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Research article

Rethinking efficiency: Growth curves as a proxy for inputs and impacts in finishing beef systems

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ABSTRACT

Quantifying and improving efficiency within beef systems is essential for economic and environmental sustainability. The industry standard for assessing efficiency is liveweight gain per day, however, this metric is limited in that it values each day of a growing animal's life as equally costly, despite the increasing maintenance requirements, inputs, and emissions associated with increasing liveweight. Quantifying the area under the growth curve (AUC) considers both time and liveweight as a cost and therefore may hold potential as a better estimate of cost, impact, and efficiency in beef systems. Liveweight data was taken from 439 finishing beef cattle split across three herds grazing on different pastures, known as 'farmlets'. Analysis was conducted in three parts: [1] Validation of AUC as a proxy for costs using data from a sub-set of 87 animals that had been part of a previous life cycle assessment (LCA) study in which dry matter intake (DMI), methane emissions (CH_4), and nitrous oxide emissions (N_2O) were calculated. [2] Calculation of AUC relative to liveweight gain (LWG AUC^{-1}) and comparison of that metric against the industry standard of liveweight gain per day (LWG day^{-1}). [3] Assessment of how LWG AUC^{-1} varied with breed, sex, and management. When comparing to LCA results, AUC correlated significantly with DMI ($r = 0.886$), CH_4 ($r = 0.788$) and N_2O ($r = 0.575$) emissions. Over the full dataset, there was a negative non-linear relationship between LWG AUC^{-1} and slaughter age ($r = -0.809$). There was a significant difference in LWG AUC^{-1} between breeds ($p = 0.046$) and farmlets ($p = 0.028$), but not sex ($p = 0.388$). LWG AUC^{-1} has the potential to act as a proxy for feed intake and emissions. In that regard it is superior to LWG day^{-1}, whilst requiring no additional data. Results highlighted the decreasing efficiency of beef cattle over time and the potential benefits of earlier slaughter. The use of LWG AUC^{-1} could allow farmers to improve their understanding of efficiency within their herds, aiding informed management decision making.

1. Introduction

There are approximately 1.5 billion cattle on the planet, along with 2.7 billion sheep and goats (FAO, 2022a). Two-thirds of agricultural land is used for grazing, representing one quarter of global land surface area (FAO, 2022b). Consequently, small changes in the efficiency of cattle can have a large impact. Improving efficiency requires accurate information to enable informed decision making. Efficiency can broadly be defined as the ratio of positive outputs/reward relative to costly inputs and negative impacts. Understanding the efficiency of cattle is essential for informed and effective management within beef systems. Measures of efficiency are based on the relationship between two components: (1) Reward – the tangible benefit gained (2) Cost – the inputs and negative impacts (equation (1)):

$$\textit{Efficiency} = \textit{reward} / \textit{cost} \tag{1}$$

Abbreviations: AUC, area under the curve; BRBX, british blue cross (breed); CH4, methane; CHX, charolais cross (breed); DMI, dry matter intake; GHG, greenhouse gas; GWC, grass and white clover; HEX, hereford cross (breed); LIMX, limousin cross (breed); LW, liveweight; LWG, liveweight gain; N2O, nitrous oxide; MG, monoculture grass; PP, permanent pasture; ST, stabiliser (breed); STX, stabiliser cross (breed).

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Improved efficiency can improve economic gain, whilst reducing environmental harm (e.g. greenhouse gas [GHG] emissions) (Waghorn and Hegarty, 2011). The industry standard for assessing beef cattle efficiency is liveweight gain (LWG) per day (LWG day^{-1}). However, this metric is limited by the use of time (days) as its cost component, meaning that it equally values each day of an animal's life in terms of resource use and emissions. This of course is not true; as animals grow, their maintenance requirements increase, consequently, so do their requirements for feed and so do their emissions (Hristov and Melgar, 2020; Kriss, 1930; Saubidet and Verde, 1976), though some costs (e.g. land rent, and labour) may be fixed. The relatively linear growth of finishing beef cattle (Martín et al., 2020) means that whilst maintenance costs are increasing, the daily liveweight gain remains relatively consistent (National Research Council, 2000). This increasing cost, yet consistent reward, means that efficiency decreases over time. However, liveweight (LW) is both a reward and an ongoing cost. By not considering the increasing daily cost of liveweight maintenance as an animal grows, metrics such as LWG day^{-1} are limited as an estimate of efficiency and risk overestimating costs for smaller animals and underestimating cost for larger animals. More sophisticated techniques are available to assess efficiency, such as direct quantification of dry matter intake (DMI), residual feed intake, and GHG emissions (Herd and Arthur, 2009; Hristov and Melgar, 2020; Laredo et al., 1991), or estimation through lifecycle assessment (LCA) (McAuliffe et al., 2018). However, the resource requirements and expertise needed for such analyses make them unfeasible on most farms. To support informed decision making there is a need for accessible metrics and improvement in how basic data is utilised.

1.1. The cost of maintenance

Maintenance is the minimum requirements of an animal to sustain itself. This requires the use of resources such as feed, water, land and labour. There are environmental costs associated with these resources, such as GHG emissions and nutrients run-off (Biagini and Lazzaroni, 2018; Filip and Middlebrooks, 1976; Jungbluth et al., 2001; Smith and Monaghan, 2003; Zonderland-Thomassen et al., 2014). As animals increase in mass, these costs increase (Russel and Wright, 1983). DMI and emissions of methane (CH_4) and nitrous oxide (N_2O) are also costs associated with production (Grossi et al., 2019). DMI represents the cost of feed and therefore has a commercial value. Cattle liveweight has a linear relationship with DMI (Huuskonen, 2009; Saubidet and Verde, 1976; Zhang et al., 2017). The availability of dry matter is a limiting factor to production as it influences carrying capacity and stocking rates (Burns et al., 1989). Meanwhile, GHG emissions represent environmental costs and gross energy loss from the diet which otherwise could have been diverted for maintenance and production. Ruminal enteric fermentation of dry matter consumed is the primary source of CH_4 emissions within beef systems (Thompson and Rowntree, 2020) and DMI has repeatedly been shown to correlate with CH_4 emissions (Bell et al., 2016; Min et al., 2020; Swainson et al., 2018).

1.2. Area under the curve (AUC)

Given the relationship of liveweight with DMI and GHG emissions, it may be possible to estimate these through using liveweight change over time as a proxy, with every kilogram of liveweight maintained for every day being one unit of cost. In practical terms, this can be quantified by calculating the area under the curve (AUC) of the animal's growth (which is equal to the sum of liveweights of every day). This could then be calculated relative to LWG in a certain period as LWG AUC^{-1} as a proxy for overall efficiency. The primary benefit of this would be accessibility to farmers as calculating the AUC would not require additional measures or resources. The objective of this study was to assess the use of AUC as a measure of beef cattle efficiency by:

1. Determining the relationship of AUC with DMI, CH_4, and N_2O and comparing that relationship to those between time (days) and DMI, CH_4, and N_2O.
2. Applying LWG AUC^{-1} to a dataset of beef cattle to assess how cattle efficiency changes over time and to assess differences between groups of cattle.

2. Methods

2.1. Sample population and data

Liveweight and abattoir data was taken from 439 finishing beef cattle reared at Rothamsted Research's North Wyke Farm Platform (Orr et al., 2019; Takahashi et al., 2018) in Devon, UK. Data spanned five grazing seasons, animals were born from 16/09/12 and 04/06/17 and slaughtered from 08/08/14 and 08/01/19. All animals came from the same suckler herd and at weaning were randomly allocated (with balanced distribution of breeds, sex and LW) into three herds, each grazing a different independently ran pasture-based finishing systems, known as "farmlets" (see Orr et al. (2019, 2016)).

2.2. Farmlets were

- Grass and white clover (GWC) – perennial ryegrass *(Lolium perene*) with a 20–30% abundance of white clover (*Trifolium repens*).
- Monoculture grass (MG) – monoculture high-sugar perennial ryegrass (cultivar Abermagic).
- Permanent pasture (PP) –predominantly perennial ryegrass (no or minimal white clover).

Median slaughter age was 624 days and mean slaughter liveweight was 610 kg (s.d 52.3). The population comprised of 222 males (steers) and 217 females (heifers). Six breeds were present: British Blue Cross (BRBX, $n = 22$), Charolais Cross (CHX, $n = 274$), Hereford Cross (HEX, $n = 45$), Limousin Cross (LIMX, $n = 29$), Stabiliser (ST, $n = 30$), and Stabiliser Cross (STX, $n = 39$). Calves grazed on pasture with their dams until weaning at around 7 months of age and were housed during witner (October/November until March/April) during which they were fed silage produced from their farmlet. In the spring (approx. 13 months old) they were turned out to pasture. The majority (76.5%) went back into housing a second time for finishing. Animals were finished at or near a target condition of R4L (EUROP grid classification system) and sent to abattoir, the precise timing was determined by best judgement of farm management based on logistics (e.g. it is not practical to send a single animal).

2.2.1. Calculations

For each animal, AUC was calculated as the sum of the daily liveweight of each animal over the study period (weaning to slaughter), this was the 'cost'. Animals were weighed every two to four weeks, weights between weigh events were estimated by linear interpolation. The sum of daily weights generated a value of 'kilogram days', which was then divided by 1000 to 'tonne days' (equation (2)).

$$AUC = \Sigma\ daily\ liveweights\ /\ 1000 \tag{2}$$

LWG AUC^{-1} was then calculated by dividing LWG between weaning and slaughter by AUC as a proxy for efficiency (reward cost^{-1}) (equation (3)) and therefore larger values represented greater efficiency. LWG day^{-1} was calculated by dividing liveweight gained between weaning and slaughter by time (days) elapsed between these two production events.

$$LWG\ AUC^{-1} = liveweight\ gain\ /\ (\Sigma\ daily\ liveweights\ /\ 1000) \tag{3}$$

2.2.2. *LCA data*

McAuliffe et al. (2018) performed an LCA (ISO 14040 framework) for the post-weaning period of one year's cohort from the study population (weaned November 2014, slaughtered Winter, 2015/16). High resolution farm and animal data (e.g. liveweight, forage digestibility, crude protein) was applied within the Intergovernmental Panel on Climate Change (IPCC) modelling framework to estimate on-farm emissions. A total of 87 animals were included, from the three farmlets, GWC (n = 29), PP (n = 30) and MG (n = 28). The sex ratio was 45 heifers to 42 steers. Three breeds were present: Charolais Cross (CHX) (n = 71), Hereford Cross (HEX) (n = 16) and Limousin Cross (LIMX) (n = 12). During the study period, animals were weighed a mean of 18 times (s.d 1.9). Mean weaning age was 215 days (s.d 26.6) and mean slaughter age was 628 days (s.d 43.2). McAuliffe et al. (2018) reported DMI, CH_4 emissions, and N_2O emissions on an individual animal basis. CH_4 was estimated for two sources: enteric fermentation and manure management. N_2O was calculated for three sources: direct from manure management, indirect from manure management through volatilisation, and indirect from manure management through leaching. For this comparative analysis, CH_4 sources were summed together and all N_2O sources were summed, resulting in three variables (DMI, CH_4, N_2O) which were considered as cost factor.

2.3. *Data analysis*

Three main stages of data analysis were conducted:

(1) **Validation of AUC:** For the 87 animals for which LCA data was available, AUC was calculated and compared to cost factors (DMI, CH_4 and N_2O), using Pearson's correlations, to assess the feasibility of AUC as a proxy for costs.

(2) **LWG AUC^{-1} vs. LWG day^{-1}:** For the same 87 animals, Pearson's correlations were conducted to compare cost factors (DMI, CH_4 and N_2O) to time (days) (which is component of LWG day^{-1} used to estimate costs). These correlations were then compared to correlations from stage 1, using a *z*-test, to assess which metric (LWG AUC^{-1} or LW days^{-1}) best accounted for costs. A direct correlation (Pearson's) between the two metrics was also performed.

(3) **LWG AUC^{-1} investigation:** Using data from all 439 animals, a Spearman's correlation was used to compare an animal age (days) with the LWG AUC^{-1} across every living day of the study period for every animal, to assess how LWG AUC^{-1} changed with animal age. General linear models were used to assess differences in LWG AUC^{-1} based on breed, sex, and farmlet and Tukey tests conducted to identify group differentiation. General linear models were used to assess the relationship between breed, sex, and farmlet, on slaughter weight and age.

Statistical analysis was conducted in RStudio (R Core Team, 2021; R Studio Team, 2020), including package 'cocor' (Diedenhofen and Musch, 2015; Dunn and Clark, 1969; Silver et al., 2004). Significance was at $\alpha = 0.05$. Figures were created in R package 'ggplot2' (Wickham, 2016).

3. Results

3.1. *Validation of AUC*

Strong correlations were found between AUC and DMI (Fig. 1). This was true at all levels, with all farmlets yielding similar correlation coefficients. The relationship appeared to be linear.

Significant and strong correlations were observed between AUC and CH_4 output (Fig. 2). This was especially true for the GWC and PP farmlet compared to the MG, which appeared to have slightly greater variation in AUC.

The relationship between AUC and N_2O emissions was significant at all levels (Fig. 3). Whilst the correlation was relatively strong for the PP farmlet, it was weak for MG. Notably, the slope appeared different from the three farmlets with GWC and MG generating a steeper relationship than PP.

3.2. *LWG AUC^{-1} vs. LWG day^{-1}*

Whilst AUC correlated significantly with the LCA factors, time (days) only correlated significantly with DMI and CH_4 emissions. In all cases, (Fig. 4). AUC yielded significantly stronger correlations than time (days) (Table 1).

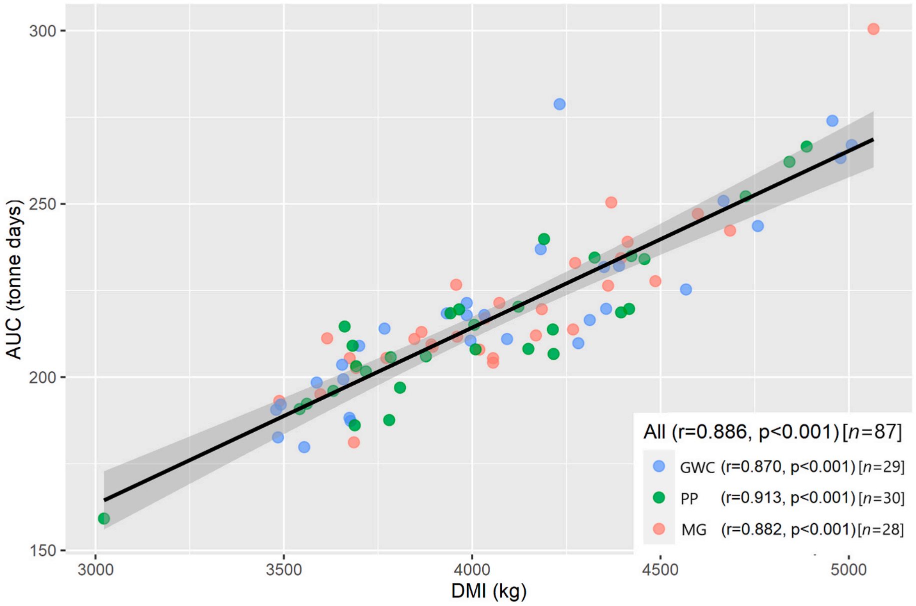

Fig. 1. Scatterplot showing correlation between AUC (tonne days) and DMI (kg). Each point represents one animal. Farmlets are differentiated by point colour. Shading represents 99% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

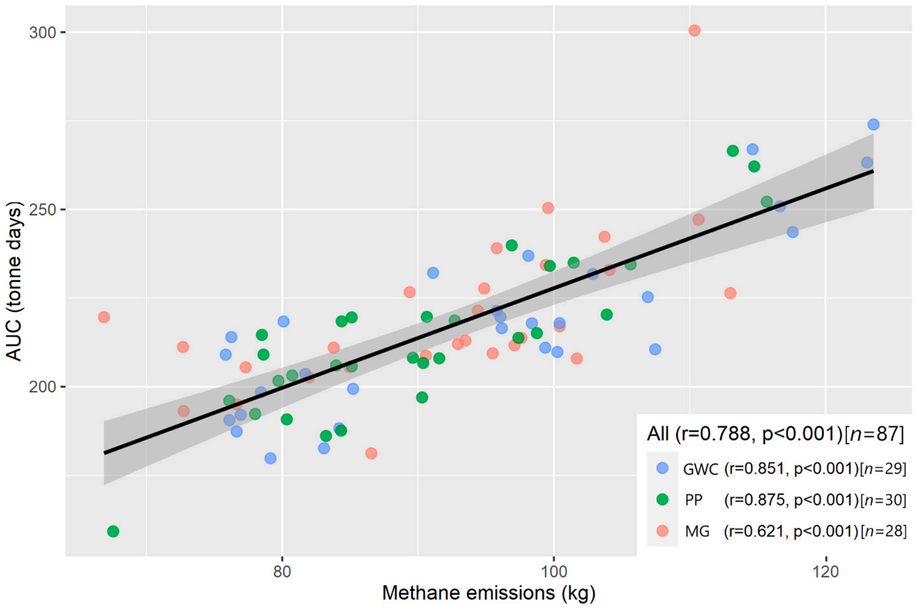

Fig. 2. Scatterplot showing correlation between AUC (tonne days) and total methane emissions (kg). Each point represents one animal. Farmlets are differentiated by point colour. Shading represents 99% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

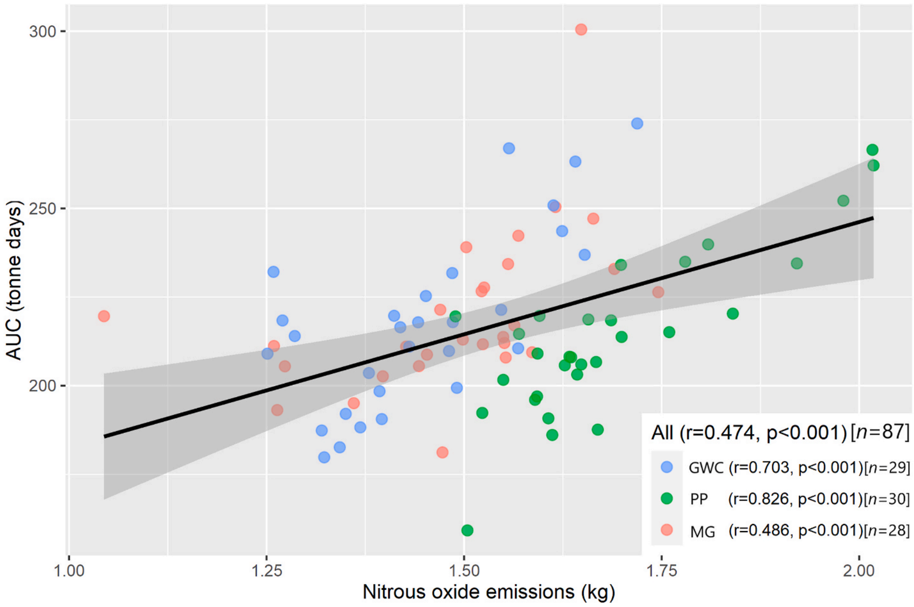

Fig. 3. Scatterplot showing correlation between AUC (tonne days) and nitrous oxide emissions (kg). Each point represents one animal. Farmlets are differentiated by point colour. Shading represents 99% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3. LWG AUC^{-1} investigation

A negative relationship ($r = -0.809$, $p < 0.001$), with a concave up decreasing curve, was found between LWG AUC^{-1} and an animal's age (Fig. 5).

LWG AUC^{-1} differed significantly between breeds ($F = 47.0$, $p < 0.001$) (Fig. 6i) with ST (2.89 s d 0.25) and STX (2.82, s.d 0.21) returning the highest values and BRBX (1.96, s.d 0.08) the lowest. This is reflected by the fact that ST and STX made up 53.3% of the top 10% of animals by LWG AUC^{-1}, despite making up just 15.7% of the population. Significant differences were present between breeds in relation to slaughter liveweight ($F = 18.78$, $p < 0.001$) and slaughter age ($F = 105.13$, $p < 0.001$). Breeds with lower slaughter ages and liveweights had a greater LWG AUC^{-1}. Differences in LWG AUC^{-1} between farmlets ($F = 3.06$, $p = 0.048$) (Fig. 6ii) were small, with the MG farmlet yielding slightly lower results (2.53, s.d 0.29) than GWC (2.60, s.d 0.32) and PP (2.57, s.d 0.30). Slaughter LWs were not significantly different between farmlets ($F = 0.12$, $p = 0.988$), averaging 614 kg (s.d 52.3). However, the time it took to reach those liveweights was significantly different ($F = 3.93$, $p = 0.020$) between farmlets with GWC finishing earliest (626 days, s.d 84.1), followed by PP (627 days, s.d 83.1), and MG (638 days (s.d 82.0). MG yielded a significantly lower LWG AUC^{-1} than both GCW and PP. Sex did not yield a statistically significant difference in LWG AUC^{-1} ($F = 0.736$, $p = 0.3914$) (Fig. 6 iii). Between sexes, there was a

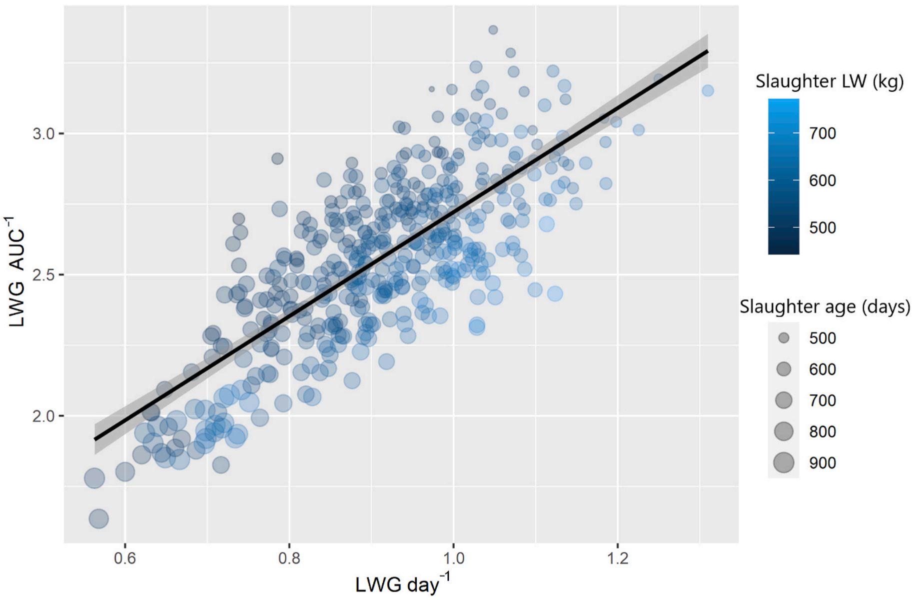

Fig. 4. Relationship between LWG day^{-1} and LWG AUC^{-1}. Each point represents one animal. Point colour represents slaughter liveweight (kg) and point size represents slaughter age (days). The trendline is linear with a 99% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1

Correlations of time with DMI, CH_4 and N_2O. Coefficient comparison: *z*-test results comparing correlation coefficients of time and AUC against the relevant LCA cost factors.

Metric:	LWG AUC^{-1}		LWG day^{-1}		Correlation comparison	
Component:	AUC		time(days)			
	R	p	r	p	z	p
DMI	0.886	<0.001	0.752	<0.001	5.581	<0.001
CH_4	0.788	<0.001	0.563	<0.001	3.045	<0.001
N_2O	0.474	<0.001	0.142	0.189	3.232	<0.001

For the whole dataset, there was a positive relationship between LWG day^{-1} and LWG AUC^{-1} ($r = 0.766$ $p < 0.001$) Higher LWG AUC^{-1} scores were associated with a lower slaughter liveweight and age.

significant difference in slaughter liveweight ($F = 213.91$, $p < 0.001$) with heifers having a mean of 584 kg (s.d 38.9) compared to steers at 643 kg (s.d 46.5). There was no statistically significant difference in slaughter age ($F = 2.378$, $p = 0.124$) between sexes with a mean heifer slaughter age of 623 days (s.d 82.6) and mean steer age of 637 days (s.d 83.1). Animals that finished on pasture had significantly better LWG AUC^{-1} (mean = 2.82) compared to those finishing during a second winter housing period (mean = 2.48) ($t = 11.3$, $p < 0.001$).

4. Discussion

AUC correlated strongly with DMI, CH_4 emissions, and N_2O emissions. Reporting AUC relative to LW gain (LWG AUC^{-1}) will therefore give an indication of efficiency. Correlations were significantly stronger than those for time (days) and, consequently, LWG AUC^{-1} appears to be

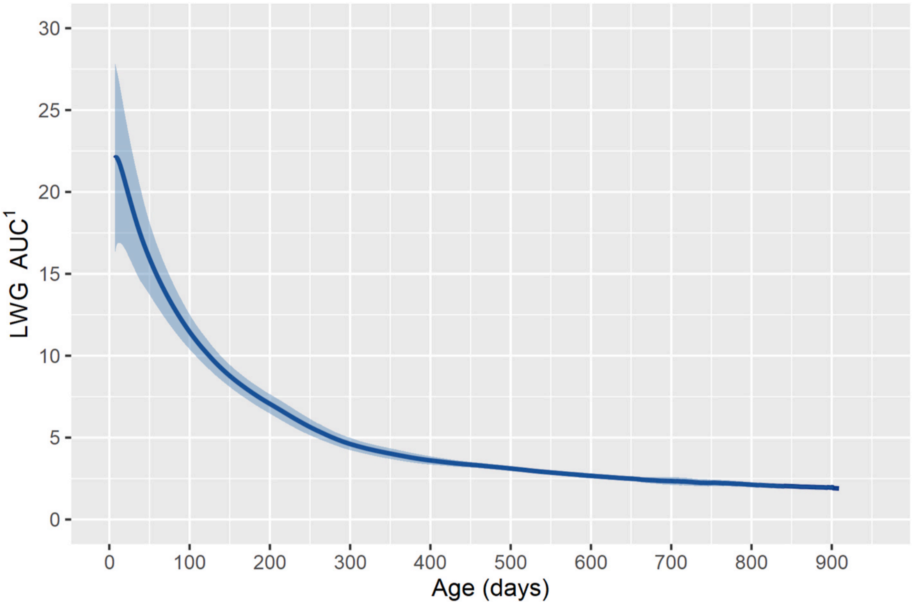

Fig. 5. Relationship between LWG AUC^{-1} and animal age (days). The bold line is the mean value for all animals and the shading represents one standard deviation.

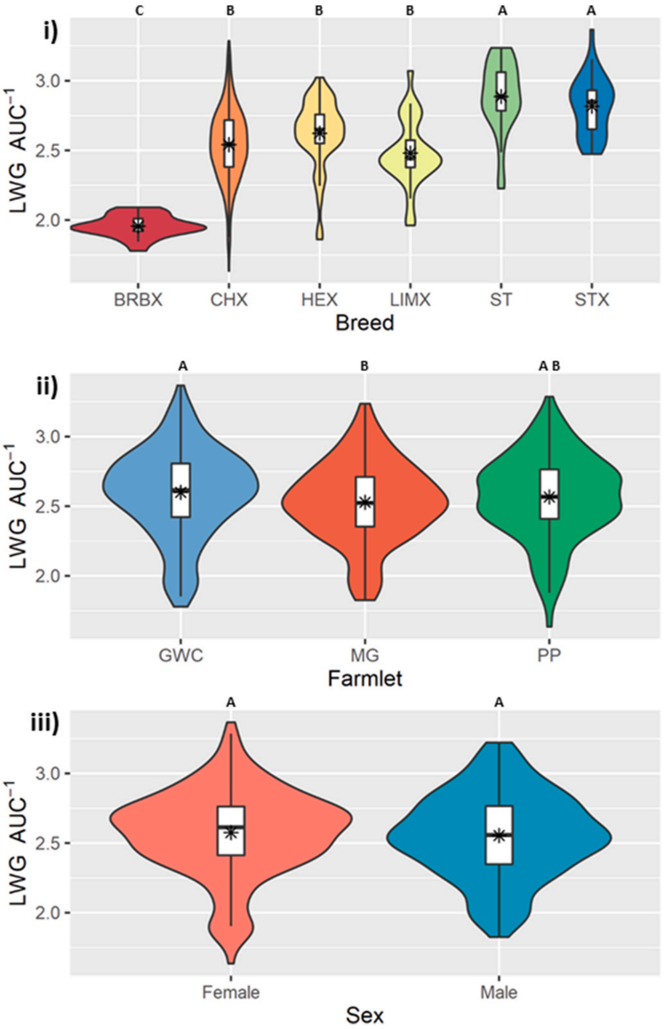

Fig. 6. Combined violin and box plots showing the relationship of breed (i), farmlet (ii), and sex (iii) on LWG AUC^{-1}. Asterisks represent mean. Within each sub-plot, groups sharing a letter in common are not statistically significant to one another.

a more accurate measure of efficiency than the industry standard of LWG day^{-1}, without the need for additional data.

Given the simplicity of the metric and low data requirements, it has a broad use case in circumstances where more sophisticated and data intensive solutions are unviable. Whilst the calculations for LWG AUC^{-1} are relatively simple, manual calculation is impractical and integration into existing farm management software is desirable. This approach may be less suitable for farms that only rarely weigh animals (e.g. just at weaning and slaughter). The metric could also provide opportunity for engagement with farmers over economic and environmental efficiency. However, the complexity of farming systems must not be underestimated, and thus LWG AUC^{-1} application is as a strictly indicative tool, to be used alongside other information, to enable informed decision making and monitor progress.

Comparison between AUC and the factors determined by McAuliffe et al. (2018) provided evidence that it has capabilities as a proxy for DMI and GHG emissions. Correlation of AUC with DMI was especially strong, reflecting that LW is a primary driver of DMI (Saubidet and Verde, 1976). Correlations were also strong for CH_4, reflecting that CH_4 emissions are driven by enteric fermentation of dry matter and thus increased DMI can lead to increased GHG emissions (Kebreab et al., 2010). The variable correlation of AUC with N_2O across farmlets suggests that the metric is best suited for like-to-like comparisons of animals within a specific group, as opposed to between groups with management differences. However, we would like to highlight that preliminary work has been conducted, repeating this comparative analysis on the next year's cohort of cattle, in which the correlations of AUC and N_2O were stronger (DMI and CH_4 remain similar). Given that liveweight data was used within the LCA methodology, some autocorrelation between that and AUC may be inevitable, however, this is reflective of how significant a driver liveweight is to DMI and GHG emissions.

The association between age and LWG AUC^{-1} s showed that earlier slaughter ages are associated with lower costs (DMI and emissions) relative to the LW produced. This is borne out in results showing greater LWG AUC^{-1} scores for animals that were finished on pasture (e.g. more quickly) than those that entered housing for a second period to be finished there. This is because earlier slaughter limits the increase in maintenance requirements (daily LW gain). When ranking by slaughter age, the third quartile animal in this study yielded an LWG AUC^{-1} 15.9% greater than the first quartile animal. Practically, these results show that a greater number of smaller cattle produce the same LW for less cost than a herd of larger cattle in smaller numbers. The relationship between slaughter age and environmental impacts has been observed elsewhere (Legesse et al., 2016; Murphy et al., 2017) and is recognised by the National Beef Association (UK) (National Beef Association, 2020). When considering earlier slaughter, finishing times must be balanced against other factors such as expected kill-out and whether the animal is 'in-spec', to ensure monetary rewards is optimised and market demand met. Across most of Europe, this is based on the EUROP grid classification system on which R4L to E4L are most desirable and yield the greatest prices (AHDB, 2022). However, target specification will differ between systems and ethoses. Slaughter age also affects the utilisation of resources. Finishing cattle too early could lead to grass being left unused, and its economic value not being actualised. Another consideration is how earlier slaughter is achieved. For example, the use of imported grains to increase growth rates would have its own economic and environmental costs (Vellinga et al., 2015). Therefore, LWG AUC^{-1} should not dictate slaughter times, but act as a tool to inform them.

The high LWG AUC^{-1} for ST and STX animals is likely driven by genetic for smaller animals that finish quickly (Stabiliser Cattle Company, 2022), meaning that they are carrying less weight for less time. The poor performance of BRBX animals is likely a consequence of the breed's 'double muscle' trait and the energy requirements to grow and maintain that. Differences in LWG AUC^{-1} between heifers and steers were non-significant and any effect, if present, was likely a consequence of slaughter age and LWs. Liveweight gain of heifers is relatively consistent up until about 600 days of age when growth plateaus (Martín et al., 2020). Sending heifers to slaughter earlier (and therefore at lighter LWs) was a management decision, which has the effect of lowering the overall LWG AUC^{-1}. Steer efficiency could be improved by bringing forward slaughter ages. The lower LWG AUC^{-1} observed in the MG farmlet is likely a consequence of the different forage and the impact of that on growth (Mwangi et al., 2019; National Research Council, 2000). This particular cultivar is relatively erect and thus land cover (dry matter per hectare) is lower than other cultivars, which may lead to a lower DMI and growth rates.

Within the calculation of LWG AUC^{-1}, LWG is considered as the reward. However, other figures could be substituted. Sale price (balanced for price fluctuations) is a key candidate as it is the true representation of economic reward and is driven by both the kill-out percentage and carcase grading, however, this could only be calculated post-slaughter.

The relative simplicity of LWG AUC^{-1} is a weakness and a strength. It is limited in its ability to account for individual differences between animals, herds, and farms. Factors such as feed type can influence GHG emission intensities of cattle (Haque, 2018; Kebreab et al., 2010; Min et al., 2020) and any large changes across such factors may mean that AUC is less accurate - the inter-farmlet difference in correlations of AUC and N_2O emission highlight this. Care should be taken if applying LWG

AUC^{-1} between disparate herds or systems. Arguably the best use-case is for benchmarking animals against each other within a defined setting.

5. Conclusion

The metric LWG AUC^{-1} better accounts for the reward/cost ratio in beef systems than the industry standard of LWG day^{-1} and may have utility for proxy estimation of DMI, CH_4 emissions, and N_2O emissions. This is achieved without the requirement for new data in excess of what many farms already collect and use for the current LWG day^{-1}. Consequently, there is broad use potential for the metric within the beef sector, particularly where more sophisticated methods are not feasible. Care must be taken in how it is applied, especially if between disparate herds and systems.

Credit author statement

AC: concept, project management, data analysis, manuscript preparation, PLG: data collection, animal management, manuscript preparation, GM: analytical/data advice, manuscript preparation, ML: funding acquisition, project management, manuscript preparation, MR: funding acquisition, project management, manuscript preparation.

Ethical statement

BBRSC's Farm Platform (Rothamsted Research, North Wyke) is an experiment granted ethical approval by Rothamsted Research's Animal Welfare Ethical Review Board in accordance with the Animal (Scientific Procedures) Act (1986).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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