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# Methods and consequences of including reduction in greenhouse gas emission in beef cattle multiple-trait selection

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## Abstract

**Background:** Societal pressures exist to reduce greenhouse gas (GHG) emissions from farm animals, especially in beef cattle. Both total GHG and GHG emissions per unit of product decrease as productivity increases. Limitations of previous studies on GHG emissions are that they generally describe feed intake inadequately, assess the consequences of selection on particular traits only, or examine consequences for only part of the production chain. Here, we examine GHG emissions for the whole production chain, with the estimated cost of carbon included as an extra cost on traits in the breeding objective of the production system.

**Methods:** We examined an example beef production system where economic merit was measured from weaning to slaughter. The estimated cost of the carbon dioxide equivalent (CO<sub>2</sub>-e) associated with feed intake change is included in the economic values calculated for the breeding objective traits and comes in addition to the cost of the feed associated with trait change. GHG emission effects on the production system are accumulated over the breeding objective traits, and the reduction in GHG emissions is evaluated, for different carbon prices, both for the individual animal and the production system.

**Results:** Multiple-trait selection in beef cattle can reduce total GHG and GHG emissions per unit of product while increasing economic performance if the cost of feed in the breeding objective is high. When carbon price was \$10, \$20, \$30 and \$40/ton CO<sub>2</sub>-e, selection decreased total GHG emissions by 1.1, 1.6, 2.1 and 2.6% per generation, respectively. When the cost of feed for the breeding objective was low, selection reduced total GHG emissions only if carbon price was high (~\$80/ton CO<sub>2</sub>-e). Ignoring the costs of GHG emissions when feed cost was low substantially increased emissions (e.g. 4.4% per generation or ~8.8% in 10 years).

**Conclusions:** The ability to reduce GHG emissions in beef cattle depends on the cost of feed in the breeding objective of the production system. Multiple-trait selection will reduce emissions, while improving economic performance, if the cost of feed in the breeding objective is high. If it is low, greater growth will be favoured, leading to an increase in GHG emissions that may be undesirable.

## Background

Concern about global warming has focussed attention on reducing greenhouse gas (GHG) emissions from farm animals [1, 2], particularly in beef cattle [3, 4]. An important aim of animal breeding is to improve the economic productivity of animals. In the absence of improvements

in feed efficiency, productivity gains are often associated with increases in feed intake, which are associated with increased overall GHG emissions [5] and GHG emissions per unit of product [6].

Many studies have shown that a reduction in GHG emissions can be achieved via breeding [6–8]. Wall et al. [7] examined strategies that can be applied in UK livestock. Quinton et al. [6] reported that decreases in total GHG emissions and GHG emissions per unit of product accompanied increases in productivity in beef cattle.

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Many of the GHG emission studies described in the literature have limitations, i.e. they use breeding objectives that inadequately specify feed intake, assess the consequences of breeding for a particular trait only, or examine the effect of productivity improvement on emissions for only part of the production chain.

In this article, we present multiple-trait selection strategies for reducing GHG emissions in beef cattle for the whole production chain from weaning to slaughter. We focus on reducing GHG emissions that are associated with feed intake, since criteria for reducing emissions independently of feed intake (referred to as residual GHG emissions) are still under development. We evaluate the outcomes and consequences of reducing emissions at the level of both the individual animal and the production system, by incorporating different levels of carbon price in the breeding objective. We also examine the consequences at different levels of feed cost, since this was shown earlier to be a major factor affecting the ranking of beef cattle for economic merit [9].

**Methods**

**Definitions**

Animal breeding is principally concerned with improving breeding value for net merit, which is usually expressed in economic terms. Commonly, the selection criterion is an index of estimated breeding values (EBV)  $\hat{\mathbf{u}}$  that are available for an industry [10, 11]. The genetic variance-covariance matrix for deriving the index has partitions  $\mathbf{G}_{11}$  for variances and covariances among EBV in the index,  $\mathbf{G}_{22}$  for variances and covariances among traits in the breeding objective, and  $\mathbf{G}_{12} (= \mathbf{G}'_{21})$  for covariances between the EBV criteria and the traits of the objective [12]. Values for the breeding objective traits for animal  $i$  are estimated as  $\hat{\mathbf{g}}_i = \mathbf{G}_{21}\mathbf{G}_{11}^{-1}\hat{\mathbf{u}}_i$  [9]. When the index is linear, weights for the EBV of the index are derived as  $\mathbf{b} = \mathbf{G}_{11}^{-1}\mathbf{G}_{12}\mathbf{v}$ , where  $\mathbf{v}$  are economic values of the breeding objective traits. The index is commonly derived as  $\mathbf{b}'\hat{\mathbf{u}}_i$ , but it can be equally derived as  $\mathbf{v}'\hat{\mathbf{g}}_i$ .

**The commercial production system**

The commercial production system that underlies the breeding objective in beef cattle can be pasture-based or grain-based, or it can include a mix of both systems post-weaning. In the example taken for this article, pasture-raised steers and surplus heifers are finished on grain for 100d and slaughtered at 22 months of age (Table 1). In grazing systems, there are two types of annual feed period—i.e. a period when the available feed is limited, meaning any increase in feed requirement will require additional feed to be supplied, and a period when additional feed is not needed because the available feed in that period is surplus to the animal's

**Table 1 Key characteristics for the example self-replacing beef cattle production system producing 100-d feedlot finished steers**

Characteristic	Value
Calendar	
Month of joining	Oct
Start month of limited feed period <sup>a</sup>	Jan
End month of limited feed period	Sept
Carbon price	
Price of carbon, \$/ton CO <sub>2</sub> -e	20
Young animals	
Age at weaning, m	7
Growth rate at pasture in limited feed period (relative to surplus feed period), - 1.0 to 1.0	0.7
Cost of extra feed at pasture, \$/ton	130
Quality of extra feed at pasture, MJ/kgDM	8
Period of feedlot finishing, d	100
Steer live weight at feedlot entry, kg	450
Cost of extra feedlot feed, \$/ton	270
Quality of extra feedlot feed, MJ/kgDM	10
Age at finished sale, m	22
Steer live weight at finished sale, kg	640
Finished steer sale price, cents/kg carcass	456
Cows (averages)	
Weaning %	85
Weight loss from calving to joining, kg	50
Live weight at joining, kg	650
Mean condition score at joining <sup>b</sup>	3-
Min. acceptable condition score at joining <sup>b</sup>	2+
Max. acceptable condition score at joining <sup>b</sup>	4+
Cost of extra cow feed, \$/ton	130
Quality of extra cow feed, MJ/kgDM	8
Live weight of surplus cows, kg	550
Sale price for surplus cows, \$	990

From the example used by Barwick et al. [9], with carbon priced at \$20/ton CO<sub>2</sub> equivalent

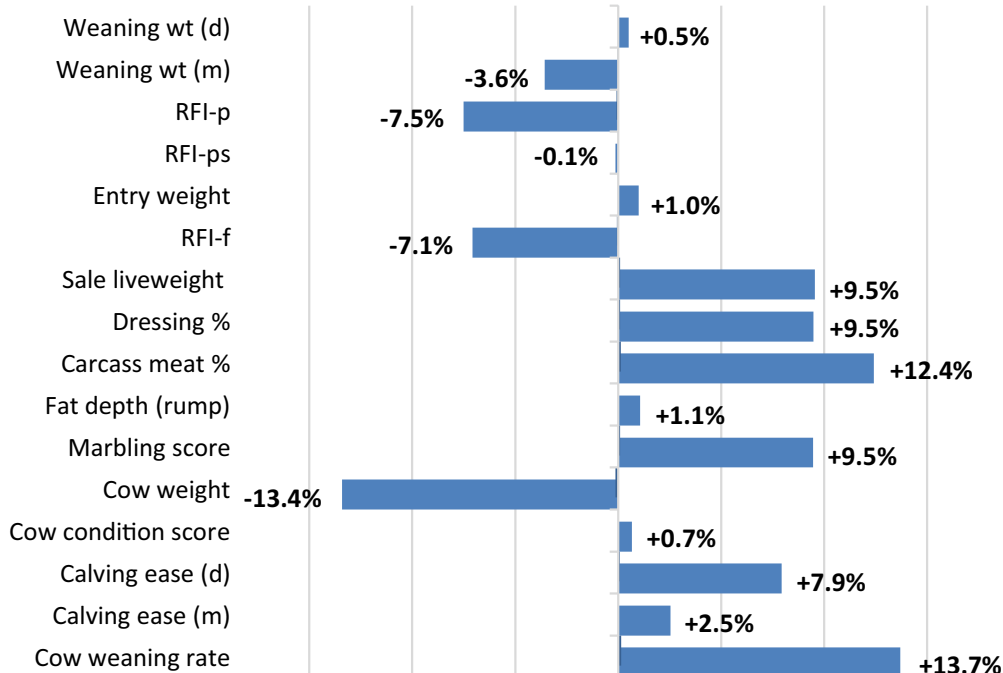
<sup>a</sup> All of the year except when surplus feed is available

<sup>b</sup> Scored on a 15-point scale from 1 - (emaciated) to 5 + (obese)

needs. In the latter case, we consider that the cost of feed is zero since no additional feed is needed. In all other cases, the feed cost is considered non-zero.

**Breeding objective**

The breeding objective examined here is net return per cow (i.e. returns net of all feed and management costs), which was assessed over the period from weaning to sale of the finished animal. Traits in the breeding objective are those that directly influence commercial production profitability. In this study, these are weaning weight (direct and maternal), residual feed intake (RFI)



**Fig. 1** Economic importance of breeding objective traits for the example of beef cattle production system in Table 1<sup>a-c</sup>. <sup>a</sup>Units are the value of a standard deviation of trait change relative to the value of a standard deviation of change in all breeding objective traits [9], <sup>b</sup>Carbon priced at \$20/ton CO<sub>2</sub>-e, <sup>c</sup>GHG emissions are assumed associated with RFI traits)

at pasture when pasture is limited, RFI at pasture when the feed available is surplus to the animal’s needs, feedlot entry liveweight, RFI in the feedlot, sale liveweight, dressing percentage, saleable meat percentage, fat depth (on the rump), marbling score, cow liveweight, cow condition score, calving ease (direct and maternal) and cow weaning rate. The economic importance of these traits is illustrated in Fig. 1 for the example beef cattle production system taken in our study. The economic importance of traits is calculated as:

$$(v_i \sigma_{Gi} / \sum |v_i \sigma_{Gi}|) \times 100,$$

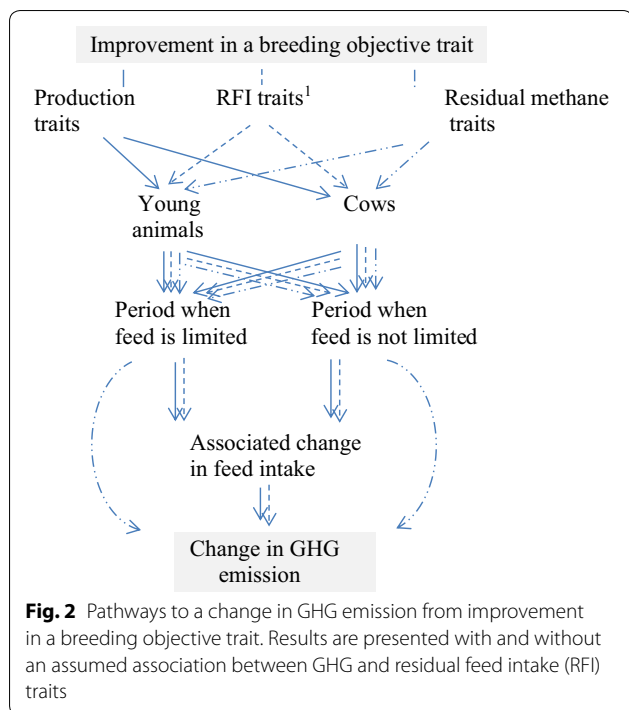
where  $v_i$  are the trait economic values and  $\sigma_{Gi}$  are the genetic standard deviations for the  $i$ th trait of the breeding objective [12]. Economic importance for each trait is expressed as a percentage of the sum of the absolute values of the product for all traits [11]. Economic importance encompasses both the economic value of traits and the genetic variation that is available for each trait in the production system. The cost of the additional feed needed for a change in these traits is included in the economic values of the traits that influence feed requirement. Changes in feed requirement are assessed using the equation systems of Freer et al. (see Chapter 1 of [13]). Residual feed intake traits describe differences in

feed intake that occur at the same weight and weight gain of animal.

The possible pathways to changes in emissions for a production system are in Fig. 2. Emissions commonly change when a trait in the breeding objective is improved, including when there is a change in either the residual GHG traits or the RFI traits. The cost of the increased carbon in the emissions is incorporated in the economic values of the breeding objective traits. Residual GHG traits are not considered in the described example because criteria for these are not yet available. Most reports suggest that GHG emissions decrease when RFI traits decrease [14–16]. However, Herd et al. [17] suggests that GHG emissions could increase when RFI decreases if, for example, the digestibility of the diet also increases. Because of the uncertainty surrounding this aspect, we present results with and without an assumed association between changes in RFI traits and GHG emission.

**Estimation of the cost of GHG emissions for breeding objective traits**

When decreasing GHG emissions is part of the breeding objective, the cost of increasing emissions is included in the economic value determined for each breeding objective trait, according to the following steps:



- Estimation of the change in feed needed as a consequence of change in the breeding objective trait.
- Estimation of the change in methane emissions associated with the change in feed, and augmentation of this to account for the increase in non-methane GHG emissions for any period during which cattle are in feedlots.
- Conversion of the augmented change in methane to CO<sub>2</sub>-e.
- Application of the nominated price of carbon to the CO<sub>2</sub>-e change.

**Prediction of GHG emission levels from feed intake**

Feed-associated GHG emissions are predicted from the feed intake of the production system. For animals at pasture, the phenotypic relationship of Charmley et al. [18] was used, i.e.:

$$MP = 20.7(\pm 0.28) \times DMI,$$

where MP is the production of methane in g/day and DMI is the dry matter intake in kg/day. This suggests that 0.0207 kg of methane is associated with an increase in feed intake of 1 kg. Then, the recommended global warming constant for methane (28; i.e. a measure of how much heat methane traps in the atmosphere over a specific time horizon relative to carbon dioxide) (Intergovernmental Panel on Climate Change [4]) is used to determine that 0.5796 kg of CO<sub>2</sub>-e is associated with 1 kg

of feed intake. Equation 7 of Johnson et al. [19] is used to predict GHG emissions when animals are in the feedlot, i.e.:

$$CH_4 = 9.90 - 1.54LOI - 0.02DE,$$

where CH<sub>4</sub> is % methane, expressed as a fraction of the animal's diet gross energy intake, LOI is the level of feed, expressed relative to the energy required for maintenance, and DE is % diet digestible energy. Average daily LOI of steers in the feedlot for the example of this article is equal to 2.32. The predicted % methane is used with feed intake (MJ/d) and the quality of feedlot feed (MJ/kg DM) to derive the amount of methane in kg generated in the feedlot. Emissions in the feedlot period are augmented by 11% to account for non-methane GHG emissions (e.g. nitrous oxide) that occur especially under feedlot conditions [4]. The augmented amount of methane is converted to CO<sub>2</sub>-e for assessing the cost of the CO<sub>2</sub>-e associated with each breeding objective trait.

**Residual GHG emission traits**

Residual GHG emission traits are not included in the example described in this paper because criteria for these are not available and there is little knowledge on their association with other traits. Excluding residual GHG emission traits will not affect results if they are not correlated with other traits, at least until criteria for these traits are available. If the production system has no feedlot phase, residual GHG emissions in the feedlot are not part of the breeding objective.

**Price of feed**

The price used for estimating the cost of feed in the breeding objective has a major impact on the ranking of beef cattle for economic merit [9]. This price can differ between young animals and cows, and for feed of different qualities (MJ/kg DM). If the production system is able to provide the additional feed needed for genetic improvement, the price of feed is a nominated \$/ton for each quality of feed. If the production system is not able to provide the additional feed, the price of feed used is an implied price that reflects the way the production system would need to change to meet the increased feed requirement. In the case in which stocking rate would need to be reduced by reducing cow numbers, for example, the implied price is the production system's net return per cow (\$) divided by the feed intake per cow (MJ).

When reducing GHG emissions is part of the breeding objective, the cost of the CO<sub>2</sub>-e associated with feed intake change is an additional cost in the calculation of the economic values of the breeding objective traits. In the example of this article, the production system is assumed to be able to supply the additional feed needed,

and the same price was used for estimating the costs of the additional feed needed when RFI traits change.

**Price of carbon**

The cost of the carbon associated with change in the breeding objective traits is an additional cost to the production system. The carbon price (per ton CO<sub>2</sub>-e) used should take any consensus on this that is reached into account.

**Available estimated breeding values**

The most relevant EBV to include in selection indexes are those that are routinely available to industry. In Australia, the EBV that are available to industry (listed here together with % accuracy levels that typically occur for active sires of the Angus breed) are: 200d weight in kg (91), 200d weight maternal in kg (79), 400d weight in kg (90), 600d weight in kg (90), net feed intake-post-weaning (NFI-p) in kg/d (62), net feed intake-feedlot (NFI-f) in kg/d (63), carcass eye muscle area in cm<sup>2</sup> (78), carcass rump fat depth in mm (79), carcass retail beef % (74), carcass intra-muscular fat % (75), mature cow weight in kg (85), birth weight in kg (94), calving ease (direct) % (75), calving ease (maternal) % (62), days to calving in d (58), and scrotal size in cm (86) (see [10] for a complete description). The NFI-p and NFI-f EBV are net feed intake EBV for the residual feed intake traits RFI-p and RFI-f. Currently, EBV for residual GHG emission traits are not available.

**The genetic variance–covariance matrix**

The genetic variance–covariance matrix for deriving selection indexes includes the partitions **G**<sub>11</sub>, **G**<sub>22</sub> and **G**<sub>12</sub> described above. These partitions may overlap. The matrix used for the example in this article relates to *Bos taurus* breeds and is similar to that used by Barwick et al. [9]. Details can be obtained from the authors on request.

**Changes in individual traits due to selection**

Changes in individual traits due to selection are calculated with standard software. For the example in this article, the MTIndex software of J. van der Werf was used. The information that is assumed available for each EBV aligns with the above-mentioned accuracies of the EBV of active Angus sires of the Australian industry. In cases in which changes in individual traits need to be estimated and the accuracies of the EBV differ between individuals, the procedure described by Barwick et al. [9] is used.

**Changes in the production system due to selection**  
*Total GHG emissions, total product, total feed and \$ net return*

Changes in the breeding objective traits that result from selection can change the feed needs of animals and hence the resulting CO<sub>2</sub>-e. The changes in total GHG emissions, total product, total feed and \$ net return for the production system are estimated by summation over the breeding objective traits, as shown in Table 2. For young animals, these total sums can be for animals at pasture, in the feedlot, or overall. Similarly, the total for cows is summed over the breeding objective traits for cows. If increased feed is needed for cows to be in acceptable joining condition, this is also added. Further summing over young animals and cows gives the total sums for the production system (Table 3).

**GHG emissions per unit of product and per unit of feed**

Reductions in GHG emissions per unit of product and per unit of feed are achieved by reducing total GHG emissions or by increasing the productivity or feed intake of the production system. The change in percentage for each of these (Fig. 3) is based on the total sums before and after selection (Table 3).

**Table 2 Method of accumulating changes in traits for assessing the effects of selection on emissions from the beef cattle production system**

Breeding objective traits (T <sub>i</sub> )	Change in trait (ΔT)	Associated change in feed intake (MJ)			Associated change in GHG emission (g) <sup>a</sup>		
		Young animal pasture (ΔPF) <sup>b</sup>	Young animal feedlot (ΔFF) <sup>c</sup>	Cow pasture (ΔCF) <sup>d</sup>	Young animal pasture (ΔPG)	Young animal feedlot (ΔFG)	Cow pasture (ΔCG)
T <sub>1</sub>	ΔT <sub>1</sub>	ΔPF <sub>1</sub>	ΔFF <sub>1</sub>	ΔCF <sub>1</sub>	ΔPG <sub>1</sub>	ΔFG <sub>1</sub>	ΔCG <sub>1</sub>
T <sub>2</sub>	ΔT <sub>2</sub>	ΔPF <sub>2</sub>	ΔFF <sub>2</sub>	ΔCF <sub>2</sub>	ΔPG <sub>2</sub>	ΔFG <sub>2</sub>	ΔCG <sub>2</sub>
T <sub>n</sub>	ΔT <sub>n</sub>	ΔPF <sub>n</sub>	ΔFF <sub>n</sub>	ΔCF <sub>n</sub>	ΔPG <sub>n</sub>	ΔFG <sub>n</sub>	ΔCG <sub>n</sub>
Total		Σ(ΔPF <sub>i</sub> )	Σ(ΔFF <sub>i</sub> )	Σ(ΔCF <sub>i</sub> )	Σ(ΔPG <sub>i</sub> )	Σ(ΔFG <sub>i</sub> )	Σ(ΔCG <sub>i</sub> )

<sup>a</sup> Emissions associated with feed intake over 12 months (in this paper, calculated with and without an association between RFI traits and GHG emission)

<sup>b</sup> Feed requirement and RFI change at pasture; restricted to the period of limited feed

<sup>c</sup> Feed requirement and RFI change over the feedlot period

<sup>d</sup> Feed requirement change over 12 months, including feed requirement for cows to be in joining condition; restricted to the period of limited feed

**Table 3 Method of assessing effects of selection on GHG emissions from the beef cattle production system**

Performance measure	Performance level <sup>a</sup>		
After selection			
Young animal pasture feed (PF <sub>A</sub> ), MJ			PF <sub>B</sub> + Σ(ΔPF <sub>i</sub> )
Young animal feedlot feed (FF <sub>A</sub> ), MJ			FF <sub>B</sub> + Σ(ΔFF <sub>i</sub> )
Young animal total feed, MJ			PF <sub>A</sub> + FF <sub>A</sub>
Cow pasture feed (CF <sub>A</sub> ), MJ			CF <sub>B</sub> + Σ(ΔCF <sub>i</sub> )
Total feed (TF <sub>A</sub> ), MJ			PF <sub>A</sub> + FF <sub>A</sub> + CF <sub>A</sub>
Young animal GHG emission at pasture (PG <sub>A</sub> ), g			PG <sub>B</sub> + Σ(ΔPG <sub>i</sub> )
Young animal GHG emission in the feedlot (FG <sub>A</sub> ), g			FG <sub>B</sub> + Σ(ΔFG <sub>i</sub> )
Young animal total GHG emission, g			PG <sub>A</sub> + FG <sub>A</sub>
Cow GHG emission at pasture (CG <sub>A</sub> ), g			CG <sub>B</sub> + Σ(ΔCG <sub>i</sub> )
Total GHG emission (TG <sub>A</sub> ), g			PG <sub>A</sub> + FG <sub>A</sub> + CG <sub>A</sub>
Effects of selection	Before selection (X <sub>B</sub> )	After selection (X <sub>A</sub> )	% Change
Total product <sup>b</sup> , kg	KG <sub>B</sub>	KG <sub>A</sub>	(X <sub>A</sub> /X <sub>B</sub> × 100) – 100
Total feed, MJ	TF <sub>B</sub>	TF <sub>A</sub>	
Total GHG emissions, g	TG <sub>B</sub>	TG <sub>A</sub>	
\$ net return <sup>c,de</sup>	DNR <sub>B</sub>	DNR <sub>B</sub> + Σ(VTC <sub>i</sub> )	
Product per unit of feed <sup>e</sup> , kg/MJ	KG <sub>B</sub> /TF <sub>B</sub>	KG <sub>A</sub> /TF <sub>A</sub>	
GHG per unit of product, g/kg	TG <sub>B</sub> /KG <sub>B</sub>	TG <sub>A</sub> /KG <sub>A</sub>	
GHG per unit of feed, g/MJ	TG <sub>B</sub> /TF <sub>B</sub>	TG <sub>A</sub> /TF <sub>A</sub>	
\$ net return per unit of feed <sup>e</sup> , \$/MJ	DNR <sub>B</sub> /TF <sub>B</sub>	[DNR <sub>B</sub> + Σ(VTC <sub>i</sub> )]/TF <sub>A</sub>	
\$ net return per unit of GHG <sup>e</sup> , \$/g	DNR <sub>B</sub> /TG <sub>B</sub>	[DNR <sub>B</sub> + Σ(VTC <sub>i</sub> )]/TG <sub>A</sub>	

<sup>a</sup> Includes level of performance of the production system before selection (per cow): young animal pasture feed (PF<sub>B</sub>), young animal feedlot feed (FF<sub>B</sub>), total young animal feed (PF<sub>B</sub> + FF<sub>B</sub>), cow pasture feed (CF<sub>B</sub>), total feed (TF<sub>B</sub>), young animal GHG emission at pasture (PG<sub>B</sub>), young animal GHG emission in the feedlot (FG<sub>B</sub>), cow GHG emission (CG<sub>B</sub>), total GHG emission (TG<sub>B</sub>), total product (KG<sub>B</sub>), \$ net return (DNR<sub>B</sub>)

<sup>b</sup> Expressed as equivalent steer beef, before (KG<sub>B</sub>) and after (KG<sub>A</sub>) selection

<sup>c</sup> Feed price before selection is based on a land value of \$400/DSE (feed required by a 50 kg dry sheep (9.7 MJ/head/d) [20]), leased at 7% p.a. [21]

<sup>d</sup> Total value of trait change, Σ(VTC<sub>i</sub>) = Σ(ΔT<sub>i</sub> from selection × economic value of T<sub>i</sub>); ΔT<sub>i</sub> assumes that selection intensity, *i* is equal to 1

<sup>e</sup> Uses total feed, before and after selection, assessed over the limited feed period

### Product per unit of feed, and \$ net return per unit of product, feed or methane

Changes in product per unit of feed and in \$ net return per unit of product, feed or methane measure the effects of selection on the biological and economic efficiency of the production system. The change in percentage for each of these is based on the total sums before and after selection (Table 3).

## Results

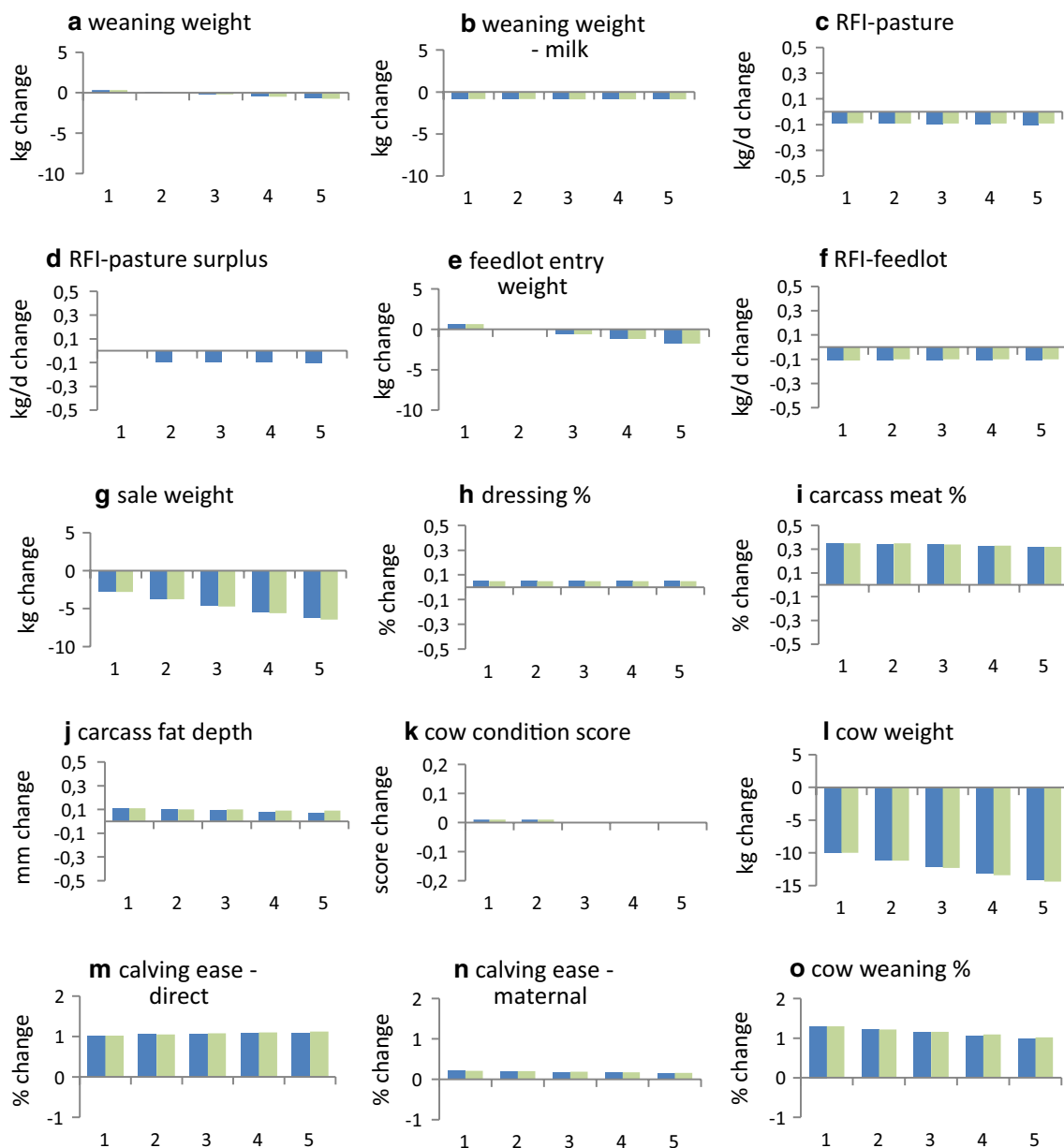
### Numerical example

Key characteristics for the example beef cattle production system analysed here, in which animals are sold for slaughter after 100d of feedlot finishing, are in Table 1. We chose this production system as an example because of the importance of pasture-grain systems to beef production globally, and because pasture-grain systems have not previously been described in the literature on breeding objectives. Tables 2 and 3 show how GHG emissions are accumulated across traits regardless of the

production system. Tables 4 and 5 show how this occurs for the example in this paper. Calculations are in Additional file 1.

### Selection when the feed needed to improve breeding objective traits is expensive

In production systems in which the cost of feed for the breeding objective is expensive (e.g. Table 1), selection is able to simultaneously reduce GHG emissions and increase economic performance. For the example in Table 1, total GHG emissions decreased by 1.1, 1.6, 2.1, and 2.6% per generation (relative to when carbon was not costed) when carbon in the breeding objective was priced at \$10, \$20, \$30 and \$40/ton CO<sub>2</sub>-e, respectively (Fig. 4c). Trends in responses for individual traits (Fig. 3), and for the production system (Fig. 4), did not differ markedly when no association was assumed between changes in RFI traits and GHG emissions. Emissions per unit of product and per unit of feed also decreased (Fig. 4f and g). When the costs of GHG emissions were not included



**Fig. 3** Effect of carbon price on individual trait responses to selection for the example beef cattle production system in Table 1<sup>a,b,c,d</sup>. (<sup>a</sup>For a single generation of selection with selection intensity  $i=1$ , <sup>b</sup>1 = \$0/ton CO<sub>2</sub>-e; 2 = \$10/ton CO<sub>2</sub>-e; 3 = \$20/ton CO<sub>2</sub>-e; 4 = \$30/ton CO<sub>2</sub>-e; 5 = \$40/ton CO<sub>2</sub>-e, <sup>c</sup>blue colour bars include GHG association with residual feed; green colour bars exclude GHG association with residual feed, <sup>d</sup>Response in carcass marbling score was 0.02 of a score for all levels of carbon price)

(i.e. when carbon was priced at \$0/ton CO<sub>2</sub>-e), reductions in total feed of the production system (0.8%) (Fig. 4b) and in total GHG emissions (0.5%) were small (Fig. 4c), and GHG emissions per unit of feed (0.4%) increased slightly (Fig. 4g). Selection was able to reduce total GHG emissions of the production system without appreciably

affecting net returns for the production system (Fig. 4d). Selection was able to improve virtually all the traits, and most traits were not affected by carbon price. The traits that were most affected by carbon price were cow weight, which decreased by up to 14 kg as carbon price increased, and sale weight, which decreased by up to 6 kg (Fig. 3).

**Table 4 Accumulated changes in traits for the example beef cattle production system in Table 1**

Breeding objective traits	Change in traits	Associated feed intake, MJ <sup>a</sup>			Associated CO <sub>2</sub> -e, kg <sup>b</sup>		
		Young animal pasture	Young animal feedlot	Cow pasture	Young animal pasture	Young animal feedlot	Cow pasture
Weaning live weight-direct, kg	-0.194	1.4	0	0.06	0.58	0	0.07
Weaning live weight-maternal, kg	-0.866	0	0	-70	0	0	-5
RFI-pasture, kg/d	-0.098	-116	0	0	-7	0	-1.8
RFI-pasture surplus, kg/d	-0.100	0	0	0	-1.3	0	-0.31
Entry live weight, kg	-0.580	-21	18	-4	-6	1.3	-0.85
RFI-feedlot, kg/d	-0.11	0	-110	0	0	-4	0
Sale live weight, kg	-4.63	0	-195	0	0	-14	-2
Dressing %	0.05	0	0	0	0	0	0
Carcass meat %	0.34	0	0	0	0	0	0
Carcass fat depth, mm	0.09	0	0	0	0	0	0
Carcass marbling score <sup>c</sup>	0.02	0	0	0	0	0	0
Cow live weight, kg	-12.14	0	0	-882	0	0	-60
Cow condition score <sup>d</sup>	0	0	0	0	0	0	0
Calving ease-direct, %	1.06	0	0	0	0	0	0
Calving ease-maternal, %	0.18	0	0	0	0	0	0
Cow weaning %	1.14	267	232	87	33	17	0.64
Total		131	-55	-870	19	-0.37	-70

Characteristics of the production system are in Table 1

Methods for accumulating changes in traits are in Table 2

<sup>a</sup> Accumulated over the limited feed period

<sup>b</sup> Accumulated over 12 months; RFI traits are assumed to have associated GHG emissions

<sup>c</sup> Scored on a 12-point scale from 1 (least) to 12 (most) [22]

<sup>d</sup> Scored on a 15-point scale from 1- (emaciated) to 5+ (obese)

### Selection when the feed needed to improve breeding objective traits is inexpensive

In production systems in which the cost of feed for the breeding objective is inexpensive, such as when the price of feed was 30% lower than that in Table 1, selection was able to reduce total GHG emissions only if carbon price was equal to or higher than about \$80/ton CO<sub>2</sub>-e (Fig. 6c). When the costs of GHG emissions were not included, total GHG emissions increased by 4.4% in one generation (Fig. 6c), or by ~8.8% in 10 years. GHG emissions per unit of product and per unit of feed both decreased as carbon price increased, although each remained greater than when feed was expensive (Figs. 5 and 6). Total GHG emissions increased and these increases were sizeable for all but the highest level of carbon price considered (Fig. 6c). Net returns to the production system increased as carbon price increased (Fig. 6d). Again, trends were not very different regardless of whether or not GHG emissions were assumed to be related to change in RFI traits (Figs. 5 and 6).

Figure 5a, d, f and j shows that weight traits increased less with increased carbon price, and selection effects were weaker on other performance traits. The increase in

cow weight became negative at a carbon price of just less than \$20/ton CO<sub>2</sub>-e (Fig. 5j). The increase in sale weight became negative at a carbon price between \$60 and \$80/ton CO<sub>2</sub>-e (Fig. 5f).

### Discussion

The price at which a production system can produce or purchase feed is the main factor that determines the cost of feed for the breeding objective. Our results show that the ability of selection to reduce GHG emissions depends on this. When feed for the breeding objective is at least moderately expensive, multiple-trait selection can reduce total GHG emissions and simultaneously increase economic performance (Figs. 3 and 4). The reduction in GHG emissions (Fig. 4c) is of the order of 3 to 5% in 10 years. Larger reductions are possible when reducing GHG emissions is the only objective of breeding [23], but this ignores that breeding usually aims at increasing economic performance.

When the cost of feed for the breeding objective is inexpensive, selection can only reduce GHG emissions if the carbon price used in the breeding objective is high. The carbon price at which GHG emissions decreased in



**Table 5 Responses to selection for the example beef cattle production system in Table 1**

Performance measure	Performance level		
After selection			
Young animal pasture feed intake (PF <sub>A</sub> ), MJ	12,740		
Young animal feedlot feed intake (FF <sub>A</sub> ), MJ	10,987		
Young animal total feed intake, MJ	23,728		
Cow pasture feed intake (CF <sub>A</sub> ), MJ	31,328		
Total feed intake (TF <sub>A</sub> ), MJ	55,056		
Young animal GHG emission at pasture (PG <sub>A</sub> ), kg CO <sub>2</sub> -e	932		
Young animal GHG emission in feedlot (FG <sub>A</sub> ), kg CO <sub>2</sub> -e	33		
Young animal total GHG emission, kg CO <sub>2</sub> -e	965		
Cow GHG emission at pasture (CG <sub>A</sub> ), kg CO <sub>2</sub> -e	2262		
Total GHG emission (TG <sub>A</sub> ), kg CO <sub>2</sub> equiv.	3228		
Effects of selection	Before selection (X <sub>B</sub> )	After selection (X <sub>A</sub> )	% Change
Total product, kg	172	171	−0.64
Total feed intake, MJ	55,851	55,056	−1.42
Total GHG emission, kg CO <sub>2</sub> -e	3279	3228	−1.58
\$Net return <sup>a</sup>	398	422	6.14
Product per unit of feed, kg/MJ	0.003097159	0.003121866	0.80
GHG per unit of product, kg CO <sub>2</sub> -e/kg	18.9	18.7	−0.95
GHG per unit of feed, kg CO <sub>2</sub> -e/MJ	0.058726425	0.058631001	−0.16
\$Net return per unit of feed <sup>a</sup> , \$/MJ	0.007126103	0.007672676	7.67
\$Net return per unit of GHG <sup>a</sup> , \$/kg CO <sub>2</sub> -e	0.12134407	0.130863803	7.85

Characteristics of the production system are in Table 1

Methods for assessing effects are in Table 2

All quantities are assessed over 12 months unless indicated

<sup>a</sup> Assessed using total feed, before and after selection, over the period of limited feed

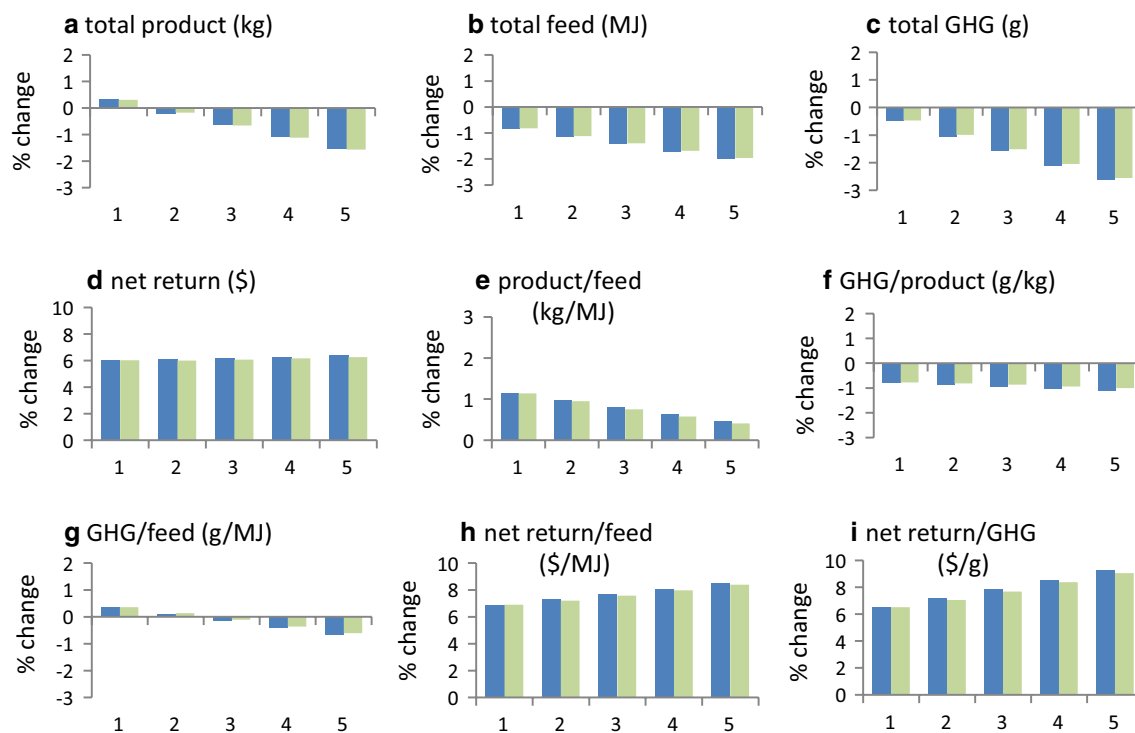
the current example was about \$80/ton CO<sub>2</sub>-e (Fig. 6c). The carbon price at which sale weight decreased was between \$60 and \$80/ton CO<sub>2</sub>-e (Fig. 5f). The resulting ~8.8% increase in GHG emissions over 10 years emphasises the importance of fully costing feed for selection decisions, and this is more critical when there is a need to also reduce GHG emissions. It shows that the management that is modelled for the development of breeding objectives needs to be close to optimal. Societal and political pressures to reduce GHG emissions may make production systems that underuse available feed, or which underestimate the cost of feed, unsustainable.

To date, the actual cost of feed for beef production has not been examined in the literature and needs to be estimated for different types of beef systems. Feed for intensive systems is often thought to be expensive, while that for grazing systems is considered less expensive. Table 6 lists several possible relationships between some characteristics of the commercial production system and whether the feed needed to improve breeding objective traits is expensive or inexpensive. Use of this type of classification, together with better information on the costs of feed, could assist selection in beef cattle.

#### Inter-relation between feed and GHG measures

Feed intake and GHG emissions are related, and thus the recording of either one can provide information on the other that is useful in selection. For example, Robinson and Oddy [24] suggest that methane measurements could be used for predicting feed intake. The phenotypic relation between feed intake and GHG emission is strong when animals are forage-fed, but less strong when they are feedlot-fed. Only about half as much variation in GHG emissions is explained by feed intake under feedlot conditions [19]. This has ramifications for determining which measures are best for reducing livestock emissions [24, 25]. Measures that are independent of feed intake, such as measures of residual GHG, are likely to be more useful for intensive systems than for grazing systems. Moreover, reductions in total GHG emissions may be greater than those described here when production is entirely feedlot-based and when residual GHG emissions can be measured.

Other modelling of the example of production system in our study was conducted to simulate production entirely from pasture or entirely from grain [see Additional file 2]. The results showed that GHG emissions



**Fig. 4** Effect of carbon price on production system responses to selection for the example beef cattle production system in Table 1<sup>a,b,c</sup>. <sup>a</sup>For a single generation of selection with selection intensity  $i = 1$ , <sup>b</sup>1 = \$0/ton CO<sub>2</sub>-e; 2 = \$10/ton CO<sub>2</sub>-e; 3 = \$20/ton CO<sub>2</sub>-e; 4 = \$30/ton CO<sub>2</sub>-e; 5 = 40/ton CO<sub>2</sub>-e, <sup>c</sup>blue colour bars include GHG association with residual feed; green colour bars exclude GHG association with residual feed)

increased when production was from pasture and GHG emission costs were ignored, and they decreased when production was from grain. Although feed intake is known to be not as accurately predicted when feed intake is from grain [19], this also emphasises that the capacity to decrease GHG emissions depends on the way feed cost is modelled.

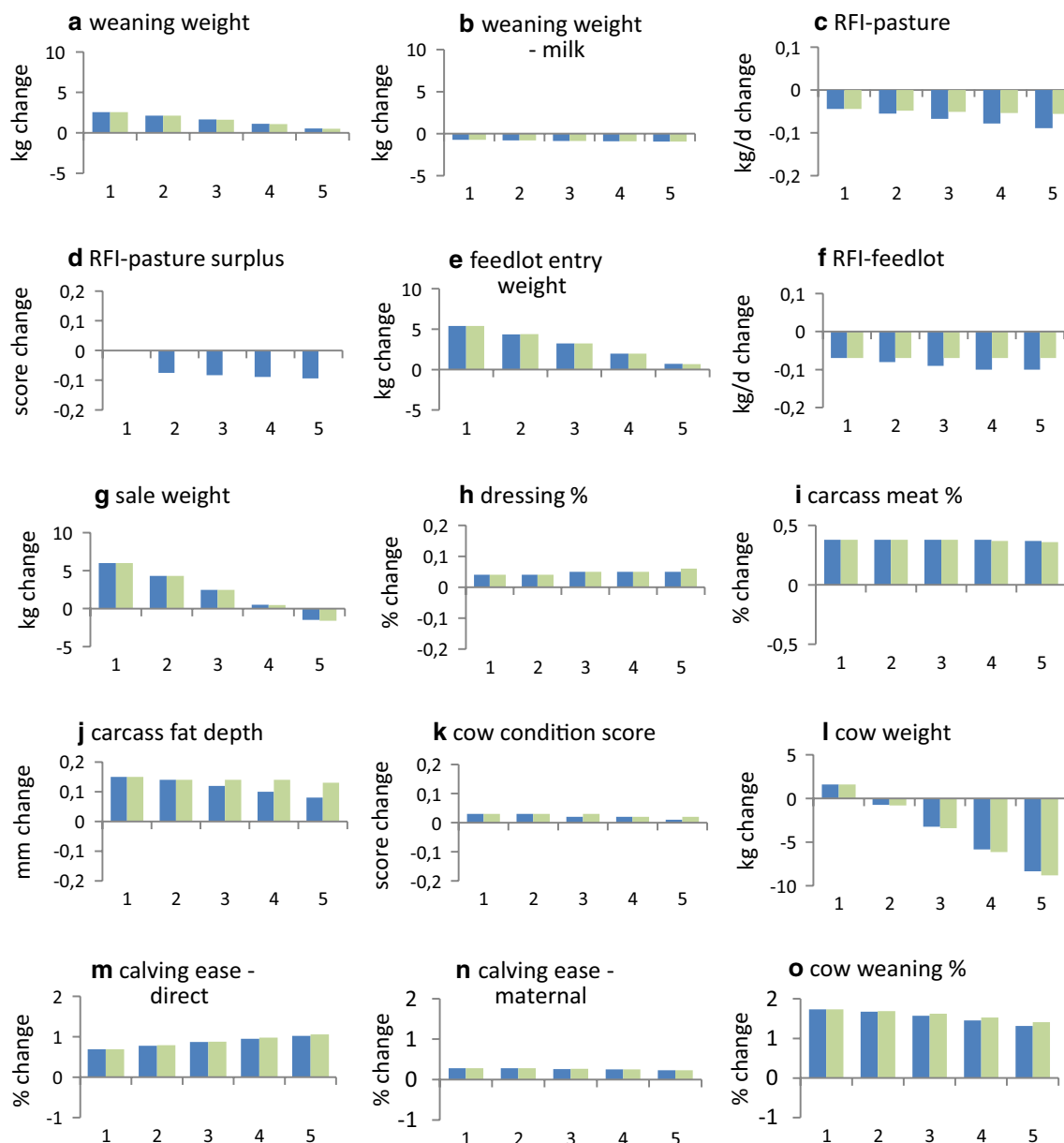
A comment is also warranted on two practical situations that can be encountered. Beef cattle selection is sometimes implemented without any consideration of the cost of feed. Our results suggest that this would increase total GHG emission for the production system by 6.2% per generation, or by ~12.4% in 10 years, and decrease net return for the production system by 1.7% per generation. Selection also sometimes occurs for animals that have only records on growth as against records for the range of traits that affect the breeding objective. Selection against growth in this circumstance would increase net returns by a small amount, but any advantage from this would be reduced when selection is not for a defined breeding objective because selection for a defined breeding objective takes all changes into account.

#### Change in the relation between feed intake and GHG emission

In the example of production system in this study, selection reduced GHG emissions per unit of feed and the size of this reduction changed with the price of carbon (Figs. 4g and 6g). This shows that the relation between GHG emissions and feed intake is not constant and that it may change under selection when a carbon price is applied. Thus, the phenotypic association between feed intake and GHG emission may need to be adjusted periodically, in accordance with the carbon price used in the breeding objective, when the aim is to reduce GHG emissions.

#### Other reductions in GHG emissions

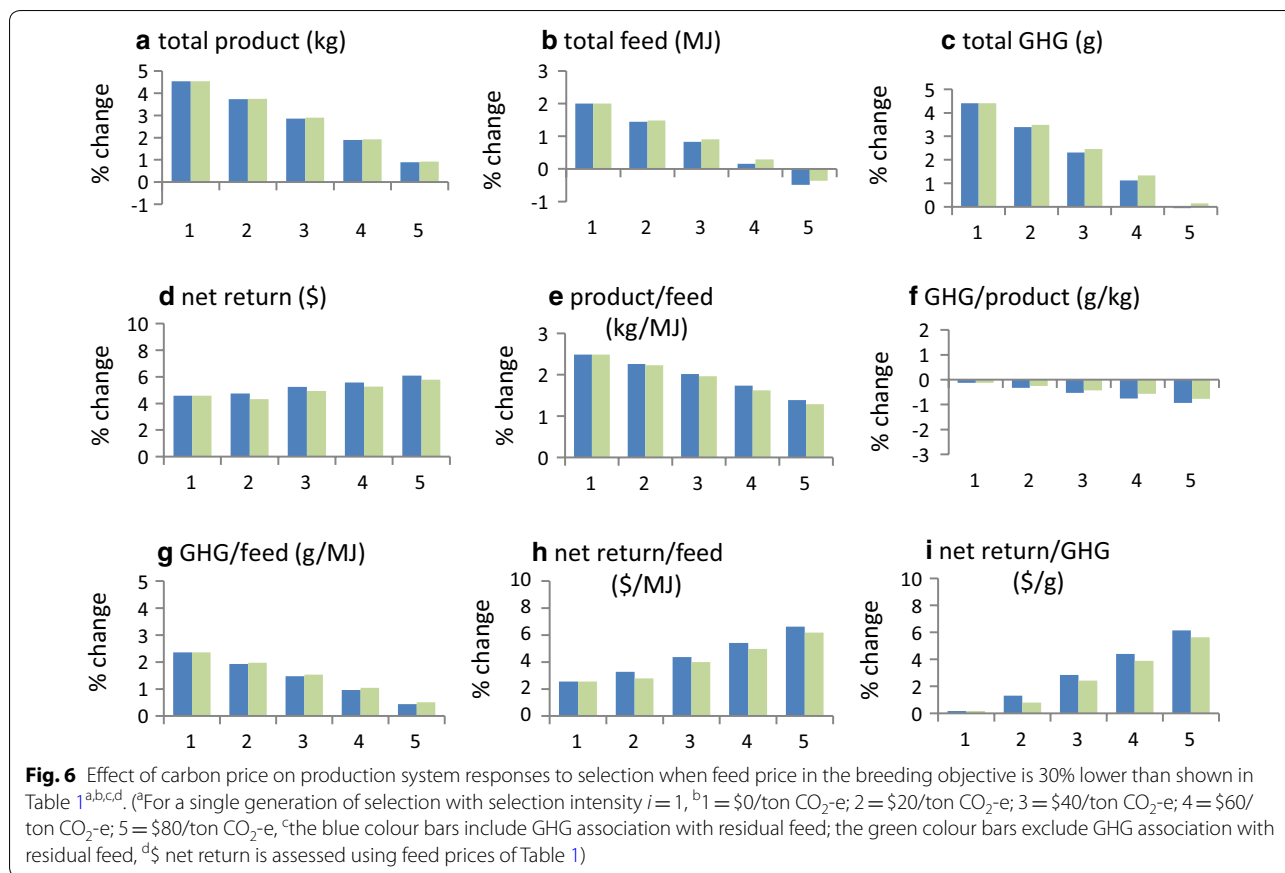
The literature is not clear on how GHG emissions vary when stocking rates change [26, 27]. In the absence of genetic selection, Clarke et al. [26] showed that GHG emissions per unit of feed increased when stocking rate increased. Our results show that selection reduced GHG emissions per unit of feed when feed was expensive (Table 6), which might align with a situation where stocking rates are high.



**Fig. 5** Effect of carbon price on individual trait responses to selection when feed price in the breeding objective is 30% lower than shown in Table 1<sup>a,b,c,d</sup>. <sup>a</sup>For a single generation of selection with selection intensity  $i = 1$ , <sup>b</sup> $b_1 = \$0/\text{ton CO}_2\text{-e}$ ; <sup>c</sup> $2 = \$20/\text{ton CO}_2\text{-e}$ ; <sup>d</sup> $3 = \$40/\text{ton CO}_2\text{-e}$ ; <sup>e</sup> $4 = \$60/\text{ton CO}_2\text{-e}$ ; <sup>f</sup> $5 = \$80/\text{ton CO}_2\text{-e}$ , <sup>g</sup>blue colour bars include GHG association with residual feed; green colour bars exclude GHG association with residual feed, <sup>d</sup>Response in carcass marbling score was 0.02 of a score for all levels of carbon price)

Hristov et al. [28] have reviewed management options for reducing GHG emissions from livestock. Other methods for reducing GHG emissions in cattle include supplementation with red algae from seaweed, for which sizeable reductions in emissions have been achieved [29]. If societal pressures continue to focus on reduction in GHG emissions from beef cattle,

all available technologies may be needed. Our results show that genetic selection will be an important part of any strategy to reduce GHG emissions, and this can be achieved using a low price of carbon when feed is otherwise expensive. When feed is inexpensive, greater growth will be favoured, leading to increased GHG emissions that may not be desirable.



**Table 6 Possible relationships between the cost of feed needed to improve breeding objective traits and characteristics of the beef cattle production system under grazing**

Feed cost for trait improvement	Characteristics of the commercial production system
Expensive Available feed fully used e.g.	High stocking rate Additional feed is needed over an extended period Poor seasons are common Poor quality feed
Inexpensive Available feed not fully used e.g.	Low stocking rate Additional feed is needed over only a short period Good seasons are common High quality feed

**Conclusions**

When the cost of feed in the breeding objective is high, multiple-trait selection can reduce total GHG emissions while increasing the economic performance of beef cattle using a low price for carbon. In the example of this article, total GHG emissions were reduced at a carbon price of less than \$10/ton CO<sub>2</sub>-e. Both total GHG emissions and GHG emissions per unit of product were reduced. When

the cost of feed in the breeding objective is low, selection can reduce total GHG emissions only if the price of carbon is high (about \$80/ton CO<sub>2</sub>-e). Selection needs to be included in any strategy to reduce GHG emissions in beef cattle. When the cost of feed for the breeding objective is inexpensive, beef cattle selection that ignores emission costs will substantially increase GHG emissions.

## Additional files

**Additional file 1.** Production system calculations.

**Additional file 2.** Further modelling.

### Authors' contributions

SB conceived the study and wrote the paper. AH was responsible for coding. BW, RH and PA contributed to aims. All authors read and approved the final manuscript.

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### Competing interests

The authors declare they have no competing interests.

### Availability of data and materials

Economic values for traits were obtained by using BreedObject Version 6. Gains in individual traits were obtained with MTIndex. Production system calculations used spreadsheet software.

### Consent for publication

Not applicable

### Ethics approval and consent to participate

Not applicable

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