig 8). Relatively high rainfall region (represented by Katanning) was an exception where cropping was more financially beneficial enterprise with more changes in climate (Fig 8). At this site and compared to the baseline, livestock had a greater CVaR of GM over a long term (Fig 8) but not in years with great climate impact that total farm and cropping GM was declined for lowest probabilities (Fig 7b).

Livestock production currently makes only a relatively small contribution to whole farm financial returns in WA, particularly in years with high cropping GM (Fig 7 a, b). The expected increase in global demand for meat (Godfray et al., 2010), even under price effects (Keyzer et al., 2005) may help the viability of greater emphasis on livestock within mixed farm systems, as would the adoption of practice changes leading to greater production and profit from livestock (Ghahramani and Moore, 2015). A climate change adaptation strategy in dryland mixed-farming systems could see

shifts in enterprise mix options towards greater numbers of livestock depending on how the climate drives the financial optimization of the whole farm system. Any transition back toward livestock would need take account of other considerations such as access to water supplies for livestock in climates with lower rainfall and runoff.

5. Conclusion

Our modelling analysis suggests that current production levels and gross margins in mixed farming systems in Western Australia will be difficult to sustain under the impact of climate change, except in the moderately high rainfall regions. At 2030, the cropping components of mixed-farm systems are predicted to suffer significant negative impact on production due to climate change in drier regions. Livestock enterprises will experience a smaller negative effect from changes in climate and their returns will continue to be less variable compared to those from cropping. Effects of eCO₂ fertilisation on crop yield and ANPP production (using current APSIM formulation) were predicted to be neutral, however there were positive responses at the moderately high rainfall site. There was positive effect from eCO₂ on pasture production which declined along the climate gradient towards the drier margin. Climate change adaptation strategies in dryland mixed-farm system management may benefit in a risk management sense from shifts in enterprise mix towards more livestock.

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Fig caption

Fig 1 (a) representative mixed farm systems across climate gradient. Numbers in brackets are long term average growing season rainfall (Apr-Oct) during 1980-1999, yellow colour in map is Australian cropping belt, (b) Schematic illustration of the biophysical interactions and modelled processes in mixed farm systems. R: rainfall, T: temperature, VPD: vapour pressure deficit, (c) relative changes in rainfall and changes in average temperature projected for 2030 compared to the baseline for potential climates. These locations represent a climate gradient of Katanning, Cunderdin, Merredin, and Mullewa, which Katanning and Mullewa are the moderately high rainfall and the driest edge of the transect.

Fig 2 Evaluation of the modelling results for surveyed yield during period of 1996-2013 by CBH (Co-operative Bulk Handling, 2013) for regions that models represent. Overall, simulated yields are expected to be greater than survey because pest and diseases effects are not included in the modelling. However evaluation can be marginal because surveyed yields are for a region that might be affected by economic shocks e.g. changes in farming system management which are not reflected in the modelling. HD: Hot and dry, HMCR: Hot and moderate changes in rainfall, WLCR: Warm with least changes in rainfall.

Fig 3 Relative changes in production and financial outputs in 2030 compared to the baseline at farm scale for each of examined potential future climate. Boxplots show changes in yearly production and financial outputs for each site.

Fig 4 Relative changes in environmental consequences and in 2030 compared to the baseline at farm scale. Boxplots show yearly changes in environmental consequences, and transpiration efficiency (TE) for each site. ANPP: annual net primary productivity, Cover: average ground cover over year, OC: organic carbon, presented for surface soil (top layer) and whole soil profile, N₂O: nitrous oxide emission, CH₄: ruminant methane emission, TE: transpiration efficiency (ANPP/transpiration).

Fig 5. Changes in coefficient of variation of GM (gross margin) over baseline, and projections for future climates of WLCR, HMCR, and HD at 4 representative sites.

Fig 6 Relative changes in crop and livestock production in 2030 for projected future climates, compared to the baseline, related to the changes in the local climate (Apr-Oct) at each simulated year x site. The fitted lines are non-parametric regressions; the shaded areas are the 95% confidence intervals. Note that the effects of relative changes in rainfall and changes in temperature are not isolated in the figures. Responds of the systems in each chart are under combined effects of eCO₂, changed temperature & rainfall, farms characteristics such as soil, plant species, stocking rate, management, etc. Pasture and livestock responses are for 3 representative sites as Mullewa doesn't have a livestock enterprise.

Fig 7 Interactions between financial outputs of Livestock and cropping over years at each representative site, (a) livestock gross margin ratio of 2030 related to the whole farm gross margin in 2030. The fitted lines are non-parametric regressions; the shaded areas are the 95% confidence intervals. (b) Empirical probability of exceedance for livestock GM (gross margin) ratio in total farm GM in the baseline and projected climates for 2030.

807 Fig 8 Changes in conditional value-at-risk of cropping, livestock, and total farm gross margin
808 compared to the baseline. A greater relative change in value-at-risk means less sensitivity to changes
809 in climate over 20 years.
810

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Table 1 Components of farm systems. Rainfall and temperature are for growing season (Apr-Oct). W: wheat, B: barley, C: canola, L: lupin, P: field pea, A: annual pasture.

item	Katanning					Cunderdin					Merredin					Mullewa				
	117°33'20"E -33°41'19"S					117°13'59"E -31°38'58"S					118°16'44"E -31°28'32"S					115°30'51"E -28°32'12"S				
Rainfall mm	369					293					290					241				
Mean temperature (°)	13					15					16					14				
Farm area (ha)	3000					3500					5000					4800				
Crop ratio	Cropping: 2000					Cropping: 2500					Cropping: 3700					Cropping: 48200				
Soils	Deep loamy duplex, Shallow sandy duplex (Alkaline sub soils), Gray sandy duplex, saline wet soils					Gravelly sand, Deep sandy duplex, Deep loamy duplex, Acid yellow sand					Yellow deep sand, Yellow & Brown sandy earths, Shallow loamy duplex/ Alkaline subsoils (loamy brown), Gravelly duplex					Red shallow loam, Coloured sands				
Sequence	AWCB, ACWB, AAACW, AAWCB, AAB					AAACW, WLWCB, WPWCB, ABWLW					AAW, WWWCB, WWCWWP, WWCWWL, WBWBB, WWWC					*WWW0, WLWC, WCW0				
Sowing window	Wheat:15 Apr-15 June Barley: 25 Apr-15 June Canola:16 Apr-15 May lupin/peas: 15 May -1 July					Wheat :15 Apr-15 June Barley: 25 Apr-15 June Canola: 16 Apr-15 May lupin/peas: 15 April -1 July					Wheat:15 Apr-15 June Barley: 15 May-5 June Canola:16 Apr-15 May lupin/peas: 15 April -15 May					Wheat: 1 May-2 June Barley: 1 May-2 June Canola:16 Apr-15 May lupin/peas: 15 April -15 May				
Fertilizer for crops	W	B	C	L	P	W	B	C	L	P	W	B	C	L	P	W	B	C	L	P
At sowing (kg N/ha)	20	20	20	0	0	20	20	20	0	0	20	20	20	0	0	20	20	20	0	0
In-crop (kg N/ha)	40	60	60	0	0	40	30	60	0	0	20	20	40	0	0	10	10	30	0	0
Pastures Species	Annual ryegrass, Subterranean clover					Annual ryegrass, Subterranean clover					Subterranean clover, Biserrula									
Livestock enterprise	SREF, Medium Merino					**SREF, Medium Merino					SREF, Medium Merino									
Stocking rate (DSE)	4.5					3.0					2.0									
Minimum stubble cover	0.60					0.60					0.60									
Maximum days on stubble	***150					***150					***150									
Wheat crops grazed	Yes					Yes					No									

*This is opportunistic cropping which in current management barley being used for 0, **SREF = Self-replacing ewe flock, *** is maximum, decreases with decline in quality of stubble with growing season rainfall.

Table 2 Applied climate projections for each of likely future climate examined in this paper.

Likely future climate	Abbreviation	Scenario	Sensitivity	GCM
Hot and dry	HD	RCP 8.5	High	GFDL CM3
Hot and moderate changes in rainfall	HMCR	RCP 8.5	High	MIROC5
Warm with least changes in rainfall	WLCR	RCP 4.5	low	HADGEM2-AO

Table 3 Annual rainfall and temperature in the baseline and relative change in 2030 compared to the baseline.

Climate factor	Site	Baseline	Changes from the baseline		
			HD	HMCR	WLCR
MeanT	Katanning	15.8 (°c)	1.0	1.1	0.5
	Cunderdin	18.4 (°c)	1.1	1.3	0.5
	Merredin	18.1 (°c)	1.3	1.4	0.5
	Mullewa	20.0 (°c)	1.4	1.6	0.7
Rainfall	Katanning	470 (mm)	-11%	-9%	-3%
	Cunderdin	375 (mm)	-12%	-10%	-3%
	Merredin	325 (mm)	-12%	-8%	-4%
	Mullewa	358 (mm)	-12%	-7%	-4%

Table 4 Relative changes in production and financial outputs of 4 representative farms in 2030 compared to the baseline. –CO₂ and +CO₂ are atmospheric CO₂ concentration in baseline level and projected for 2030. All metrics are for whole farm averaged over different soil and rotation systems. GM: gross margin, HD: Hot and dry, HMCR: Hot and moderate changes in rainfall, WLCR: Warm with least changes in rainfall. Standard deviations are presented in supplementary material.

		Katanning		Cunderdin		Merredin		Mullewa	
	Output	+CO2	-CO2	+CO2	-CO2	+CO2	-CO2	+CO2	-CO2
HD	Wheat yield	6.3%	2.6%	-3.6%	-3.9%	-5.7%	-6.2%	-15.9%	-15.8%
	Barley yield	-2.1%	-0.2%	16.6%	16.4%	-1.4%	-1.4%	-14.5%	-14.5%
	Canola yield	-2.7%	-4.4%	-19.0%	-19.2%	-16.9%	-16.9%	-21.0%	-21.1%
	Lupin yield	n/a	n/a	-15.4%	-15.4%	-22.5%	-22.5%	-27.2%	-27.3%
	Sold stock weight	1.2%	-1.8%	-3.3%	-7.0%	-2.1%	-2.1%	n/a	n/a
	Shorn wool	-0.3%	3.1%	-5.9%	-6.4%	-4.9%	-7.4%	n/a	n/a
	Cropping income	2.0%	-0.7%	-4.3%	-4.5%	-7.4%	-7.7%	-16.3%	-16.3%
	Livestock income	1.9%	-4.3%	-7.5%	-8.0%	3.5%	6.8%	n/a	n/a
	Cropping GM	3.1%	-0.5%	-7.2%	-7.6%	-12.9%	-13.5%	-22.8%	-22.8%
	Livestock GM	2.2%	-6.4%	-10.6%	-10.8%	1.1%	1.7%	n/a	n/a
	Income	2.0%	-2.0%	-4.6%	-4.9%	-6.5%	-6.6%	-16.3%	-16.3%
	Cost	0.9%	0.2%	0.1%	0.0%	-0.1%	0.4%	-0.1%	0.0%
Gross margin	2.6%	-3.3%	-7.6%	-8.0%	-11.3%	-11.7%	-22.8%	-22.8%	
HMCR	Wheat yield	6.3%	2.9%	-3.9%	-3.9%	-0.6%	-1.1%	-8.6%	-8.6%
	Barley yield	-2.5%	-4.8%	14.8%	14.2%	4.8%	4.9%	-9.8%	-9.7%
	Canola yield	-2.1%	-3.9%	-16.6%	-16.8%	-9.1%	-9.2%	-14.9%	-14.9%
	Lupin yield	n/a	n/a	-13.5%	-13.8%	-10.5%	-10.5%	-19.1%	-19.1%
	Sold stock weight	2.1%	-1.0%	-1.9%	-7.7%	0.1%	-3.2%	n/a	n/a
	Shorn wool	1.6%	1.6%	-3.4%	-4.2%	-2.1%	-3.8%	n/a	n/a
	Cropping income	1.1%	0.3%	-4.3%	-4.4%	-1.1%	-1.1%	-9.6%	-9.5%
	Livestock income	4.1%	-2.4%	-1.1%	0.3%	0.8%	0.8%	n/a	n/a
	Cropping GM	2.9%	-0.9%	-7.1%	-7.3%	-1.5%	-1.7%	-13.3%	-13.3%
	Livestock GM	4.5%	-3.9%	-0.3%	0.6%	-0.7%	-2.0%	n/a	n/a
	Income	2.1%	-0.7%	-3.9%	-3.9%	-1.0%	-0.9%	-9.6%	-9.5%
	Cost	-0.3%	1.9%	-0.2%	0.0%	-0.4%	0.2%	0.0%	0.0%
Gross margin	3.7%	-2.3%	-6.3%	-6.3%	-1.4%	-1.7%	-13.3%	-13.3%	
WLCR	Wheat yield	1.7%	-1.4%	-2.4%	-2.8%	-2.6%	-2.8%	-4.3%	-4.4%
	Barley yield	1.3%	-0.5%	10.7%	10.7%	3.8%	3.5%	-1.7%	-2.3%
	Canola yield	-1.1%	-1.0%	-3.9%	-4.2%	-2.2%	-2.2%	-5.2%	-5.5%
	Lupin yield	n/a	n/a	-3.9%	-4.5%	-0.8%	-0.8%	-8.1%	-8.3%
	Sold stock weight	2.5%	0.5%	1.0%	-4.1%	0.2%	-0.6%	n/a	n/a
	Shorn wool	-1.3%	1.1%	-2.3%	-2.6%	-0.3%	0.0%	n/a	n/a
	Cropping income	-1.9%	-1.6%	-0.7%	-1.1%	-2.0%	-2.2%	-3.9%	-4.0%
	Livestock income	4.7%	0.6%	1.9%	-1.8%	5.5%	7.7%	n/a	n/a
	Cropping GM	-0.4%	-2.1%	-1.0%	-1.6%	-2.8%	-3.3%	-5.4%	-5.6%
	Livestock GM	6.3%	-0.1%	1.3%	-4.3%	7.4%	8.6%	n/a	n/a
	Income	0.3%	-0.9%	-0.5%	-1.1%	-1.4%	-1.5%	-3.9%	-4.0%
	Cost	-3.6%	-0.4%	0.0%	0.1%	-1.0%	-0.8%	0.0%	0.0%
Gross margin	2.8%	-1.2%	-0.7%	-1.9%	-1.7%	-1.9%	-5.4%	-5.6%	

Table 5. Relative changes in environmental metrics of 4 representative farms in 2030 compared to the baseline. $-\text{CO}_2$: with atmospheric CO_2 concentration in the baseline level. All metrics are for whole farm averaged over different soil and rotation systems. ANPP: annual net primary productivity, TE: transpiration efficiency (ANPP/transpiration), N_2O : nitrous oxide emission, CH_4 : ruminant methane emission. Standard deviations are presented in supplementary material.

Output	Katanning		Cunderdin		Merredin		Mullewa		
	+CO2	-CO2	+CO2	-CO2	+CO2	-CO2	+CO2	-CO2	
HD	Total ANPP	-1.0%	-4.6%	-5.6%	-6.6%	-10.7%	-5.9%	-2.1%	-16.4%
	Crop ANPP*	-1.6%	-1.8%	-4.8%	-5.1%	-10.5%	-10.7%	-2.1%	-16.4%
	Pasture ANPP	-0.2%	-8.4%	-13.3%	-22.4%	-13.4%	-24.7%	n/a	n/a
	Farm ground cover	-0.7%	-1.1%	-4.0%	4.8%	-4.1%	-4.3%	-3.9%	-1.8%
	Farm deep drain	-37.2%	-39.0%	-45.1%	-45.3%	-69.6%	-69.2%	-75.6%	-75.6%
	Farm TE	4.5%	-0.5%	-2.1%	-2.8%	-0.2%	-0.5%	-2.2%	-4.7%
	Cropping TE	-4.9%	-4.9%	-3.2%	-3.2%	-1.1%	-1.1%	-2.2%	-4.7%
	Pasture TE	9.1%	-1.4%	-1.2%	-11.2%	3.9%	-6.0%	n/a	n/a
	N ₂ O emission	-14.0%	-16.9%	-7.8%	-7.6%	-30.3%	-30.6%	-54.0%	-54.0%
	CH ₄ emission	0.5%	0.2%	-4.1%	-5.6%	-1.4%	-1.9%	-2.6%	-2.5%
HMC	Total ANPP	0.8%	-4.8%	-4.1%	-5.2%	-5.1%	-5.9%	-11.9%	-12.0%
	Crop ANPP*	-1.5%	-3.8%	-3.8%	-4.1%	-5.1%	-5.2%	-11.9%	-12.0%
	Pasture ANPP	3.8%	-6.1%	-7.6%	-16.1%	-5.2%	-16.1%	n/a	n/a
	Farm ground cover	-0.5%	-1.8%	-3.5%	-4.2%	-1.5%	-2.1%	-1.6%	-1.7%
	Farm deep drain	-29.0%	-31.0%	-38.8%	-39.6%	-52.9%	-53.9%	-59.4%	-59.5%
	Farm TE	5.5%	-0.4%	-1.1%	-2.3%	0.9%	0.1%	-3.9%	-3.1%
	Cropping TE	-3.8%	-4.2%	-2.4%	-2.4%	-0.3%	-0.3%	-3.9%	-3.1%
	Pasture TE	11.8%	-0.3%	2.4%	-8.9%	8.7%	-4.6%	n/a	n/a
	N ₂ O emission	-6.3%	-8.9%	-2.1%	-3.0%	-14.7%	-15.5%	-31.4%	-31.3%
	CH ₄ emission	1.3%	0.6%	-1.4%	-3.1%	0.5%	-0.9%	-2.4%	-2.4%
WLC	Total ANPP	3.5%	-1.4%	-0.2%	-1.3%	-0.7%	-1.3%	-5.7%	-5.8%
	Crop ANPP*	0.2%	-1.2%	-0.5%	-0.8%	-0.9%	-1.0%	-5.7%	-5.8%
	Pasture ANPP	8.0%	-1.7%	2.9%	-6.0%	2.0%	-5.5%	n/a	n/a
	Farm ground cover	0.8%	0.1%	-0.9%	-1.3%	-0.5%	-0.8%	0.5%	0.4%
	Farm deep drain	-10.0%	-12.0%	-13.5%	-13.8%	-26.8%	-27.5%	-25.6%	-25.3%
	Farm TE	4.6%	-1.1%	-0.5%	-1.4%	0.8%	-0.1%	-2.1%	-2.0%
	Cropping TE	-2.2%	-2.5%	-1.4%	-1.3%	0.0%	0.0%	-2.1%	-2.0%
	Pasture TE	10.7%	-0.9%	4.6%	-4.1%	6.8%	-4.2%	n/a	n/a
	N ₂ O emission	-1.9%	-5.7%	0.5%	0.4%	-8.3%	-9.2%	-18.4%	-19.3%
	CH ₄ emission	0.5%	0.3%	-0.3%	-1.5%	0.5%	0.5%	-1.2%	-1.1%

Figure1

Figure2

Figure3

Figure4

Figure5

Figure6

Figure7

Figure8