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The concordance between greenhouse gas emissions, livestock production and profitability of extensive beef farming systems

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Abstract. Here we examine the concordance among emissions, production and gross margins of extensive beef farming systems by modelling a range of scenarios for herd management, animal genotype and pasture nutritive quality. We based our simulations on a case-study farm in central Queensland, Australia, and studied the influence of interventions designed for emissions mitigation, increasing productivity, or increasing gross margin. Interventions included replacing urea supplementation with nitrate, finishing cattle on the perennial forage leucaena (L), herd structure optimisation (HO), higher female fecundity (HF), and a leucaena finishing enterprise that had net farm emissions equal to the baseline (leucaena equal emissions; LEE). The HO intervention reduced the ratio of breeding cows relative to steers and unmated heifers, and lowered the ratio of costs to net cattle sales. Gross margin of the baseline, nitrate, L, LEE, HO and HF scenarios were AU$146 000, AU$91 000, AU$153 000, AU$170 000, AU$204 000 and AU$216 000, respectively. Enterprises with early joining of maiden heifers as well as HO and HF further increased gross margin (AU$323 000), while systems incorporating all compatible interventions (HO, HF, early joining, LEE) had a gross margin of AU$315 000. We showed that interventions that increase liveweight turnoff while maintaining net farm emissions resulted in higher gross margins than did interventions that maintained liveweight production and reduced net emissions. A key insight of this work was that the relationship between emissions intensity (emissions per unit liveweight production) or liveweight turnoff with gross margin were negative and positive, respectively, but only when combinations of (compatible) interventions were included in the dataset. For example, herd optimisation by reducing the number of breeding cows and increasing the number of sale animals increased gross margin by 40%, but this intervention had little effect on liveweight turnoff and emissions intensity. However, when herd optimisation was combined with other interventions that increased production, gross margins increased and emissions intensity declined. This is a fortuitous outcome, since it implies that imposing more interventions with the potential to profitably enhance liveweight turnoff allows a greater reduction in emissions intensity, but only when each intervention works synergistically with those already in place.

Additional keywords: agroforestry, economics, enteric methane, fecundity, grazing, *Leucaena leucocephala*, perennial legumes, urea, weaning rates.

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Introduction

Greenhouse gas (GHG) emissions from the Australian livestock sector are projected to account for 72% of total agricultural emissions by 2020 (DCCEE 2013). The majority of the Australian beef herd is located in Queensland (ABS 2013), and is mainly composed of cattle stocked on unimproved rangelands (Gleeson *et al.* 2012; Callaghan *et al.* 2014). These grazing regions are characterised by C4 grasses that have rapid maturity, low crude protein and low metabolisable energy compared with temperate pastures (Minson 1990). In the absence of supplementary feed, forages with low digestibility and energetic value result in poor animal productivity and high methane emissions per unit meat production, with liveweight (LW) gains during dry seasons being low or even negative (Dixon and Coates 2008). These factors suggest that methods for improving LW gain and reducing emissions from extensive livestock enterprises would be advantageous to beef farmers and conducive to reducing sector emissions.

One method for improving LW gain of extensive cattle production systems is via addition of dietary supplements, such as non-protein nitrogen (Callaghan *et al.* 2014). Supplements based on urea are designed to provide additional rumendegradable nitrogen, stimulating intake of forage and promoting a LW response in the order of 0.1–0.25 kg/day (McLennan *et al.* 1981; Hennessy *et al.* 2000). Research suggests that urea supplements can be replaced with nitrate (NO_3) as an alternative source of nitrogen for rumen microbiota, since nitrate metabolism in the rumen has a high affinity for hydrogen and can reduce methanogesis (Nolan *et al.* 2010; van Zijderveld *et al.* 2011). Although nitrate offers potential to serve as a non-protein nitrogen replacement for urea while reducing methane emissions, there are several knowledge gaps in its application. In northern Australia, there is limited labour and capital infrastructure to enable intensive feeding of beef cattle, and it is logistically impractical to feed large numbers on a daily basis due to the scale of the grazing operations. Supplements are, therefore, generally fed free-choice as solid lick blocks or as loose mixes (Callaghan *et al.* 2014). Research to date has focussed on feedlot and moderate- to high-digestibility forage diets, with few experiments focussing on how nitrate influences the emissions intensity of extensive beef cattle grazing low-quality pastures.

Adoption of perennial forages with high digestibility is another avenue for reducing emissions intensity of beef cattle production in rangeland environments (Shelton and Brewbaker 1998; Harrison *et al.* 2015*b*). *Leucaena leucocephala* (leucaena) is a productive perennial legume shrub that grows with companion pasture grasses in tropical regions (Larsen *et al.* 1998; Radrizzani *et al.* 2010). Leucaena is long-lived, drought-tolerant and is recognised as a high-value fodder for ruminants due to its palatability and nutritional characteristics, including high crude protein (CP) and non-bloating attributes (Jones and Bunch 2000; McSweeney *et al.* 2011; Kennedy and Charmley 2012). Together, these traits deliver ruminant weight gains that are superior to most other tropical forage systems (Aregheore 1999). In northern Australia, there are more than 120 000 animal equivalents (one AE = 455 kg steer/year; McLean and Blakeley 2014) grazing 250 000–300 000 ha of leucaena–grass pastures (Michael Burgis, pers. comm. 2015), most of which are cattle finishing systems (Dalzell *et al.* 2006). At current rates of adoption, the area dedicated to leucaena plantations is expected to exceed 500 000 ha by 2017 (Shelton and Dalzell 2007). Leucaena grazing enterprises are typically conducted in subtropical regions with relatively high soil fertility, and it has been suggested that ~13 million hectares in northern Australia could be suitable for growing leucaena (Shelton and Dalzell 2007). Leucaena also has the capacity to reduce enteric methane emissions by suppressing methanogenesis (Ouwerkerk *et al.* 2008; McSweeney *et al.* 2011; Kennedy and Charmley 2012), and by redirecting rumen fermentation towards other more useful end products, can potentially increase the energy available for growth or lactation. Together with enhanced LW gains, these findings suggest the leucaena grazing is conducive to a reduction in GHG emissions per unit beef produced (emissions intensity).

Reducing the number of unproductive animals can improve both emissions intensity and gross margin (Bentley *et al.* 2008; Browne *et al.* 2015). Previous work has shown that the number of unproductive animals can be reduced by maintaining a smaller number of more productive animals, improving weaning rates, achieving early puberty and mating of female animals, or increasing cow longevity (Hristov *et al.* 2013). Increasing female fecundity can shift the balance of the herd towards young stock provided the farm stocking rate is maintained, which in turn increases the number of animals sold relative to adult stock retained on farm (Harrison *et al.* 2014*b*). This practice enhances LW turnoff and reduces emissions from breeding animals, which are generally the highest emitters (Charmley *et al.* 2008). Animals with poor fertility also increase herd GHG emissions because farmers need to keep more replacement animals to maintain constant levels of production (Beukes *et al.* 2010; Hristov *et al.* 2013). For a self-replacing breeding herd, there is likely to be other interventions capable of reducing breeders relative to livestock sold, such as earlier fattening and selling of heifers that are surplus to the number required to maintain constant breeders, or optimising herd structure towards animals with the capacity for the greatest LW gain.

The aim of this study was to examine the relationships between LW turnoff or emissions intensity with gross margin when different farm-system interventions were imposed individually or in combination on a baseline beef cattle enterprise in central Queensland, Australia. Interventions included feeding nitrate supplements or forages with the ability to reduce enteric methane and improve LW gain, increasing female fecundity, optimisation of herd structure and combinations thereof.

Modelling mitigation practices

A combination of commercial modelling packages developed for herd structure optimisation, enterprise economic planning or determining net farm GHG emissions were used to conduct the study. The baseline farm model was calibrated using advice from regional sources and data were collected from an extensive beef enterprise near Longreach in central Queensland (Cullen *et al.* 2015). For equivalence across comparisons, the stocking rate of each scenario was matched with that of the baseline, except for two scenarios where net farm emissions were matched with those of the baseline (leucaena equal emissions (LEE) scenarios, see below).

Animal classification terminology, baseline herd and enterprise characteristics

In the present study, we follow terminology used for cattle in northern Australia (Holmes 2012; Harrison *et al.* 2015*b*) and adopt the following definitions throughout:

Calves: all animals less than 1 year old
Weaners: all animals aged between 5 months and 1 year
Heifers: females aged from 1 to less than 3 years old
Cows: females aged 3 years or older
Breeders: females mated in the reproductive herd (heifers or cows)
Spays: unmated females separated from the reproductive herd (heifers or cows)
Steers: castrated males aged 1 year or older
Bulls: uncastrated males aged 1 year or older

Herd structures were generated using Breedcowplus V6.0 Holmes (2012), a steady-state model that optimises animal numbers annually according to management and initial numbers of heifers, weaning and culling percentages, mortality rates, and trading of animals at different ages. The model requires inputs for costs and prices for cattle sold, allowing users to contrast gross margins resulting from alternative trading scenarios, management and herd structures.

Details of the baseline property are documented in Cullen *et al*. (2015); only an overview is given here. The farm consisted of 23 000 ha located 65 km south of Longreach in central Queensland (Qld), Australia (23.44°S, 142.25°E). This region has a subtropical continental climate with summer-dominant rainfall and a mean annual rainfall (1970–2012) of 435 mm (BoM 2013). The majority of pasture-land types consist of low-quality perennial tussock grasses and annual grasses (Orr and Holmes 1984). Information from regional experts and farm records of herd structure, including animals mated, LW and age of breeders, sale times and sale LW, were used as calibration data for modelling the baseline farm. Since herd management of the case-study property was considered atypical of the region, expert advice was used to develop and model generic herd management. The generic herd used as the baseline was predominantly developed using central Qld examples provided in Breedcowplus V6.0 (Holmes 2012), since these files contain data including management policies and herd structures relevant to industry and are typified by central Qld beef enterprises. Herd management and LW turnoff of the case-study property were considered more advanced than those of other farms in the region due to early joining of maiden heifers and the use of high-fecundity females; thus, data from the case-study farm were used to parameterise the 'early joining' (EJ) and 'high fecundity' (HF) scenarios described below. Details of the case-study farm and the influence of EJ and HF relative to generic management are further described in Cullen *et al*. (2015). The size of the baseline herd was set to 1750 AE (1 adult equivalent = 455 kg steer at maintenance), resulting in an average annual stocking rate of 0.08 AE/ha, which is comparable to the long-term average regional value of 0.13 AE/ha (D. Phelps, pers. comm.; Turner *et al.* 1993). Heifers were first mated at 2 years of age and every year thereafter (weaning rates were low in second-calf heifers due to the high stress imposed during pregnancy and calf raising; weaning rates were higher in mature cows after culling of heifers with low fertility). Cows were sold after 12 years, with peak calving occurring in December each year. A self-replacing herd was adopted such that all heifers were added to the breeding herd after weaning. Weaner heifers surplus to the number required to maintain constant breeder numbers were separated and later sold as spayed (empty) animals (Table 1). Heifers were sold at 20 or 30 months in August or June, respectively, and cows older than 3 years in March. The majority of steers were sold aged 20 months in August and the remainder aged 31 months in July. The LW of bulls retained on farm was set to 950 kg and surplus bulls were sold at 800 kg LW in March, following Cullen *et al*. (2015). The ratio of bulls to cows was set to 2%; 25% of the number of bulls required each year were purchased and the remainder were home-grown. Annual mortality rates for females, steers and bulls were set at 2.0%, 1.5% and 6.0%, respectively. Further details of weaning rates, heifer joining (mating) ages, percentages sold from each age class and animal LW at sale for all scenarios other than the baseline are given in Table 1.

For each scenario except the nitrate scenario detailed below, all animals excluding bulls and calves were provided with urea at rates recommended by industry. For a representative comparison of cost and lick block composition, we used prices and lick block formulations for urea and nitrate from the same commercial provider. Urea lick blocks contained 15.5% N as fed (Ridley AgriProducts 'Rumevite[R] 30% urea + P' lick block, Townsville, Qld, Australia; M. Callaghan, pers. comm.). At these supplementation rates, it was estimated that animals in the baseline herd consumed 89–156 g Rumevite lick/head.day (14–24 g N/head.day), depending on animal age and sex. These rates were within the recommended guidelines for this product of 50–200 g Rumevite/head.day (Ridley 2015).

Enterprise scenario analyses

Scenarios modelled were designed for emission mitigation, increasing LW turnoff or both, with single or multiple changes made to the baseline farm system. For equivalence across scenarios, animal numbers were adjusted such that stocking rates were equal with those of the baseline. We applied an exception to this rule in modelling two scenarios involving leucaena (details below), since these grazing systems permit higher stocking rates and animal production than do comparable extensive grass pastures (Harrison *et al.* 2015*b*; Taylor and Eckard 2015). We benchmarked the leucaena scenarios against the baseline by matching net farm emissions (LEE), since farmers tend to adopt such grazing systems to increase LW turnoff rather than to reduce emissions (Shelton and Brewbaker 1998).

Nitrate-supplementation scenario

The nitrate scenario (N) was designed for GHG mitigation and associated carbon offset income by replacing urea lick blocks with molasses calcium nitrate lick blocks at isonitrogenous supplementation rates; all other herd management assumptions were set to baseline values (Table 1). The baseline nitrate content of the pastures modelled was 0.2, 0.6, 0.4 and 0.01 g/kg NO_3 in spring, summer, autumn and winter, respectively, being typical of unimproved pastures in central Qld (Turner *et al.* 1993; Johnson *et al.* 2001). Nitrate was assumed to be supplemented to all animals except weaners and bulls at the upper limit suggested for unaccustomed animals of 1.0 g NO_3/kg $LW^{0.75}$.day (Leng 2008) between June and December. Nitrate lick blocks were assumed to contain 35% $CaNO_3$ (7.3% N as fed, M. Callaghan, pers. comm.). Total nitrate consumption rates including that from forage plus supplement were multiplied by the Australian National Greenhouse Gas Inventory methods (DCCEE 2014) estimate of dry matter intake (DMI) to provide a total daily nitrate intake per head. Nitrate toxicity in ruminants occurs between 10 and 25 g NO_3/kg DMI (Leng 2008), with animals consuming more than 8.5 g NO_3/kg DMI having their total voluntary intake reduced by 7.25% (van Zijderveld *et al.* 2011). At a rate of 1.0 g NO_3/kg $LW^{0.75}$.day, animals would consume 10–12 g NO_3/kg DMI, after accounting for the restriction in voluntary intake. Intakes were converted to enteric methane abatement using the stoichiometry of the reduction of

Table 1. Heifer joining age, calf weaning rate, percentage of heifers and steers sold and carbon offset-scheme details used in the scenarios modelled

Scenario abbreviations: N, nitrates; L, leucaena; LEE, leucaena equal emissions; HO, herd optimisation; HF, high fecundity. The final three columns represent combined scenarios. Further descriptions of each scenario are given in Materials and methods. Surplus weaner heifers sold are surplus to the number of weaner heifers required to maintain constant breeder numbers. Surplus weaner heifers spayed are separated from the breeding herd before mating. n.a., not applicable

Parameter	Age (years)	Baseline	N	L	LEE	HO	HF	HO–HF–EJ	HO–HF–EJ–L	HO–HF–EJ–LEE
Weaning rate (% of cows retained)	1–2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	95	95	95
	2–3	72.5	72.5	72.5	72.5	72.5	85.5	85.5	85.5	85.5
	3–4	30	30	30	30	30	90.3	90.3	90.3	90.3
	>4	72.5	72.5	72.5	72.5	72.5	90.3	90.3	90.3	90.3
Surplus weaner heifers sold or spayed (%)	<1	0	0	0	0	100[A]	100[B]	100[A]	100[A]	100[A]
Female weaner sale weight (kg LW)	<1	147	147	147	147	147	147	147	147	147
Male weaner sale weight (kg LW)	<1	147	147	209	209	147	147	147	209	209
Heifer or cow sales pre-mating (% start of year)	1–2	0	0	0	0	5	0	5	5	5
	2–3	0	0	0	0	5	0	5	5	5
	3–4	2	2	2	2	5	2	5	5	5
	>4	27.5	27.5	27.5	27.5	5	27.5	5	5	5
Heifer or cow sales post-mating (% mated)	1–2	0	0	0	0	5	0	5	5	5
	2–3	6	6	6	6	5	6	5	5	5
	3–4	6.5	6.5	6.5	6.5	5	6.5	5	5	5
	>4	7	7	7	7	5	7	5	5	5
Heifer or cow weight at joining (kg LW)	1–2	240	240	240	240	240	240	240	240	240
	2–3	360	360	360	360	360	360	360	360	360
	>3	475	475	475	475	475	475	475	475	475
Heifer or cow weight at sale (kg LW)	1–2	350	350	350	350	350	350	350	350	350
	2–3	430	430	430	430	430	430	430	430	430
	>3	500	500	500	500	500	500	500	500	500
Spayed heifer sale weight (kg LW)	1–2	350	350	350	350	350	350	350	357	357
	2–3	430	430	430	430	430	430	430	481	481
Steer sales (%)	1–2	90	90	90	90	100	90	100	100	100
	2–3	10	10	10	10	0	10	0	0	0
Steer sale weight (kg LW)	1–2	370	370	420	420	370	370	370	420	420
	2–3	500	500	574	574	500	500	500	574	574
Heifer age at first joining (years)		2	2	2	2	2	2	1	1	1
Carbon offset scheme compliance cost (AU$/year)		0	14 000	14 000	0	0	14 000	14 000	14 000	0

[A]Surplus weaner heifers spayed and sold aged 30 months.
[B]Surplus weaner heifers sold aged 12 months.

nitrate to ammonia, with each mole of nitrate producing 1 mol of ammonia and reducing methane production by 1 mol or 22.4 L (Leng 2008; van Zijderveld *et al.* 2010). To correct for the dose–response effect, final abatement potential was calculated by multiplying potential methane reduction by $-0.17 \times$ g NO_3/kg $LW^{0.75}$ + 1.13 (van Zijderveld *et al.* 2011). This figure was deducted from the total enteric methane estimated using the Australian National Greenhouse Gas Inventory methods for beef cattle (DCCEE 2014). Since nitrates were fed as isonitrogenous replacements for urea, there was no influence of nitrate supplementation on nitrogenous GHG emissions.

Leucaena grazing scenario

The leucaena scenario (L) was designed to examine the effects of forages with antimethanogenic properties and the potential for increasing the rate of LW gain compared with rangeland pasture grasses, with calibration data on relative LW gains, diet composition, enteric methane mitigation and forage nutritive characteristics adopted from experiments reported in Harrison *et al*. (2015*b*). The L scenario was modelled assuming all steers were pastured on leucaena plantations and companion grasses typical of subtropical coastal regions in Qld (Turner *et al.* 1993; Harrison *et al.* 2015*b*). We assumed that 400 ha of established, unfertilised and rainfed leucaena aged 10 years was available for grazing on the basis of the size of leucaena paddocks developed for grazing in comparable studies (Taylor and Eckard 2015), and recent farmer survey data (Radrizzani *et al.* 2010). It was assumed that the leucaena paddock was located *en route* to the saleyards and formed part of the Longreach farming enterprise in terms of property area and overall stocking rate; thus, transport and management of stock to this paddock incurred no additional costs compared with other scenarios, assuming the requirements for labour and land area were the same as for the other scenarios. The leucaena paddock was located near Rockhampton (Qld), a region with soil types and climate characteristics suitable for growth of rainfed leucaena. Male calves were transported to the leucaena block after weaning at 5 months of age; female calves were assumed to join the herd at Longreach and were sold following baseline policies. The LW gain of animals grazing the leucaena relative to the LW gain of animals on grass-only pastures was set in accord with values reported by Harrison *et al*. (2015*b*). Growth rates varied with animal age and time of year; on average, animals with access to leucaena were 27% heavier than were animals on grass pastures, as reflected by higher sale weights of male weaners and steers for L scenarios in Table 1, and higher sale weights of spayed heifers for LEE scenarios. Other than LW at sale, herd management properties were as for the baseline. It was assumed that the dietary ratio of leucaena relative to grass and the forage nutritional characteristics followed values documented by Harrison *et al*. (2015*b*); faecal near-infrared spectroscopy measurements over 12 months revealed apparent dietary contents that were 2.9–4.3% higher in CP and 2.6–3.6% greater *in vivo* dry matter digestibility than were diets of animals grazing grass pastures (Supplementary material S1, available for this paper). The extent of enteric methane mitigation of forage diets containing leucaena was based on values documented by Harrison *et al*. (2015*b*), with subsequent revisions detailed in Supplementary material S2. In brief, open-path lasers were used to determine methane emissions at the paddock scale on Belmont Research Station (23.22°S, 150.38°E) between 23 March and 6 April 2013, between 8 June and 27 July 2013, and between 11 March and 8 April 2014. Emissions were measured at the herd scale for each treatment and expressed on an average animal basis using a backward Lagrangian stochastic model (Flesch *et al.* 1995; Supplementary material S2). Measurements indicated that methane emissions from cattle with access to leucaena were 8% ± 10% lower than those from cattle grazing grass pastures, depending on time of year (WindTrax Touchdown coverage = 1.00; Supplementary material S2). The relative difference between methane emissions at each measurement time from cattle groups grazing either grass or leucaena pastures was used to inform the modelling analyses by adjusting the relative enteric methane emissions determined using the Beef Greenhouse Accounting Framework (B-GAF, see below). The L scenario also accounted for additional soil organic carbon (SOC) sequestered by roots, since literature suggests that leucaena belowground biomass can penetrate between 2.0 and 6.0 m deep (Shelton and Dalzell 2007). We adopted the average SOC value measured from four plots located at two sites in Qld (Radrizzani *et al.* 2011; Conrad 2014), such that leucaena plants aged ~10 years sequestered an additional 270 ± 120 kg SOC/ha.year (1.0 ± 0.4 t CO_2-equivalent (CO_2-e)/ha.year) compared with grass pastures.

Leucaena with equal emissions scenario

Literature suggests that farmers adopt leucaena because such systems permit higher stocking rates and animal production than do comparable extensive grass pastures in environments (Shelton and Dalzell 2007; Harrison *et al.* 2015*b*; Taylor *et al.* 2015). To increase the stocking rate to a realistic level, we benchmarked a second L scenario against the baseline using net farm emissions (LEE). The average annual number of animals carried on farm was increased such that net farm emissions matched those of the baseline, causing herd size to increase to 1843 AE (0.08 AE/ha). Total animal numbers in each age category increased accordingly, resulting in higher LW turnoff. All other assumptions, including e.g. diet characteristics and SOC, were as for the L scenario.

Herd optimisation (HO) scenario

The aim of this scenario was to improve the farm business model by reducing costs per unit LW production, and to allow contrasts with other scenarios that increased gross margin by GHG mitigation or higher LW turnoff. The ratio of costs to net cattle sales in the HO scenario was reduced to 0.15 from the baseline value of 0.17, by optimising the sale time and age of steers and heifers and increasing the number of weaner heifers that were spayed (unmated and separated from the breeding heifers). Since stocking rates were benchmarked with the baseline, more steers and spayed heifers on the property necessitated a reduction in size of the breeding herd. Fewer heifers joining the breeding herd due to increased rates of spaying meant that overall sales of mated and unmated heifers in the breeding herd were also reduced (Table 1, Fig. 1). HO

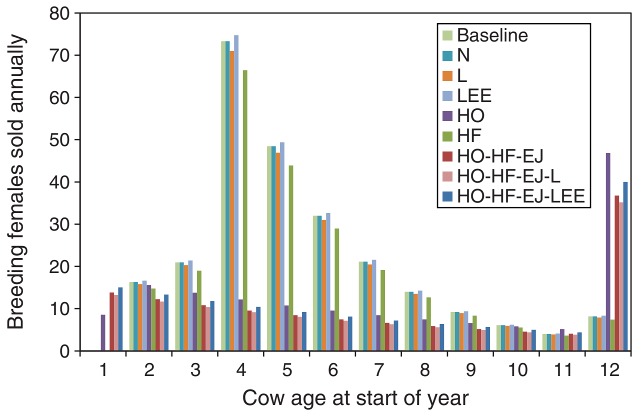

Fig. 1. Age distribution of breeding females sold annually for the baseline and for eight alternative farming system scenarios. Abbreviations are defined in Table 1.

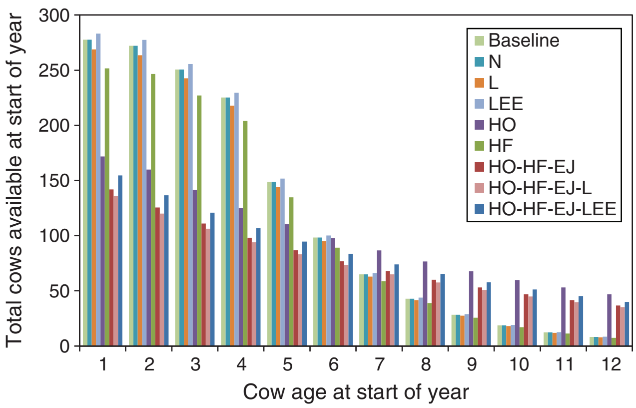

Fig. 2. Age distribution of females for the baseline farm and eight alternative farming system scenarios. Abbreviations are defined in Table 1.

was conducted by (1) spaying all weaner heifers surplus to the number required to maintain constant numbers of adult breeders, and selling them at 30 months (instead of allowing surplus weaner heifers to join the breeding herd), (2) reducing both pre- and post-mating breeder sales to 5% across all age structures, and (3) selling all steers at 20 months old (instead of selling 90% aged 20 months and 10% aged 31 months). Compared with the baseline, HO resulted in fewer adult cows aged 1–6 years and more adult cows aged 7–12 years (Fig. 2).

High-fecundity (HF) scenario

Increasing female fecundity can increase profitability and reduce the emissions intensity of livestock enterprises (Harrison *et al.* 2014*b*; Ho *et al.* 2014; Cullen *et al.* 2015; Dick *et al.* 2015), mainly because sales of juvenile animals increase relative to the number of adult breeding animals retained on farm (Beauchemin *et al.* 2011; Harrison *et al.* 2014*a*). The HF scenario assumed the use of cross-breeding with Angus bulls (*Bos taurus*) to increase weaning rates from Brahman heifers, as well as annual selection for cows with higher reproductive performance by culling on the basis of pregnancy testing. The HF scenario was based on case-study farm data documented by Cullen *et al.* (2015), wherein Angus and Brahman bulls were attributed the same LW and purchase costs. The weaning rates of females aged 2–3 years or females aged >3 years in the HF scenario were increased to 86% and 90%, respectively, on the basis of case study farm data reported by Cullen *et al.* (2015). Pre- and post-mating sale proportions of heifers were maintained at baseline levels, so all surplus weaner heifers were sold aged 12 months to prevent increasing the size of the breeding herd.

Combining the HO, HF and L scenarios with early joining of maiden heifers

Because our modelling allowed for trade-offs between sales, production and emissions, we also examined the impacts of three scenarios that combined interventions that were profitable and benefitted production or reduced emissions when imposed individually. These scenarios also assumed earlier joining (EJ) of maiden heifers to reduce an unproductive group of the herd and increase LW turnoff (Harrison *et al.* 2014*a*; Cullen *et al.* 2015). All three combined-intervention scenarios included HF females, HO and EJ of maiden heifers, with animals pastured on either rangeland grasses (HF–HO–EJ), leucaena (HF–HO–EJ–L), or on leucaena and with net emissions to equal to baseline emissions (HF–HO–EJ–LEE). We did not examine N feeding in combination with other interventions as this was not profitable, nor EJ as a single intervention, as this scenario has been previously documented by Cullen *et al.* (2015). Calf mortality rates in the combined scenarios were increased by 1% relative to the baseline, 3% for females and 2.5% for males, reflecting higher calf deaths from heifers joined as yearlings. Following the HO scenario, it was assumed that (1) all surplus heifers were spayed at weaning and sold aged 30 months, (2) pre- and post-mating breeder sales were reduced to 5% across all age structures, and (3) all steers were sold at 20 months old. Weaning rates for heifers joined as yearlings were 95%, in accord with cross-breeding and the HF trait (Cullen *et al.* 2015); weaning rates for older heifers and cows for the three scenarios were set to values specified in the HF scenario, and animal LW at sale followed those of the L scenario. For the scenarios that included leucaena, we assumed that steers were transported to the leucaena paddock after weaning at 5 months, and that spayed heifers were transported aged 24 months and sold aged 30 months (Table 1).

Costs, prices and gross-margin analyses

Gross-margin analyses were conducted using Breedcowplus, assuming an imputed interest of 10% of the capital value of the herd. Animal husbandry costs included those for vaccination and veterinary services (Table 2; Cullen *et al.* 2015). Sale prices received per unit LW and selling costs per animal shown in Table 3 were sourced from Cullen *et al.* (2015) and were set in accord with property management records. The percentage commission and other costs incurred at selling were set at 1.58% of the value of each animal and AU\$3.50/head for all age structures and scenarios, respectively. Bulls were purchased for AU\$5000/head. Prices per unit LW of animals grazing leucaena and pasture grasses were assigned identical values

Table 2. Annual husbandry costs for animals retained on farm or sold
Financial data are expressed in AU$ and are long-term averages from case-study farmer records (Cullen *et al.* 2015). All scenarios include costs of phosphorus and urea supplementation, except for the Nitrate scenario where costs of nitrate were substituted for costs of urea

Animal category and age in years	All scenarios except Nitrate and Leucaena scenario		Nitrate scenario		Leucaena scenario	
	Retained	Sold	Retained	Sold	Retained	Sold
Calves, <1	29.00	29.00	29.00	29.00	29.00	29.00
Heifers, 1–2	21.11	10.84	42.51	20.27	21.11	10.84
Heifers and cows, ≥3	27.16	12.92	58.83	27.99	27.16	12.92
Spayed heifers, 1–2	27.16	12.92	58.83	27.99	30.16	12.92
Steers, 1–2	18.36	8.09	39.76	17.52	21.36	8.09
Steers, 2 to <3	24.56	10.96	53.21	23.74	27.56	10.96
Bulls, all ages	22.37	0.00	22.37	0.00	22.37	0.00

Table 3. Prices received per unit liveweight, sales commission and other costs for animals sold
Financial data are long-term averages from case-study farmer records (Cullen *et al.* 2015)

Animal category and age in years	Price (AU$/kg LW[A])	Freight (AU$/head)	Total selling and freight costs (AU$/head)
Female calves, <1	1.70	4.50	14.45
Heifers, 1 to <2	1.60	4.50	16.85
Heifers, 2 to <3	1.55	8.30	22.33
Cows, ≥3	1.40	60.00	74.56
Unmated heifers, 1 to <2	1.50	60.00	71.80
Unmated heifers, 2 to <3	1.55	4.50	18.53
Unmated cows, ≥3	1.40	60.00	74.56
Male calves, <1	1.74	60.00	70.10
Steers, 1 to <2	1.74	60.00	73.67
Steers, 2 to <3	1.60	60.00	76.14
Culled bulls, all ages	1.25	60.00	79.30

[A]Liveweight at sale differed according to enterprise and scenario (see Table 1).

following abattoir data (Harrison *et al.* 2015*b*), which did not reveal significant differences in carcass attributes between grass-fed and leucaena-fed animals. Carbon offset income from Australian Carbon Credit Units under a scheme such as the Emissions Reduction Fund (DoE 2015*a*) was included where appropriate, with emissions offset in each scenario calculated relative to the emissions from the baseline herd, and with carbon mitigation income valued at AU$13.95/t of CO_2-e emissions. Since this analysis compared the gross margin and emissions of steady-state enterprises assuming farm systems were already implemented, costs and emissions associated with changing from the baseline farm using an intervention were not included. Costs incurred as part of participation in the government carbon offset scheme were valued at AU$14 000 per year on the basis of our recent work with northern cattle farmers and the beef industry, assuming that farmers would complete an annual statement outlining activities performed and compliance with GHG abatement methodologies. Carbon offset income and related costs were included for all scenarios except for the HO, LEE and HO–HF–EJ–LEE scenarios; the HO scenario was designed for improving the ratio of costs to net sales, while the LEE scenarios assumed equal emissions with the baseline farm. Urea lick blocks were costed at AU$1000/t as fed (M. Callaghan, pers. comm.). For the 182 days of the dry season, this resulted in costs of AU$0.09–AU$0.16/head.day for animals retained for the whole year (AU$18–AU$27/head.year) and AU$0.09–AU$0.14/head.day for animals sold (AU$8–AU$13/head.year). Nitrate supplementation was assumed in the form of molasses calcium nitrate lick blocks with a cost of AU$1100/t. The N-supplementation scenario resulted in costs of AU$0.19–AU$0.34/head.day for animals retained for the whole year (AU$40–AU$59/head.year) and AU$0.19–AU$0.31/head.day for animals sold within the year (AU$18–AU$28/head.year). Animals finished on leucaena were drenched with a probiotic containing bacteria, allowing breakdown of the toxic amino acid mimosine. Following commercial guidelines, animals required only one drenching; drench costs were valued at AU$3.00/head (QLD 2015). Other animal husbandry costs are given in Table 2.

Whole-farm GHG emissions and emissions intensities

Whole-farm GHG emissions were estimated using the Beef Greenhouse Accounting Framework (B-GAF; see http://www.greenhouse.unimelb.edu.au/Tools.htm, verified 10 December 2015, and Browne *et al.* 2011) which uses Australian National Greenhouse Gas Inventory methods prescribed by the DCCEE (2014). GHG emissions included those from soil carbon sequestration and livestock (enteric and manure methane, urine, dung and indirect emissions from ammonia volatilisation as well as organic nitrogen leaching and runoff), but not emissions associated with electricity or diesel. Whole-farm emissions intensities were computed as the dividend of annual net farm GHG emissions and annual meat sales from all stock (t CO_2-e/t LW sold). No change in nitrous oxide emissions associated with nitrate feeding was assumed because the N scenario was computed at isonitrogenous rates with the baseline.

Results

When urea supplements were replaced with calcium nitrate (N in Table 4), livestock production was unchanged, but enteric methane and emissions intensity were reduced by 4%. The high cost of the nitrate supplement relative to urea resulted in a 37% reduction in gross margin, despite a carbon-offset income of AU$2025/year.

The enterprise with the L scenario had fewer animals than the baseline because individuals were larger, and the requirement to maintain stocking rates (adult equivalents) meant that total LW turnoff of the L scenario was similar to that of the baseline (Table 4, Fig. 3). The gross margin of the L scenario was AU$7399 greater than that of the baseline, largely due to higher LW turnoff but also a 12–14% reduction in net farm emissions and emissions intensity. Emissions of the L scenario were reduced due to enteric methane mitigation and SOC sequestration, even though nitrous oxide emissions were 11% greater than the baseline.

When stocking rates of the L scenario were increased to match net emissions with those of the baseline under the premise that leucaena pastures support more animals than do pastures containing lower-quality grasses (Shelton and Dalzell 2007), there was an increase in animals carried by 2% and annual LW turnoff by 8% or 19 t (LEE, Table 4, Fig. 3). More animals in the LEE scenario increased herd capital value and direct costs, but higher costs were more than offset by additional LW turnoff, which increased gross margin by AU$24 200. Emissions intensity of the LEE scenario was 8% lower than that of the baseline.

Herd optimisation (HO) resulted in fewer adult breeders retained on farm and a higher proportion of animals sold, which increased the number of weaners per cow mated by 5% and reduced the capital value of the herd by 4% (Table 4, Figs 1–3). Despite a 6% increase in costs, these attributes increased gross margin by 40%, to AU$203 785. Since HO did not reduce net emissions and had little effect on the total LW turnoff, emissions intensity was similar to that of the baseline.

Herds with HF females (Table 4) had fewer adult breeders than the baseline to balance higher weaner numbers and to maintain constant stocking rate (Fig. 2). The HF scenario increased total LW turnoff by 9% as a result of more than 30% increases in sales of weaners, steers and heifers (Fig. 3). Reducing the number of adult cattle on farm for the whole year was also beneficial from an emissions perspective; this management change reduced enteric methane by 3% and emissions intensity by 10%, resulting in a small carbon offset income of AU$1213. The high number of steers and heifers sold in the HF scenario resulted in the greatest increase in gross margin of any single intervention applied to the base farm (48%, Table 4).

Combining the HO strategy with enterprises running HF females and joining heifers as yearlings (HO–HF–EJ) had a similar effect as the HF intervention on animals sold, increasing steer and heifer sales by more than 30%. A key difference of the HO–HF–EJ scenario from the HF scenario was that LW increased due to sales of both steers and spayed heifers in the former (25% and 44%, respectively, relative to the baseline), whereas the additional LW turnoff in the HF scenario was attributed to increased sales of steers and weaners (Fig. 3). Relative to the baseline, total LW sold and gross margin of the HO–HF–EJ scenario increased by 22% and emissions intensity was reduced by 20% (Table 4).

Where leucaena was used with the HO–HF–EJ series of interventions, the total number of cattle carried was reduced by 5% relative to the baseline due to higher LW (Fig. 3, Table 4). The HO–HF–EJ–L adaptation significantly reduced adult breeder numbers, resulting in a 60% reduction in cow LW sales, since all heifers that were surplus to the number required to maintain adult breeders were paddocked separately pre-mating and sold aged 30 months (Fig. 3). The corollary of greater heifer sales as well as higher LW turnoff of steers was a 29% increase in total LW sold (304 t LW/year, Table 4). Gross margin was increased due to the relatively high carbon offset income associated with GHG mitigation caused by leucaena (more than AU$6000); this value was the highest offset income of all adaptations examined. The collective benefits of lower costs, higher sales and GHG mitigation of the HO–HF–EJ–L adaptation resulted in an 85% increase in herd gross margin (Table 4).

When net farm emissions of the HO–HF–EJ–L intervention were matched with the baseline to facilitate higher stocking rates afforded by leucaena–grass pastures, gross margin further increased to AU$314 755, such that the gross margin of the HO–HF–EJ–LEE enterprise was over 100% greater than the baseline gross margin. Increases of more than 40% in steer and heifer sale numbers resulted in a 47% greater total LW turnoff than the baseline. Increasing the numbers of animals sold relative to total breeders mated meant that direct costs were 30% more than the baseline, but this was more than compensated for by an increase in net cattle sales.

For the N, L, LEE and HF scenarios and across all female ages, the number of breeding females sold annually was greater than that of scenarios with the HO intervention, primarily because more mated cows were sold between 2 and 10 years old in the former scenarios (Fig. 1). This resulted in a greater LW turnoff of breeding heifers and cows in the N, L, LEE and HF scenarios, and conversely, greater sales of unmated females in scenarios with the HO intervention (cf. Figs 1, 3).

There was little concordance between either net emissions, LW production or emissions intensity with gross margin when individual interventions were applied to the base farm (Points 1–6 in Fig. 4), but linear relationships emerged when multiple interventions were applied to the baseline farm system (Points 7–9 in Fig. 4). Concomitant introduction of several interventions increased LW production, increased gross margin, and reduced emissions intensity (adjusted R^2-value for the relationships between emissions intensity or total LW sold, with gross margin increasing from 0.00 to 0.49 and from 0.00 to

Table 4. Annual values of livestock carried on farm or sold, economics and greenhouse gas emissions of an extensive beef enterprise in central Qld, Australia

Alternative farming-system scenarios included nitrate lick supplementation (N) or leucaena grazing (L), optimisation of herd age structure (HO), higher fecundity (HF) females, earlier joining (EJ) of maiden heifers or a combination of interventions. The stocking rate for each scenario was matched with that of the baseline for equivalence, except for the two leucaena 'equal emissions' scenarios (LEE and HO–HF–EJ–LEE) that matched net farm emissions with those of the baseline under the assumption that leucaena systems permit higher stocking rates

Parameter	Baseline	Nitrates (N)	Leucaena (L)	Leucaena equal emissions (LEE)	Herd optimisation (HO)	High fecundity (HF)	HO–HF–EJ	HO–HF–EJ–L	HO–HF–EJ–LEE
Animal numbers and weaning rates									
Total adult equivalents	1750	1750	1750	1843	1750	1750	1750	1750	1992
Total cattle carried	1809	1809	1751	1844	1767	1762	1799	1721	1959
Weaner heifers retained	283	283	274	289	175	257	146	140	159
Total breeders mated	982	982	950	1001	932	889	866	829	943
Total calves weaned	567	567	549	578	586	739	742	710	808
Total cows and heifers sold	254	254	246	259	264	343	339	324	369
Total steers and bullocks sold	279	279	270	284	289	363	362	346	394
Weaners/total cows mated (%)	58	58	58	58	63	83	86	86	86
Liveweight sales (t LW)									
Heifers	7.0	7.0	6.8	7.2	9.7	6.4	10.1	10.4	11.8
Cows	118.8	118.8	114.9	121.1	63.3	107.6	49.7	47.6	54.1
Spayed or surplus females	0.0	0.0	0.0	0.0	48.6	0.0	91.9	98.3	111.9
Steers	106.8	106.8	117.5	123.7	106.8	139.1	133.9	145.4	165.5
Bulls	3.0	3.0	2.9	3.0	2.8	2.7	2.6	2.5	2.9
Total liveweight sold	236	236	242	255	231	256	288	304	346
Economics (AU$)									
Average female price	627	627	627	627	809	550	898	689	689
Capital value of herd	1 018 622	1 018 622	1 021 800	1 076 101	973 656	968 216	935 273	949 823	1 081 170
Net cattle sales	322 332	322 332	335 966	353 820	378 156	401 117	510 844	450 605	512 917
Direct costs excluding bulls	53 775	95 899	52 136	54 907	56 912	56 375	62 757	61 300	69 776
Carbon offset income	0	2025	5769	0	0	1213	975	6334	0
Costs/net sales (dimensionless)	0.17	0.30	0.16	0.16	0.15	0.14	0.12	0.14	0.14
Gross margins including carbon offset income	145 589	91 490	152 988	169 799	203 785	216 013	322 905	268 837	314 755
Gross margin per adult equivalent	83	52	87	92	116	123	185	154	158
Greenhouse gas emissions (t CO_2-e)									
CH_4 – enteric	3165	3020	3133	3523	3168	3079	3093	3036	3456
N_2O – indirect	49.9	49.9	55.9	63.0	50.1	49.6	50.6	74.7	85.1
N_2O – dung, urine	111.5	111.5	123.9	139.3	111.9	110.7	112.9	162.3	184.8
Net farm emissions	3425	3280	3012	3424	3429	3338	3355	2971	3424
Emissions intensity (t CO_2-e/t LW sold)	14.5	13.9	12.4	13.4	14.8	13.1	11.6	9.8	9.9

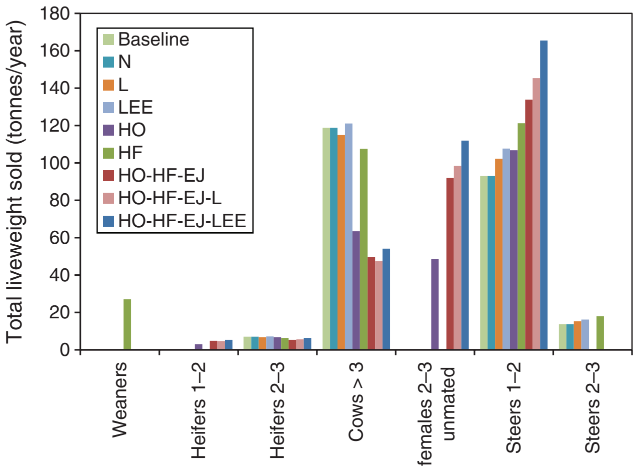

Fig. 3. Total liveweight sold annually from each herd category for the baseline farm and eight alternative farming system scenarios. Unmated females were paddocked and sold separately to breeding females. Abbreviations are defined in Table 1.

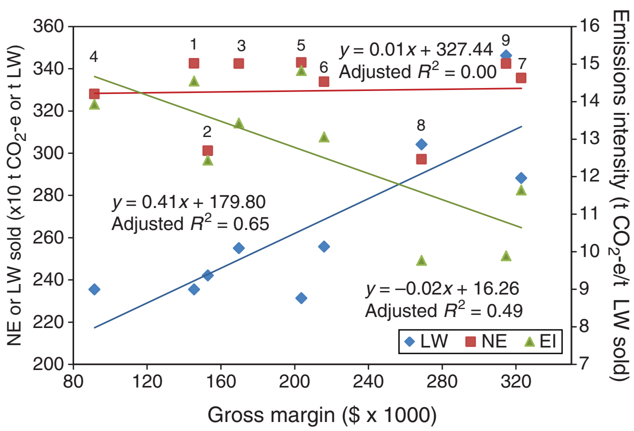

Fig. 4. Relationships between net farm emissions (NE), liveweight sold (LW) and emissions intensity (EI) with gross margin for the baseline farm and eight alternative farm system scenarios. Numbers above data points represent each scenario, with 1 = baseline, 2 = leucaena (L), 3 = leucaena equal emissions (LEE), 4 = nitrates (N), 5 = herd optimisation (HO), 6 = high fecundity (HF), 7 = HO–HF–EJ, 8 = HO–HF–EJ–L and 9 = HO–HF–EJ–LEE. Lines are regressions of best fit between each ordinate variable and gross margin.

0.65, respectively), underscoring the benefits of implementing several adaptations.

Discussion

Combining interventions can achieve the greatest gains in gross margins and reductions in emissions intensity

The most fundamental result of this study was that individual interventions would not appear to achieve the magnitude of the benefits in LW production, gross margin and emissions intensity realised when using multiple compatible interventions. In cases where single interventions achieve beneficial changes in all three metrics, the magnitude of change tended to be much smaller than when combined interventions were applied. For instance, farm systems with leucaena (L) had the lowest emissions intensity of any single intervention (L in Table 4), but did not have the highest gross margin. However, when L farming systems were combined with systems that also had HF females and joined heifers as yearlings (HO–HF–EJ), not only was emissions intensity further reduced but gross margin was greater than that of any single intervention. Such effects occurred because combined interventions improve a farm system at several different biophysical points or via different economic pathways. In this case, farm systems with L increased LW gain and reduced emissions, farm systems with HF and EJ of females increased gross margin and LW turnoff, and farm systems that optimised herd structure reduced their cost to sale ratios (Table 4). Together, the three interventions increased LW turnoff, reduced emissions and increased gross margin.

The magnitude of benefit gained from combined interventions would be contingent on the farm system analysed, including enterprise structure, herd management, sale prices, prevailing climate and forage species. The present study was conducted as a static analysis using records from the case-study farm averaged over several years, but realistically, the vicissitudes of climate would vary the production and the extent of GHG mitigation caused by different interventions over time, and similarly changes in the cost–price ratio may change the relative ranking of gross margins across interventions. Nonetheless, previous studies support and provide confidence in our results. Beauchemin *et al*. (2011) conducted an 8-year life-cycle assessment (LCA) of a beef production system with progeny fattened in a feedlot, accounting for CO_2 emissions from both on and off farm sources. They found that 80% of emissions were from the cow–calf system that allowed grazing of the native prairies, whereas only 20% of emissions were from the feedlot system. Beauchemin *et al*. (2011) showed that individual strategies reduced emissions intensity by up to 8%, but, by combining several additive intervention strategies, such as feeding oilseeds, improving forage quality and improving weaning rates, a 17% reduction in LCA emissions intensity was possible. In contrast to the breeding system, strategies applied to the feedlot only had a small impact on GHG emissions, reducing emissions intensity by less than 2% when applied individually or by 3–4% when applied in combination. In a study of intensive pasture-based dairy systems in New Zealand, Beukes *et al*. (2010) used a partial LCA and 3 years of climate data and found that emissions could be reduced by up to 27% for constant production when several mitigation strategies were imposed. These differences highlight the fact that although combined interventions can achieve improvements in emissions intensity, the magnitude of improvement clearly depends on the enterprise structure.

We also demonstrated a discordance between changes to farm systems designed for increasing gross margin or for GHG mitigation. If the farm system intervention is designed to increase gross margin, for example, by increasing the proportion of animals sold to those retained on farm and increasing the ratio of sales to costs (Table 4), then systems that result may have similar or higher emissions intensity and net emissions, than the baseline (cf. HO and baseline in Table 4). However, if a change to the farm system is designed for maximising mitigation, then systems that are capable of several alternative types of

GHG mitigation across the soil–plant–animal nexus are most preferable, such as L scenario, which mitigates enteric methane emissions and increases SOC sequestration. The disparity between farming-system optimisation for gross margin or for GHG mitigation is highlighted by comparison of the L system with the same system with greater animal numbers, so as to match baseline emissions (cf. L with LEE in Table 4). Where the LEE scenario resulted in 17% greater gross margin than the baseline, there was no GHG mitigation; in contrast, the L scenario reduced net emissions and emissions intensity by 12% and 14%, respectively, but only achieved a 5% greater gross margin than the baseline.

Increasing the number of animals sold relative to animals retained for the whole year can break the strong positive association between production and emissions

Reduced emissions intensity can be achieved only by decoupling emissions from production, which, in most cases, is a strong and positive association. This means that increasing production from livestock systems almost inevitably results in increased emissions (Harrison *et al.* 2014*a*). Of the interventions examined here, increasing the number of animals sold relative to adults retained on farm for the whole year decoupled the emissions–production linkage, increased gross margins and reduced emissions intensity. We demonstrated that increasing the number of juvenile stock sold relative to the number of adults retained on farm can be achieved through changes to herd characteristics, such as adoption of HF breeders. Reducing the number of adult breeders by increasing female fecundity (HF) was clearly beneficial from an emission perspective, with the strategy reducing enteric methane by 3% and emissions intensity by 10%. This result parallels findings shown by others for farming systems that improve female fecundity (Bentley *et al.* 2008; Harrison *et al.* 2014*b*; Alcock *et al.* 2015). If stocking rates are maintained, females with higher fecundity have more offspring, which reduces the ratio of adult to juvenile animals (Harrison *et al.* 2014*a*, 2014*b*). Since growing animals have a lower bodyweight than do adults, fewer emissions are produced per unit LW gain because whole herd energy use is shifted towards growth and away from maintenance (Harrison *et al.* 2014*a*). Although the HF system resulted in small carbon offset income (AU$1213), the 48% increase in gross margin of this system was largely attributable to greater turnoff of steers and weaners (Table 4, Fig. 3).

Weaning rates from second- and third-year heifers in the HF scenario were 86% and 90%, respectively (Table 1), using data from the case-study farm reported in Cullen *et al*. (2015). These values were attained via crossbreeding to achieve early puberty, as well as female culling based on fertility. However, weaning rates from cattle in extensive regions in Qld are typically lower. Farm survey data for second-lactation heifers and cows older than 5 years found weaning rates of between 62–67% and 67–77%, respectively (McGowan *et al.* 2014*a*, 2014*b*). Major factors determining whether cows became pregnant within 4 months of calving included country type (region), calving time, body condition score between pregnancy and weaning, cow age, phosphorus deficiency and pasture quality (Fordyce *et al.* 2014; McGowan *et al.* 2014*a*, 2014*b*). Realistic target weaning rates for tropically adapted cattle in northern Australia in average or high-rainfall years are ~80% (McGowan and Holroyd 2008), but this may reach 90% in extremely good seasons with excellent management (McGowan *et al.* 2014*b*). These data suggest that the case-study farm used in the HF scenario achieved high weaning rates relative to regional averages, and a future iteration of our modelling could examine the impact of a range of weaning rates on the relationship between gross margins and emissions intensities.

Comparable results to those of past work lends credence to our assumptions about well managed HF beef breeds in rangeland environments. At Boulia in western Qld, Cullen *et al*. (2015) showed that for a constant stocking rate, herds with high fertility increased beef LW turnoff and reduced emissions intensity by 12%, similar to the increase in LW turnoff and reduction in emissions intensity found here. In the Barkly Tablelands of the Northern Territory, Bentley *et al*. (2008) showed that increasing the weaning rates from 55% to 80% by changing from shorthorn to composite breeds reduced methane emissions per unit of beef LW weaned by 31%. An LCA study by Eady *et al*. (2011) in northern Australia reported emissions-intensity values ranging from 17.5 to 22.9 t CO_2-e/t LW and from 11.6 to 15.5 t CO_2-e/t LW for two farms in which weaners or finished steers were the primary product, respectively. Our baseline and HF emissions-intensity values (14.5, 13.1 t CO_2-e/t LW, respectively) fall on the lower side of these values because Eady *et al*. (2011) computed their values based on 'cradle-to-farm gate' scenarios that included more sources of emissions than in our study, such as pasture burning and pumping water.

Changes to herd structure by increasing sale numbers of young stock relative to adults retained for the whole year can reduce the ratio of costs to net sales, which can benefit gross margins (Table 4). We increased animal sales by selling steers at a younger age, by selling all surplus weaner heifers, and by reducing pre- and post-mating sales of female breeders. Together these changes reduced herd capital value, breeder numbers and opportunity costs, and also increased net cattle sales. Clearly, there would be other alternatives to optimising herd structure, particularly if the enterprise specialisation differed from the farm used as a case study here. However, not all changes to herd structure that increase the ratio of juveniles sold to adults retained on farm can achieve both increased gross margins and reduced emissions intensity, as demonstrated by the HO intervention. Livestock producers attempting to increase gross margin and reduce emissions would do better to consider other options, such as improving pasture quality or animal growth efficiency through genetic gain (Beukes *et al.* 2010; Ash *et al.* 2015).

There could be other risks associated with the HO intervention that were not considered here. Although the HO scenario reduced the turnover rate of cows in the breeding herd, the average age of the herd increased relative to the baseline, which could result in a trend towards an older breeder herd. Further, the freight costs used in all scenarios were lower for younger animals, a circumstance that in reality may not reflect all enterprises. We adopted these costs from the case-study farm records reported in Cullen *et al*. (2015; Table 3); however, it is plausible that transporting younger stock could erode profit margins because transport cost per unit LW is lower for mature animals.

Leucaena as a farming system for enhancing gross margin and reducing emissions intensities

Farm systems that implemented grazing of leucaena had substantive benefits above those of the baseline with respect to not only emission mitigation and reduced emissions intensity, but also gross margins. This indicates that forage systems capable of both GHG mitigation and enhanced LW gain via higher nutritional quality deserve further attention in extensive beef enterprises. Our analyses attributed costs associated with drenching cattle with an inoculum to prevent toxicity after ingesting leucaena forage, but did not assume other costs associated with clearing land, maintaining or renovating leucaena plantations. Nonetheless, past literature also suggests that grazing systems incorporating leucaena tend to be more profitable than those based purely on rangeland grasses (Shelton and Brewbaker 1998; Shelton and Dalzell 2007; Harrison *et al.* 2015*b*), supporting the results found here. In essence, leucaena provided a forage source that was both more nutritive, sequestered more carbon, and resulted in lower enteric methane emissions than did rangeland grasses, and in combination these characteristics increased LW turnoff and gross margin, while reducing net emissions.

The 14% reduction in emissions intensity in the L scenario was due to enhanced LW gain as well as enteric methane mitigation and SOC sequestration. This figure is less than the 24% reduction in emissions intensity attributed to grazing of leucaena in other studies of extensive beef enterprises (Harrison *et al.* 2015*b*) but confirms past reports of greater beef turnoff attributed to leucaena systems in these environments (Shelton and Brewbaker 1998; Galgal *et al.* 2006; Shelton and Dalzell 2007). The concurrent benefits in emission mitigation and economic value realised by this farming method suggests that other forage types suitable for grazing in subtropical regions are worthy of investigation, with particular focus on those capable of enteric methane mitigation, carbon sequestration, or both. This is even more relevant for forages with relatively high CP content that may increase productivity but that may also increase nitrous oxide emissions, as observed here with leucaena. For example, Kennedy and Charmley (2012) showed that cattle fed diets of either Rhodes grass (*Chloris gayana*) and leucaena or Rhodes grass and Burgundy bean (*Macroptilium bracteatum*) had a similar enteric methane production per unit DMI, but Burgundy bean had a lower CP content. Cattle fed diets of Burgundy bean had lower concentrations of rumen ammonia, suggesting that nitrous oxide production from Burgundy bean would be less than that of leucaena. Nevertheless, although nitrous oxide production from the leucaena system was 12% greater than that from the baseline, net farm emissions from the leucaena system were still 12% lower than the emissions from the baseline, due to reduced enteric methane emissions and SOC sequestration. This highlights the fact that interventions that reduce enteric methane have the greatest influence on net farm emissions because enteric methane dominates farm emission profiles (e.g. Beauchemin *et al.* 2011; Harrison *et al.* 2015*a*).

Scenarios that increase production and maintain net farm emissions are more profitable than scenarios that maintain production and reduce emissions

We compared the influence of scenarios that were grazed at the same stocking rate as the baseline (L, HO–HF–EJ–L) with the influence of scenarios that increased stocking rates such that net emissions were equal with the baseline (LEE, HO–HF–EJ–LEE; Table 4). For combined interventions, systems with leucaena had 5% greater stocking rates and gross margin than did the baseline, indicating that farmers would be better positioned from an economic perspective to focus on increasing production rather than focussing on emission mitigation.

Our assumption that leucaena can carry up to 5% higher stocking rates is highly conservative and well within the stocking pressure that leucaena can sustain above typical pastures that grow in subtropical regions. We assumed that the leucaena block was located near Rockhampton (Qld), a region that has an average annual rainfall and temperature range of 800 mm and 17−28°C, respectively, and fertile clay soils. In subtropical Qld regions with these environmental characteristics, leucaena receiving 600 mm rainfall per year has been estimated to support 1.2–1.6 AE/ha.year, greater than the 0.67–0.8 AE/ha.year range reported for well managed perennial grass pastures in comparable agroclimatic districts (Johnston 1997; Dalzell *et al.* 2006; Shelton and Dalzell 2007; Bowen *et al.* 2015). These values imply that the leucaena finishing block modelled here would be capable of supporting the increased cattle numbers assumed in the L scenarios with stocking rates higher than the baseline (LEE scenarios, Table 4).

Crediting farmers for reductions in emissions intensity

We computed carbon offset income as the reduction in net farm emissions of the scenario with the intervention, relative to the baseline emissions. An alternative approach could have been to compute offset income as the change in emissions intensity. This method would credit farmers who invoked interventions that enabled production of a set amount of beef with fewer emissions than from the same amount of beef produced during a historical reference period for the baseline herd; indeed, such methods are the basis of the Australian Beef Cattle Herd Management methodology (DoE 2015*b*). A payment scheme based on emissions intensity rather than net emissions would mean that all interventions examined here (except the HO scenario) would qualify for credits, including the L scenarios with net emissions equal to the baseline.

Feeding nitrates for GHG emission mitigation

The carbon offset income resulting from nitrate feeding was less than 2% of the gross farm income for the N scenario. This income was minimal compared with the more than doubling of gross margin in the combined interventions. We did not analyse a scenario with nitrate feeding in combination with one or more other interventions, because the cost of nitrate was prohibitively expensive compared with the cost of urea. On the basis of the formulation and manufacturing costs of molasses calcium nitrate lick blocks, it is likely that commercial quantities of nitrate could be sold at a market price similar to that of existing urea blocks. However, the comparatively lower N concentration in the block formulation dictates that daily consumption must be 2.1 times the intake of urea blocks to achieve an equivalent N intake (Callaghan *et al.* 2014). The gross margin of the N scenario was 37% ($54100) less than that of the baseline, despite more than AU$2000 in carbon offset income. This demonstrates that the cost of supplementing rangeland cattle with nitrates primarily to secure carbon offset income would mean paying ~27 times more for the implementation than the gross offset income would generate. Clearly, feeding nitrates to beef cattle would not be an economic proposition, unless the primary driver of non-protein nitrogen adoption was to redress a protein deficiency, with the offset income being a secondary consideration.

Conclusions

We showed that application of several additive interventions to a farm system can result in concordant benefits of increased LW production, reduced emissions intensity and greater gross margin. Indeed, there was little association between either LW turnoff and emissions intensity as a function of gross margin when each regression included only single interventions. In contrast, significant relationships between LW or emissions intensity with gross margin emerged when combinations of interventions were included in each regression. This finding is a win–win for farmers and industry, since it implies that imposing several beneficial and additive interventions to beef farming systems can successively increase gross margin and reduce emission intensity. Our study assumed that interventions were already in place and that each scenario had been previously established, so these outcomes would differ if producers actively transitioned their baseline system by imposing one or more interventions. This study also underscored the financial benefits associated with adopting interventions that benefit production over interventions that mitigate emissions, as shown by scenarios that maintained stocking rate and reduced emissions compared with scenarios that maintained emissions and increased stocking rate. Adopting farming practises that improved animal production relative to the number of breeding animals retained on farm and inhibited enteric methane production achieved much larger reductions in emissions intensity than did supplementing animal diets with nitrate.

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