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Would greenhouse gas emission intensities in sheep enterprises be reduced by use of sustainable and profitable management options?

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Abstract

Greenhouse gas emissions (GHG) from broadacre livestock production constitute around 16% of total Australia's agricultural emissions. To study the diversity of Australian sheep farming enterprises a combination of modelling packages was used to calculate GHG emissions from three representative sheep enterprises (Merino ewe production for both wool and meat, Merino-cross ewes with an emphasis on lamb production, and Merino wethers for wool production) at 28 sites across eight climate zones in southern Australia.

Differences between profitability, wool and meat productivity, dry sheep equivalents (DSE) and GHG emissions intensity (EI) between 11 pasture management or animal genotype options (that had been previously determined in interviews with farmers) were assessed relative to baseline farms in each zone ('Nil' option).

In general, options that increased production and profit had minimal impact on EI per hectare but reduced EI per DSE, and per unit wool and meat production. Increasing soil fertility allowed the greatest increases in stocking rates, resulting in the highest profitability. The lowest profitability and highest EI was caused by sowing 40% of the farm to lucerne as its pasture production was low relative to the baseline grass. In general, enterprises with the lowest and highest EI were Merino ewes and Merino wethers, respectively. Emissions per DSE or per product were typically highest in regions with dry and hot summers, mainly because these regions had longer seasons with high evaporative demand that restricted pasture growth and stocking rates relative to the continuous generation of livestock emissions. Overall, a negative relationship between EI and profitability for GHG per DSE or per product suggests that management options capable of increasing farm profitability also tend to reduce EI, which would be a beneficial outcome for the environment, industry and farmers alike.

Introduction

Greenhouse gas (GHG) emissions from livestock dominate current Australian agricultural emissions and are projected to account for 72% of total agricultural emissions by 2020 (DCCEE 2013). Past research examining strategies for GHG mitigation from the livestock sector has primarily been reductionist, focussing on either a single intervention strategy (e.g. rumen microbial manipulation), a given GHG (typically CH_4), or on measurements of GHG fluxes at the individual animal level (SF_6 tracer techniques) (Harrison *et al.* 2010). Further analyses of intervention strategies to livestock enterprise management and animal genotype are required to generate a holistic view of biophysical feedbacks occurring within these systems, since such analyses can reveal important interactions between key and sensitive variables (Harrison *et al.* 2014b; Alcock *et al.* 2015). For instance, improving animal diet quality can increase liveweight gain with little change in production of enteric CH_4 and can lead to lower GHG emissions per unit animal product (hereafter, emissions intensity or EI). However, improved diet quality may also result in greater dry matter intake (DMI) per animal, such that no net change or even a net increase in GHG emissions can be observed at the livestock level (Eckard *et al.* 2010). Livestock level assessments of GHG emissions are also necessary in any regional scale analysis to appropriately account for the diversity of plant and animal genotypes, environments and management systems typically encountered at larger scales (Moore and Ghahramani 2013a).

Previous work has assessed the relative production efficacy and profitability of a range of interventions to pasture management and animal genotype to southern Australian livestock production, both under current and future climates (Ghahramani and Moore 2013; Moore and Ghahramani 2013b). This work demonstrated that a foremost current limitation to livestock production in southern Australia is the constraining effect of a minimum ground cover requirement on stocking rates, and thus proposed several adaptation options to address the risk of soil erosion. Ghahramani and Moore (2013) showed that important pasture adaptation options in ameliorating the negative impact of lower rainfall and higher temperatures expected with future climate change include increasing soil fertility by addition of phosphorus, adding lucerne to a proportion of the feed-base and confinement feeding of livestock during summer, in that order. Moore and Ghahramani (2013b) reported that breeding animals for greater fleece weight (at constant body size) was likely to invoke the greatest improvements in forage conversion efficiency, and, to a lesser extent, breeding ewes for higher conception rates was also a viable option for crossbred ewe enterprises to increase pasture utilisation, similar to results documented in a ewe fecundity study (Harrison *et al.* 2014b). Together, these studies highlighted the fact that combinations of feedbase and livestock genetic adaptations could be complementary or counter-productive, with the former governing forage availability and forage consumption and the latter influencing the efficiency with which forage was converted to animal product (Moore and Ghahramani 2013b).

Adaptations to sheep enterprises do not always affect profitability, production and net GHG emissions in a mutually aligned direction (Harrison *et al.* 2014b; Ho *et al.* 2014). (Alcock *et al.* 2015) showed that average annual profitability of self-replacing Merino flocks increased by 18% by reducing the joining age of maiden ewes, even though total wool production did not change and net GHG emissions increased. The corollary is that such adaptations tend to have a wide range of effects on EI, and that adaptations increasing productivity do not necessarily reduce EI.

Here we build upon previous modelling works (Ghahramani and Moore 2013; Moore and Ghahramani 2013b;) and application of equations from the Australian National Greenhouse Gas Inventory (Browne *et al.* 2011) in determining the effects of pasture intervention options and variation in animal genotypic traits on net farm GHG emissions and EI. Because these modelling studies were carried out within a larger program of research, development and extension (Pattinson 2011), they were able to collate detailed data from farmers and extension agents regarding the management, type and distribution of sheep enterprises across southern Australia, which has been adopted here. We have calculated both methane and nitrous oxide emissions and included the interactions of intervention options (options) with type of enterprise and climatic zone in the statistical analyses of results.

The primary aim of this study was to determine if both greenhouse gas emission intensities could be reduced and profit increased by changing current management conducted on sheep enterprises across southern Australia with realistic pasture management or animal genotype interventions.

Materials and Methods

Study location attributes and enterprises examined

To capture the highly diverse nature of broadacre livestock farming enterprises across southern Australia we used the GRAZPLAN simulation models (Ghahramani and Moore, 2013; Moore and Ghahramani, 2013a, 2013b) and equations from the Australian National Greenhouse Gas Inventory (Browne *et al.* 2011) to determine livestock emissions of three representative sheep enterprises across southern Australia, where sites were classified according to their rainfall and dominant livestock enterprise land use. Enterprises specialised in either (1) Merino ewe production for both fine wool and lambs for meat, (2) Merino × Border Leicester cross ewes with an emphasis on lamb production, or (3) Merino wethers for fine wool production, following previous work (Moore and Ghahramani 2013a). In an attempt to encompass the diversity in soil types, climates and typical forage species found in the 1 x 10^6 m^2 study area across southern Australia, statistical areas level 2 within the study area (SA2s; Australian Bureau of Statistics) were classified into a set of 28 sites with approximately equal gross value of agricultural production (GVAP, see Moore and Ghahramani 2013a). The SA2s were grouped according to their average annual rainfall and land use (i.e. the proportions of GVAP attributable to cropping, sheep, and cattle production), producing a final set of 28 sites (Table 1).

A single Australian Bureau of Meteorology (BoM) weather station was selected to represent each site on the basis of weather and management data availability; all simulations were conducted using historical climates measured between 1980 and 1999. Climates and soil types across the study site varied widely, with ranges in annual rainfall and temperature at the locations modelled of 299-1091 mm and 11.6-19.1°C, respectively, and with soil types ranging from deep sands to red-brown earths to sandy-clay loams (Table 1). Pasture composition and average above-ground primary production (ANPP) also varied substantially across the study area but in general pastures consisted of an annual or perennial grass combined with a perennial legume. To simplify the analysis further and to enable insight into how farm productivity, profitability and emissions were related to prevailing climate, we sub-classified each site in Table 1 into similar climatic zones following a Köppen classification system (cite) and long-term average climatology records (BoM 2015). Further information on site characteristics, climate, pasture and soil data is given in Table 1 of Moore and Ghahramani (2013a) and Table 3 of Ghahramani and Moore (2013).

To facilitate comparisons between sites, identical livestock genotypes were modelled within each enterprise in all climate zones (Table 2). Management policies (livestock replacement, the timing of the reproductive cycle, the sale of young stock and thresholds for supplementary feeding) were described separately for each of the 28 site x 3 enterprise combinations following Moore and Ghahramani (2013a). Information on typical management systems elicited by State agency officers in producer workshops was used where possible; otherwise expert opinion, literature accounts and preliminary simulations were used to derive sensible values. The date of age at purchase and age at sale of crossbred ewes and wethers at each location were simulated in line with the reproductive cycle of adult ewes in the Merino ewe enterprise. At locations in the cereal-livestock zone stubble availability was modelled by removing livestock from the paddocks when there was less than 800 kg/ha of available green herbage in any paddock; these animals were provided with an *ad libitum* diet approximating that which can be expected for sheep on stubble paddocks (Moore and Ghahramani 2013a).

[Insert Tables 1 and 2 near here]

Stocking rates, supplementary feeding and ground cover

Optimally sustainable stocking rates (OSSR) were determined for each of the 84 enterprise × site combinations by optimisation based on maximising profit while minimising the annual frequency of days in which ground cover was less than 0.7 (Moore and Ghahramani, 2013). A ground cover threshold of 0.7 was assumed to minimise the risk of soil erosion (Lang and McCaffrey 1984). The minimum ground cover frequency was allowed to vary with growing-season rainfall, for consistency with the stocking rates elicited for each grazing system. To compute greenhouse gas emissions, pasture and livestock variables and ground cover values were recorded on a daily basis in each simulation then aggregated over years for each site. The OSSR for each location × enterprise combination was identified by interpolating relevant simulation results, and all other statistics were interpolated from the simulation outputs at that stocking rate following Moore and Ghahramani (2013a). All results shown here are reported at the OSSR for each location x enterprise combination.

Long-term average annual production and operating profit

Long-term average annual livestock sales, wool production and profitability are shown in Table 1. Operating profit ($/ha) was used to compare enterprises and adaptation strategies since this metric is likely to be a major determinant of choices made by Australian producers given the relatively unregulated and low-subsidy environment in which livestock production occurs. The definition of operating profit used here follows that of Moore and Ghahramani (2013a) and is comparable to profit at full equity. Operating profit was calculated as total enterprise income including that from wool and animal sales less costs (the sum of variable costs, fertiliser, stock, salaries and fixed costs; further details are shown in supplementary material of Ghahramani and Moore (2013). Costs and prices were computed as 5-year average values (2006–2010) and were assumed to remain constant over time and across enterprises where possible (Ghahramani and Moore, 2015). Fertiliser costs associated with maintaining soil fertility were estimated after Ghahramani and Moore (2013) as a function of the stocking rate and maintenance soil phosphorus requirement.

Intervention to pasture management

Pasture options examined here for their impacts on GHG emission are those examined by Ghahramani and Moore (2013). Options were identified from literature reviews and livestock producers experience gathered in a series of workshops (Pattinson 2011). Briefly, the strategies were:

- High and very high soil fertility: Increasing soil nutrients via phosphorus availability (in the GRAZPLAN models soil fertility is modelled using a scalar that ranges from 0 to 1). Baseline soil fertility varied across locations and was based on local practise and soil condition; where possible values were decided in project workshops in consultation with producers and local advisors. Higher soil fertility was examined by raising the fertility scalar in each paddock by 0.1 (H). At locations where the fertility scalar in at least one paddock was less than 0.7, a second level of fertility was also considered (VH), where the fertility scalar in each paddock was raised by 0.2 or to a maximum of 0.9;
- Two levels of confinement feeding: placing all animals in a feedlot between 1 December and 31 July each year when total pasture above-ground biomass fell below 2000 or 1000 kg/ha to prevent soil erosion; animals were returned to pasture when total green biomass exceeded 500 kg/ha;
- Two levels of increased proportions of whole farm area sown to lucerne: either 20% or 40%; we posited that this summer-active perennial species might increase pasture biomass and ground cover during summer, thereby reducing soil erosion risk. If the pastures at a location already included a lucerne component, the new lucerne paddock was additional to that already existing;
- Removing annual legumes: removing annual legume species was postulated to reduce competition with and permit greater growth of grass species, thereby reducing potential for low ground cover and soil erosion risk over summer.

Livestock breeding options

All animal options studied were identical to those examined by Moore and Ghahramani (2013b). Briefly these strategies were:

- Greater body size (body weight) was examined under the rationale that maintenance energy requirements relative to body weight decreases as body weight increases, leaving more energy for growth, wool production or reproduction. This was explored further using SheepExplorer (Freer *et al.* 1997, http://www.grazplan.csiro.au/?q=node/15), which is based on the same parameters and equations as used in GrassGro. This was run with the wool-liveweight relationships reported by Ferguson *et al.* (2011) to model the impact of liveweight on efficiency of ME use and wool production on a set amount of feed.
- Animals with higher fleece weight were assessed since animals expressing this trait would be expected to divert a greater proportion of their energy intake into wool growth, assuming the energy diversion did not compromise survival or reproduction.
- Higher conception rates were considered, as greater reproduction rate will result in a greater energetic efficiency, because it increases the proportion of young, growing livestock. Later, Harrison *et al.* (2014b) shown that ewe fecundity in the ewes enterprises increased in livestock production without concurrently increasing net farm GHG emissions or stocking rate and reduced emissions intensity.
- For the crossbred ewe enterprise, sires with higher body weight were examined under the presumption that larger rams would yield larger offspring, and such offspring should have greater growth rates allowing earlier sale.

Livestock greenhouse gas emissions

Greenhouse gas (GHG) emissions were determined using equations for broadacre sheep grazing specified by the Australian Government Department of Climate Change and Energy Efficiency (DCCEE 2012). In contrast to previous work determining livestock emissions of prime lamb enterprises on a seasonal basis (Alcock *et al.* 2014), the present study computed emissions on a daily time-step aggregated into monthly data, which was considered more accurate given temporal variation in pasture quality and quantity, livestock number and liveweight. GHG emissions were calculated on a carbon dioxide equivalent basis (CO_2-e) for methane from enteric fermentation and manure deposition, and nitrous oxide from leaching and surface water run-off (indirect) and livestock urine and faeces. All emissions and end products were aggregated into annual totals across all livestock classes where appropriate. Dry sheep equivalents (DSE) for breeding ewes and other stock classes were calculated based on the season of lambing for the site / enterprise and relative mature size. Autumn, winter and spring lambing breeding Merino ewes were given DSE values of 2.2, 2.0 and 1.7

respectively, while crossbred ewes had these values multiplied by 1.2 due to their larger size (Morley, 1994).

Statistical analysis

Least squares, linear models of main effects (management option, zone, enterprise and year) and significant 2 way interactions were fit to the dependent variables using JMP (2014). The least squares means (LSM) of management option main effects for total GHG emissions per ha, per DSE and per tonne product were plotted against profit per ha to calculate linear relationships between profit and emissions intensity (EI) for the management options across zones, enterprises and years. Student t-tests ($P<0.05$) were used to determine the significance of differences between treatment effects. The LSM of total GHG equals the sum of the LSMs of the GHG components (enteric methane, manure methane, indirect N_2O and N_2O from excreta).

Results

The model fit to GHG per ha had the best fit (Table 3). The significant model effects for each dependent parameter are also shown in Table 3. As an example, the third model in Table 3 with significant effects was:

Total GHG per dse (tCO_2-e/dse) = option + enterprise + zone + option*zone + enterprise*zone…….$R^2 = 0.48$, RMSE = 0.19

[insert Table 3 here]

While the option by zone interaction was significant for EI parameters, very few of the animal management options were significantly different within any zone versus the ‘nil’ option for that zone. For example, the only animal management option * zone combination for total GHG per dse with a significantly lower EI was in the hot (summer drought) zone, where the LSM of higher conception rate was 0.6006 tCO_2-e/dse versus 0.6490 tCO_2-e/dse for the ‘nil’ option in that zone.

The profit and GHG parameter LSMs for each Köppen zone in Table 3 are shown in map form in Figure 1.

[Insert Figure 1 here]

The LSM for the main effects of options, enterprises and zones for all parameters are shown in Tables 4, 5 and 6 respectively. There are many significant differences between different options, enterprises and zones. In general livestock sales and operating profit were greatest for cross-bred ewe enterprises, and wool production was greatest for wether/ewe enterprises, although there was considerable variation across sites and between enterprises within sites. In all enterprises operating profit was more closely related to livestock sales than to wool production, and livestock numbers in turn were closely associated with ANPP.

[insert Tables 4, 5 and 6 here]

An example of the percentages of the components of total GHG are shown for options, enterprises and zones in Figures 2-4 respectively, for GHG (tCO_2-e)/ t wool. The percentages of 76.6, 0.02, 13.6 and 9.8% for enteric methane, manure methane, indirect nitrous oxide and excreta nitrous oxide components respectively, were similar for the other EI parameters across options, enterprises or zones.

[Insert Figures 2-4 here]

Profit versus EI

The total GHG per ha and GHG per dse regressions versus profit per ha are shown in Fig. 5. The total GHG per tonne of wool and meat regressions versus profit per ha are shown in Fig. 6. The best options with the highest profit and lowest EI were based on pasture, not animal, management options.

[insert Figures 5, 6 and 7 here]

The correlations of the LSM across options are shown in Table 7. Profit and GHG per ha had a low correlation while GHG per dse or wool or meat produced had high correlations. The SheepExplorer predictions of individual and total fleece weight for mobs of sheep of different liveweight grazing a set amount of 1500 kg DM are shown in Figure 7. The most wool per ha was obtained by running more, smaller sheep.

[insert Table 7 near here]

Discussion

Emissions intensity decreased as profitability increased

A main result of this study was the significant, negative relationships between emissions per dse, per unit meat or per unit wool production shown in Figs. 5 and 6 that indicate management options generating the highest profitability tended to be those with the lowest EI. This suggests that sheep farmers in extensive grazing enterprises who adopt best management practices to increase profitability will also tend to reduce the emissions intensity of product sold, which is a win-win outcome for the sheep meat and wool industries and the environment alike.

The relationship between profitability and emission intensity was negative across all climate zones and management options because although there was a strong, positive association between profitability and total animal production (Table 1), total emissions per ha remained relatively constant with increasing profitability (Fig. 5). This finding partially contradicts earlier conclusions by Harrison *et al.* (2014a) and Alcock *et al.* (2015), which intimated that no management intervention – to farm management, animal genotype or otherwise – was likely to achieve simultaneous improvements in all of production, profitability, net farm emissions and wool or meat emissions intensity. Here we found that interventions achieving the highest and lowest enterprise profitability tended to have the lowest and highest emissions intensity, respectively (Figs 5, 6).

The divergence in conclusions between our study and those conducted previously may be due to several reasons. Harrison *et al.* (2014a) and Alcock *et al.* (2015) examined only one location, whereas ours included 28 sites spread across eight distinct climatic zones, and most of the interventions simulated in each previous study (lambing time, lamb sale age or sale weight, botanical pasture composition, joining maiden ewes at a younger age, increasing lamb weaning rates, increasing feed-use efficiency and/or methane yield) were not examined here. This reinforces that authors should clearly state all relevant assumptions and methods used in their studies to frame their conclusions. It also indicates that more robust conclusions can be drawn from studies that include a higher number of contrasts (sites, options, combinations of options etc.), and underscores the importance of global studies with multiple comparisons, such as studies of emissions intensities across livestock enterprises (Herrero and Thornton 2013).

Soil fertility and confinement feeding of animals during summer were most preferable over the long-term

Not all management options examined in this study improved both emissions intensity and profitability compared with baseline levels, but both levels of higher soil fertility and confinement feeding when pasture biomass was below 2000 kg/ha conformed to this relationship. Across climate zones and enterprises, increasing soil fertility resulted in the greatest profitability, because increasing soil nutrient status improved net primary production and resulted in more home-grown animal feed, similar to results found in other analyses of southern feedbase systems (Phelan *et al.* 2014; Phelan *et al.* 2015a). Greater pasture biomass improved ground cover, reduced risk of soil erosion by animal traffic and facilitated higher stocking rates. Confinement 2000 feeding of animals in summer also allowed greater conservation of ground cover and facilitated higher stocking rates. Since there was a strong positive correlation between stocking rates and profitability across zones, higher soil fertility and confinement feeding resulted in greater financial returns. These results agree with other studies of site-specific nutrient management and profitability (Dobermann *et al.* 2002) and imply that the soil fertility levels simulated here were amenable to improvement, though presumably the relationship between fertility and profitability would follow a trend of diminishing marginal returns beyond which profitability would fall.

Incorporating lucerne or removing annual legumes from the feedbase were least preferable over the long-term

Although removing annual legumes from pastures reduced long-term average profitability across enterprises, this intervention reduced emissions intensity per product sold, and so did not have a mutually detrimental impact on profit and emissions intensity (Fig. 6). However, incorporation of legumes with perennial phenology (lucerne) had counterproductive effects on not only farm profitability, wool and meat production, but also on emissions intensity. This result conflicts with evidence provided in a review suggesting that forage-legume based ruminant systems tend to have less negative impact on emissions, emissions intensity and total herbage production when compared with ruminant systems based only on grasses or cereals (Phelan *et al.* 2015b). We specifically identify this conflict because it highlights an important limitation of our study. Phelan *et al.* (2015b) attributed the main advantages of forage legumes as their low reliance on nitrogen fertiliser and higher protein content when compared with grass pastures.

Although our modelling accounted for increased nitrous oxide emissions associated with higher protein content of pastures, we did not account for higher nitrogen use associated with fertilisation of grass pastures, which might have significantly increased nitrous oxide emissions and offset some of the benefit we discussed above surrounding increased soil fertility. The GRAZPLAN models we used to simulate the dynamics of pasture and animal production based soil fertility on phosphorus availability, rather than nitrogen (Moore *et al.* 1997), and so obviated emissions associated with use of nitrogen fertiliser. Nonetheless, we believe our results reflect common practices undertaken by farmers across extensive grazing regions in Australia because graziers tend to fertilise their pastures with superphosphate fertilisers and little nitrogen (Mokany *et al.* 2010 Harrison *et al.* 2015)), and because although we removed lucerne from the feedbase at each site, pastures at most sites still contained forage legumes (Ghahramani and Moore 2013). It should also be noted here that we assumed relatively small differences in emissions across options associated with changes in soil carbon. This assumption was based on the fact that we compared all management options on a like-for-like basis, wherein stocking rates were optimised for each site x climate combination such that long-term average ground cover was comparable (for more details on this method see Harrison *et al.* 2014a). Changes in emissions associated with stocking rates *per se* including animal excreta or manure, were both accounted for and documented here (Figs 2-4).

Animal Management options

The animal management options compared were increased body weight, higher fleece weight, higher ewe fecundity, and for the crossbred ewe enterprise, sires with higher body weight. None of these options had significantly higher profit per ha, dse, t wool or per t meat than the baseline 'Nil' option when considered over all zones, however a few animal management options were significantly better within particular zones.

Selecting for larger body weight, ram size in crossbreds and, to a certain extent, fleece weight, was based on the rationale that maintenance energy requirements relative to liveweight decrease as liveweight increases (Moore and Ghahramani 2013b). This hypothesis bears closer examination as other workers have questioned this. For example, Large (1970) found from feeding experiments with Scottish Half bred ewes mated to Suffolk rams that the highest values for the biological efficiency of meat production at the flock level were obtained from small breeds of ewes producing large litters and crossed with a large breed of ram, leading to a high growth rate and final size in the lamb. A relatively small increase in litter size in the small breeds of ewe (i.e. from one to two lambs) may result in a level of efficiency as high as that achieved by a larger breed with a large litter size (i.e. three to four lambs) without having to resort to techniques such as the artificial rearing of lambs. Dickerson (1978) reviewed efficiency from a flock perspective, rather than an individual animal perspective and concluded that body weight *per se* is of little importance in determining either feed energy conversion or total economic efficiency in animal meat production, when compared with functional output per unit of body weight, in reproduction, growth and body composition. His recommendations were to first choose the mature body weight best adapted to the environmental, breeding system and market factors for the species and area of production, and secondly, focus primarily on improvement of genetically variable functional components of performance: reproductive rate, relative growth rate, body composition and wool production. This suggests that a further iteration to this study might be to examine the collective influence of different genotypes in different climatic zones, such as more heat stress tolerant genotypes in the northern semi-arid regions, since here we examined only pure Merino or Merino-cross breeds (Fig. 1).

Thompson *et al.* (1985) found that selection for weaning weight changed the shape and magnitude of the individual’s food-intake curve, with the weight-plus sheep having a higher food intake (i.e. appetite) in the early stages of growth and a greater asymptote than the weight-minus animals. Selection for high and low weaning weight also resulted in an increase and a decrease in mature weight respectively. Both strains had a similar growth efficiency, although when calculated as gross food conversion efficiency, the weight-plus sheep were higher than the weight-minus animals at the same body weight, whereas there was no difference between strains at the same age. Thus selection for higher weight did not result in higher feed efficiency when individual sheep were compared at the same age. To reach the same proportion of their mature body weight, both strains consumed about the same amount of food per unit of body weight. Bigger sheep will probably only be best when there is a carcass weight threshold for finished lambs (W. Pitchford, pers. comm.). Lambs from bigger ewes finish faster, thus have less days of maintenance. Ewe body weight has a positive economic value for sale weight, but there is a negative value on feed intake. That said, a number of meat selection indices will still result in increasing mature weight because of the high emphasis on young growth.

It was found from the modelling with SheepExplorer (Freer *et al.* 1997, http://www.grazplan.csiro.au/?q=node/15)that the ME required for maintenance and grazing in individual sheep was almost linear with respect to live weight (Fig. 7), so the ‘dilution of maintenance’ effect in larger animals was negligible, or arguably much overrated. Total wool produced at the flock level was predicted to increase with more, smaller sheep having the same total MEI from a given area of grazed land (1500kg DM), despite their total flock maintenance requirements being slightly higher.

The results here suggest that to achieve lower EI, combinations of animal management options may be needed (Ghahramani and Moore, 2015), as was also suggested by Harrison et al. (2014b), as single options did not result in any significant reductions.

Variation in enterprise profit and emissions intensities across climate zones

Averaged across years, enterprises and management options, climate zones with no dry season and warm or mild summers were most profitable because they were conducive to greater pasture growth and higher stocking rates over the long term, and enterprises with greater stocking rates were generally more profitable (Fig. 1). Climate zones supporting the lowest stocking rates (warm (persistently dry), distinctively dry (and hot) and hot and warm (summer drought)) on average had the lowest operating profit over the long-term and across enterprises (Table 4). Area-based emissions displayed a similar pattern, with higher emissions in regions supporting higher stocking rates and *vice-versa* (Table 2 and Figure 1).

Regions classified as hot with persistent summer droughts had by far the greatest emissions intensities per unit product, followed by regions with warm and persistently dry zones, and climate zones with the lowest emissions intensities were those with no dry seasons and warm to mild summers (Figs 1, 4, Tables 4 and 6). These results imply that the efficacy of sheep production in southern Australia in terms of GHG emissions per unit product is greater in temperate regions with cooler climates and higher rainfall; in general such regions are closer to the coast (Fig. 1). On the other hand, more inland sites with semi-arid and arid climates supported lower pasture growth due to greater evaporative demand and lower rainfall, particularly during summer. Even though stocking rates were lower in these regions compared with temperate zones, hot, persistently dry regions with summer drought most often had higher emissions intensities. The agro-ecological variation in emissions intensities observed here resonates with global studies of livestock emissions intensities (Opio *et al.* 2013) and is largely related to pasture growth rates and nutritive value, with cool temperate regions conducive to superior quality pastures and more biomass, which together facilitate higher animal growth rates and meat and wool production. A broader implication of these results for industry is that farmers at inland sites in the wheat-sheep belt of Australia who partake in carbon trading schemes (such as the recently floated Australian Emissions

Reduction Fund) may be at a disadvantage relative to their counterparts located closer to the coast or in more southern environments.

Livestock greenhouse gas emissions profiles and emissions intensity comparisons to past work

We used a combination of modelling packages to determine how realistic changes in management of sheep enterprises would influence the relative emissions profiles of methane from enteric fermentation and manure, as well as nitrous oxide emissions from excreta and indirect sources, such as nitrate leaching and ammonia volatilisation. Similar to past work examining the emissions profiles of sheep and beef farms (Harrison *et al.* 2014a; 2014b; 2015), we found that enteric methane dominated the emissions profile, contributing 70-80% of net farm emissions. We also showed that emission component profiles were relatively consistent, irrespective of management option, absolute net emissions or enterprise (e.g. Figs 2, 3).

Our emissions intensity results of ~30 t CO_2-e/t wool and ~10 t CO_2-e/t meat (Table 4, Fig. 6) concord with previous studies that have examined livestock emissions of Australian wool and prime lamb farming enterprises (Alcock *et al.* 2015; Harrison *et al.* 2014a; 2014b) in Australia, which lends credibility to our assumptions and modelling approach.

Conclusion

In general, options that increased production and profit had minimal impact on EI per hectare but reduced EI per DSE, and per unit wool and meat production. Increasing soil fertility allowed the greatest increases in stocking rates so this management option resulted in the highest profitability relative to the baseline. The option with the lowest profitability and highest EI was sowing 40% of the farm area to lucerne, probably because average above-ground net primary production of lucerne was low relative to baseline grass species. In general, enterprises with the lowest and highest EI were Merino ewes and Merino wethers, respectively. Emissions per DSE or per unit product were typically highest in regions with distinctively dry and hot summers, probably because these regions had longer seasons with high evaporative demand that restricted pasture growth and allowable stocking rates relative to the continuous generation of emissions. Overall, a negative relationship between EI and profitability when GHG per unit DSE or per product suggests that management options capable of increasing farm profitability also tend to reduce EI, which would be a beneficial outcome for the environment, agricultural industries and farmers alike. To achieve lower EI, combinations of animal management options may be needed, as single options did not result in any significant reductions.

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References

Alcock, DJ, Harrison, MT, Cullen, BR, Rawnsley, RP, Eckard, RJ (2014) Can animal genetics and flock management be used to reduce greenhouse gas emissions but also maintain productivity of wool-producing enterprises? *Agricultural Systems* http://dx.doi.org/10.1016/j.agsy.2014.06.007.

Alcock, DJ, Harrison, MT, Rawnsley, RP, Eckard, RJ (2015) Can animal genetics and flock management be used to reduce greenhouse gas emissions but also maintain productivity of wool-producing enterprises? *Agricultural Systems* **132**, 25-34.

BoM (2015) 'Climate classification maps. Bureau of Meteorology, Australian Government. Available: http://www.bom.gov.au/jsp/ncc/climate_averages/climate-classifications/index.jsp?maptype=kpn#maps [Accessed 13 April 2015].' Available at

Browne, NA, Eckard, RJ, Behrendt, R, Kingwell, RS (2011) A comparative analysis of on-farm greenhouse gas emissions from agricultural enterprises in south eastern Australia. *Animal Feed Science and Technology* **166-67**, 641-652.

DCCEE (2012) 'National Inventory Report 2010: The Australian Government Submission to the UN Framework Convention on Climate Change April 2012, vol. 1.' (Department of Climate Change and Energy Efficiency: Canberra, ACT, Australia)

DCCEE (2013) Department of Climate Change and Energy Efficiency 2012, Agriculture emissions projections 2012, DCCEE, Canberra, ACT. Available: http://www.climatechange.gov.au [Accessed 8 April 2013].

Dickerson, GE (1978) Animal size and efficiency: basic concepts. *Animal Science* **27**, 367-379.

Dobermann, A, Witt, C, Dawe, D, Abdulrachman, S, Gines, HC, Nagarajan, R, Satawathananont, S, Son, TT, Tan, PS, Wang, GH, Chien, NV, Thoa, VTK, Phung, CV, Stalin, P, Muthukrishnan, P, Ravi, V, Babu, M, Chatuporn, S, Sookthongsa, J, Sun, Q, Fu, R, Simbahan, GC, Adviento, MAA (2002) Site-specific nutrient management for intensive rice cropping systems in Asia. *Field Crops Research* **74**, 37-66.

Eckard, RJ, Grainger, C, de Klein, CAM (2010) Options for the abatement of methane and nitrous oxide from ruminant production: A review. *Livestock Science* **130**, 47-56.

Ferguson, MB, Thompson, AN, Gordon, DJ, Hyder, MW, Kearney, GA, Oldham, CM, Paganoni, BL (2011) The wool production and reproduction of Merino ewes can be predicted from changes in liveweight during pregnancy and lactation. *Animal Production Science* **51**, 763-775.

Freer, M, Moore, AD, Donnelly, JR (1997) GRAZPLAN: Decision support systems for Australian grazing enterprises - II. The animal biology model for feed intake, production and reproduction and the GrazFeed DSS (vol 54, pg 77, 1997). *Agricultural Systems* **58**, 77-126.

Ghahramani, A, Moore, AD (2013) Climate change and broadacre livestock production across southern Australia. 2. Adaptation options via grassland management. *Crop & Pasture Science* **64**, 615-630.

Ghahramani A, Moore AD. (2015) Climate change systemic adaptations for grasslands and livestock; effects on production, profitability, and trade-offs with CH4 and other ecosystem services. Agricultural Systems. **133**, 158-166.

Harrison, MT, Christie, KM, Rawnsley, RP, Eckard, RJ (2014a) Modelling pasture management and livestock genotype interventions to improve whole-farm productivity and reduce greenhouse gas emissions intensities. *Animal Production Science* **54**, 2018-2028.

Harrison, MT, Jackson, T, Cullen, BR, Rawnsley, RP, Ho, C, Cummins, L, Eckard, RJ (2014b) Increasing ewe genetic fecundity improves whole-farm production and reduces greenhouse gas emissions intensities: 1. Sheep production and emissions intensities. *Agricultural Systems* **131**, 23-33.

Harrison, MT, Kelman, WM, Moore, AD, Evans, JR (2010) Grazing winter wheat relieves plant water stress and transiently enhances photosynthesis. *Functional Plant Biology* **37**, 726-736.

Harrison, MT, McSweeney, C, Tomkins, NW, Eckard, RJ (2015) Improving greenhouse gas emissions intensities of subtropical and tropical beef farming systems using Leucaena leucocephala. *Agricultural Systems* **136**, 138-146.

Herrero, M, Thornton, PK (2013) Livestock and global change: Emerging issues for sustainable food systems. *Proceedings of the National Academy of Sciences* **110**, 20878-20881.

Ho, C, Jackson, T, Harrison, MT, Eckard, RJ (2014) Increasing ewe genetic fecundity improves whole-farm production and reduces greenhouse gas emissions intensities: 2. Economic performance. *Animal Production Science* **54**, 1248-1253.

Lang, RD, McCaffrey, LAH (1984) Ground cover—its effects on soil loss from grazed runoff plots, Gunnedah. *Journal of Soil Conservation, New South Wales* **40**, 56-61.

Large, RV (1970) The biological efficiency of meat production in sheep. *Animal Science* **12**, 393-401.

Mokany, K, Moore, AD, Graham, P, Simpson, RJ (2010) Optimal management of fertiliser and stocking rate in temperate grazing systems. *Animal Production Science* **50**, 6-16.

Moore, AD, Donnelly, JR, Freer, M (1997) GRAZPLAN: Decision support systems for Australian grazing enterprises. 3. Pasture growth and soil moisture submodels, and the GrassGro DSS. *Agricultural Systems* **55**, 535-582.

Moore, AD, Ghahramani, A (2013a) Climate change and broadacre livestock production across southern Australia. 1. Impacts of climate change on pasture and livestock productivity, and on sustainable levels of profitability. *Global Change Biology* **19**, 1440-1455.

Moore, AD, Ghahramani, A (2013b) Climate change and broadacre livestock production across southern Australia. 3. Adaptation options via livestock genetic improvement. *Animal Production Science* 111-124.

Morley, F.H.W. (1994) Grazing systems. In "Merinos, Money & Management" ed. Morley, F.H.W. Postgraduate Committee in Veterinary Science, University of Sydney, Sydney.

Opio, C, Gerber, P, Mottet, A, Falcucci, A, Tempio, G, MacLeod, M, Vellinga, T, Henderson, B, Steinfeld, H, (2013) Greenhouse gas emissions from ruminant supply chains – A global life cycle assessment. Food and Agriculture Organization of the United Nations (FAO), Rome.

Pattinson, R (2011) Can southern Australian livestock producers adapt to a changing climate? In '52nd annual conference of the Grassland Society of Southern Australia. (Ed. J Hirth) pp. 129-132. Grassland Society of Southern Australia: Tooborac, Vic.

Phelan, DC, Harrison, MT, P, KE, Parsons, D (2015a) Management opportunities for boosting productivity of cool-temperate dairy farms under climate change. *Agricultural Systems* **In press**,

Phelan, DC, Parsons, D, Lisson, SN, Holz, GK, MacLeod, ND (2014) Beneficial impacts of climate change on pastoral and broadacre agriculture in cool-temperate Tasmania. *Crop and Pasture Science* **65**, 194-205.

Phelan, P, Moloney, AP, McGeough, EJ, Humphreys, J, Bertilsson, J, O'Riordan, EG, O'Kiely, P (2015b) Forage Legumes for Grazing and Conserving in Ruminant Production Systems. *Critical Reviews in Plant Sciences* **34**, 281-326.

Thompson, JM, Parks, JR, Perry, D (1985) Food intake, growth and body composition in Australian Merino sheep selected for high and low weaning weight. 1. Food intake, food efficiency and growth. *Animal Science* **40**, 55-70.