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The nutritional value of meat should be considered when comparing the carbon footprint of lambs produced on different finishing diets

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Introduction: Lamb production systems are under increasing pressure to reduce their environmental footprint, particularly emissions of greenhouse gases (GHGs) such as methane. However, the metrics used to express the carbon footprint of lamb seldom consider its nutritional density and contribution to balanced diets in humans. Lamb production systems vary considerably, from low-input pastoral systems to higher-input systems feeding concentrates for the latter 'finishing' period. To date, no studies have explored the effect of finishing diet on the carbon footprint of lamb meat on a nutritional basis.

Methods: Data from 444 carcasses were collected from four abattoirs across Wales, United Kingdom. Lambs were derived from 33 farms with one of four distinct finishing diets: *forage crops* (n = 5), *grass* (n = 11), *concentrates* (n = 7), and *grass and concentrates* (n = 15). Carcass data were analysed using mixed effects models. Significant differences were found in fatty acid composition of two large commercial cuts of meat from different finishing diets. To illustrate the effect of different measures of footprint, mass (kg dwt) and omega-3 polyunsaturated fatty acid content (g omega-3) were selected as functional units. GHG emission estimates were calculated using Agrecalc.

Results: The *concentrates* diet had the lowest average mass-based product emissions [25.0 kg CO_2e/kg deadweight (dwt)] while the *grass* systems had the highest (28.1 kg CO_2e/kg dwt; p < 0.001). The *semimembranosus* muscle cut from the *forage crops* diet had the lowest average nutrition-based product emissions (19.2 kg CO_2e/g omega-3); whereas the same muscle cut from lambs finished on the grass and concentrates diet had the highest nutrition-based product emissions (29.4 kg CO_2e/g omega-3; p < 0.001).

Discussion: While mass-based functional units can be useful for comparing efficiencies of different farming systems, they do not reflect how farming systems impact the nutritional differences of the final product. This study demonstrates the importance of considering nutrition when expressing and comparing the carbon footprints of nutrient-dense foods such as lamb. This approach could also help inform discussions around the optimal diets for lamb production systems from both a human nutrition and environmental sustainability perspective.

KEYWORDS

sheep systems, farm management, fatty acids, human nutrition, environmental impacts of meat, Omega-3, nutritional LCA, sustainable agriculture

1 Introduction

Lamb production systems are under increasing pressure to reduce their environmental footprint, particularly greenhouse gas (GHG) emissions such as methane (Garnett, 2011; Gerber et al., 2013; Jones et al., 2014a). In recent years, carbon footprinting of farms and the resultant produce (e.g., meat) has been increasingly used to estimate resultant environmental impacts (Edwards-Jones et al., 2009; de Vries and de Boer, 2010; Röös et al., 2013; Jones et al., 2014b). Calculating a farm's carbon footprint offers the opportunity to identify sources of high emissions as well as compare emissions from different farming systems. However, such approaches rarely consider the carbon footprint of lamb relative to its nutritional density as a food product, as the standard functional unit for expressing lamb carbon footprint is per unit of product, e.g., kg CO_2e/kg of liveweight (lwt) or kg CO_2e/kg of deadweight (dwt; Edwards-Jones et al., 2009; Jones et al., 2014a,b; Ripoll-Bosch et al., 2013). While this mass-based functional unit is useful for comparing efficiencies of different farming systems (Hyland et al., 2016; McAuliffe et al., 2018a), it does not reflect the nutritional value of the product to humans. Several different approaches have been taken to address this, including using a nutritional functional unit to model carbon footprint while considering nutrient density (McLaren, 2021; McAuliffe et al., 2023a).

Ensuring an appropriate nutrient to use as a functional unit is paramount, as this can directly affect carbon footprint calculations. Previous research has used protein as a nutritional functional unit (e.g., Poore and Nemecek, 2018; Xu et al., 2018). Protein as a nutritional functional unit is useful due to simplicities in data processing; however, it can be considered a rudimentary approach as it does not reflect the impact of individual amino acids and intricacies associated with digestion and absorption (Sonesson et al., 2017; McLaren, 2021). Consequently, protein quality has been incorporated into nutritional functional units. For example, McAuliffe et al. (2023b) used an assessment called the Digestible Indispensable Amino Acid Score (DIAAS), which generates a protein quality "adjusted" functional unit. While this is a useful metric for studies comparing a single nutrient, a product's complete nutritive value is not accurately reflected. Nutrition density scores (NDS) provide a single functional unit in which multiple nutrients can be assessed. The most cited approach for using NDS to express emissions is the Nutrient Rich Food (NRF9.3; Fulgoni et al., 2009) scoring system which accounts for nine nutrients including protein, selected minerals and vitamins, polyunsaturated fatty acids (PUFA) and three nutrients which are to be limited, namely, saturated fatty acids (SFA), sodium and added sugars. Given the complexities and importance of carbon footprinting for environmental targets, policy and consumers, the use of an appropriate functional unit is paramount for accurate determination of a product's nutrient density and carbon footprint (Capper, 2021).

Research has identified that while protein and amino acid profiles of meat remain largely constant across the diets on which livestock are reared, fat content and lipid profiles are heavily influenced by animal nutrition (Scollan et al., 2006). Most notably, grass-based systems have been found to have higher levels of omega-3 PUFA than systems feeding concentrates (Fisher et al., 2000; Warren et al., 2008). Omega-3 PUFA is a functional unit of great importance due to its potential health benefits and nutraceutical properties in humans, e.g., reducing the risk of cardiovascular disease and other inflammatory diseases (Swanson et al., 2012). Consequently, omega-3 PUFA as a single nutrient functional unit has been explored to express emissions, particularly when comparing farming systems (McAuliffe et al., 2018b). Lamb production systems also vary across the world, from low-input pastoral systems to higher-input systems feeding concentrates for the latter 'finishing' period. In the United Kingdom, many farms are typically grass-based systems, but some will provide supplementary concentrates and/or forage crops [e.g., swede (*Brassica napus*) or stubble turnips (*Brassica rapa*)] during the autumn/winter finishing period as grass availability and quality reduces (Barry, 2013).

To date, no studies have explored the effect of finishing diets on the carbon footprint of lamb expressed on a nutritional basis. Using data gathered on farms adopting one of four distinct finishing diets and data from the produced meat, this study applies a dual approach to evaluate the impacts of diet on the carbon footprint of lamb expressed on both a mass and nutritional basis, using omega-3 PUFA in 1 kg of fresh muscle as a functional unit.

2 Methods

2.1 Farm data collection

This paper is based on data from a larger 5-year study that included four balanced design trials. The Welsh Lamb Meat Quality Project conducted research trials across the United Kingdom, exploring on-farm and processing factors that may influence meat eating and nutritional quality. The on-farm factors were investigated across four trials, and included treatments of breed type, lamb gender, muscle cut, lamb finishing diet, daily liveweight gain, seasonality, lamb sire, and processing factors including length of meat ageing period, carcass hanging and packaging (Hybu Cig Cymru – Meat Promotion Wales, 2023). Lamb numbers per treatment were balanced within each trial; however, numbers differed across trials due to lamb availability. Trials were conducted with four Protected Geographical Indication (PGI) approved Welsh abattoirs (DEFRA, 2021) that had previous experience of participating in large trials.

The abattoirs identified lamb producers that could supply lambs for the project (based on the specific trials treatments that were required, e.g., supply lambs of a certain sex, finished on specific diets). A minimum of 24 lambs per farm were needed to reach a target slaughter date. The overall study aim was to research Welsh lamb eating quality across the range of systems that reflect production across the year. As such, the diet of the lambs was representative of those at different seasons / time of year. For example, forage-based crops can only be sown and used for finishing lambs at certain times (Hybu Cig Cymru – Meat Promotion Wales, 2018).

Farm data were collected from 33 farms feeding one of four distinct finishing diets: *forage crops* ($n=5$), *grass* ($n=7$), *concentrates* ($n=6$), and *grass and concentrates* ($n=15$). The *forage crop* diet consisted of brassicas, fodder beet and forage rape. In the *concentrates* finishing system, lambs were all fed indoors on a diet of concentrates, barley, crimped barley or coarse mix, whereas the *grass* and the *grass and concentrates* diets were all fed outdoors and exclusively on grass and grass and concentrates, respectively. Farm data were self-reported by participating farmers using digital farm information surveys. All farms produced lambs to PGI Welsh lamb standards (DEFRA, 2021). In total, there were 60 lambs fed the *forage crop* diet, 90 lambs fed the *grass* diet, 66 lambs fed the *concentrates* diet, and 228 lambs fed the *grass and concentrates* diet (Table 1). Lambs were born between January 2020 and April 2022 and their age was recorded as the number of days between the average lambing date and the date of slaughter. Lambs consisted of several breeds: terminal sire ($n=382$), hill ($n=38$) and cross-breeds ($n=24$). Previous studies have found breed could potentially affect meat-eating quality (Fisher et al., 2000; Arsenos et al., 2002), therefore breed was controlled for in the statistical design of the study. Terminal sire breeds included Aberfield, Abermax, Charollais, Lleyn, Primera, Suffolk and Texel. The hill breed type included Beulah Speckled Face, Welsh Mountain and Torddu. Lambs were a mixture of male (entire $n=288$; castrated $n=72$) and females ($n=84$; Table 1). Individual lamb weights were recorded on a fortnightly basis over the 6-week finishing period to calculate their liveweight gain for that period. In cases where specific data were difficult to obtain or where any data were missing, recently published UK data or standardised estimates were used. This was sourced predominantly from SRUC's Farm Management Handbook (Beattie, 2022) and Feedipedia (Heuzé et al., 2015). For example, data were collected for diet type; however, actual feed consumption was not included. Therefore, assumptions were made on forage and concentrate intake based on example finishing systems and values from SRUC's Farm Management Handbook (Beattie, 2022).

2.2 Carcass data collection

Lambs were selected at the target carcass weight of 16–22 kg and conformation grade of E, U, R and fat class 2, 3 L, 3H (Hybu Cig Cymru – Meat Promotion Wales, 2012). From the farms selected that provided whole farm data, 444 carcasses were available for analysis. Carcasses were weighed directly after slaughter to calculate the killing out percentage (KO%). Three of the largest lamb muscles used in other lamb sensory scientific studies (Bonny et al., 2018; Pannier et al., 2018; MSA, 2019; Pannier et al., 2019) were selected using the Meat Standards Australia cooking protocol, being the *longissimus dorsi* (Loin; $n=444$), *semimembranosus* (Topside; $n=203$) and *gluteus medius* (Chump cut; $n=96$). The *longissimus dorsi* was analysed for all lambs (number of lambs from each diet, breed type and gender can be found in Section 2.1). The *semimembranosus* analysed included 36 lambs fed the *forage crop* diet, 36 lambs fed the *grass* diet, 18 lambs fed the *concentrates* diet, and 113 lambs fed the *grass and concentrates* diet. Lambs from the *semimembranosus* analysed also consisted of several breeds: terminal sire ($n=173$), hill ($n=8$) and cross-breeds ($n=22$). All *semimembranosus* samples analysed came from ram lambs ($n=203$). Eight days post slaughter, the muscle pH was recorded for each cut. Muscles were stored at −20°C until nutritional analysis.

2.3 Nutritional analysis

Fatty acid composition was determined by the method of O'Fallon et al. (2007). Lean lamb muscle was hydrolysed with potassium hydroxide in methanol. The potassium hydroxide was neutralised, and the free fatty acids methylated by acid catalysis using sulphuric acid. Fatty acid methyl esters were extracted into hexane and analysed by GC-FID using a CP-SIL 88 column (100 m × 250 μm × 0.2 μm). Intramuscular fat was determined by the method of Folch et al. (1956) with the percentage of extracted fat calculated gravimetrically.

For total amino acid analysis, 100 g of fresh muscle was hydrolysed in constant boiling hydrochloric acid. Samples were then dried down, diluted and analysed on a Waters 2,695 pump/injector system. The individual amino acids were separated by ion exchange chromatography on a strong cation exchange resin using sodium citrate buffer gradients of increasing pH. The ninhydrin reagent was pumped using a Waters 1,515 isocratic pump. The ninhydrin reaction occurs in a heated reaction coil at 125°C, and the derivatized amino acids are detected using a Waters 2,487 variable wavelength UV/VIS detector.

Mineral analysis was carried out using a two-stage microwave digestion followed by Inductively Coupled Plasma Optical Emission

TABLE 1 Summary of the mean key performance indicators (± standard error) over the 6-week finishing period and number of farms carbon footprinted for each finishing diet.

	Diet				
	Forage crops	Grass	Concentrates	Grass and concentrates	Value of *p*
No. of farms (No. of lambs)	5 (60)	7 (90)	6 (66)	15 (228)	
Liveweight at start of finishing period (kg)	37.3 ± 0.36[a]	33.0 ± 0.86[b]	35.7 ± 0.27[a]	33.4 ± 0.36[b]	<0.001
Liveweight gain (g/day)	179 ± 8.48[a]	213 ± 11.40[a]	189 ± 10.63[a]	268 ± 8.15[b]	<0.001
Total weight gain over finishing period (kg)	6.7 ± 0.32[a]	8.6 ± 0.48[b]	7.3 ± 0.31[ab]	10.2 ± 0.17[c]	<0.001
Liveweight at slaughter (kg)	44.0 ± 0.29[a]	42.0 ± 0.54[b]	43.0 ± 0.34[ab]	43.6 ± 0.26[a]	<0.01
Killing out percentage (%)	46.6 ± 0.38[a]	45.8 ± 0.56[a]	46.3 ± 0.32[a]	46.8 ± 0.20[a]	>0.05
Carcass weight (kg)	20.5 ± 0.16[a]	19.1 ± 0.21[b]	19.9 ± 0.15[a]	20.3 ± 0.11[a]	<0.001

Different lower-case letters indicate statistically significant differences at the 5% level.

Spectroscopy using wavelengths 238.2 and 213.9 nm for iron and zinc, respectively. ERM-BB184 Bovine Muscle from the Joint Research Centre of the European Commission was used as a quality control material. ISO 17034 certified reference standards for zinc and iron were purchased from ROMIL Ltd., Cambridge, United Kingdom.

The full nutritional analysis methods are available in the Supplementary material.

2.4 Emission estimates

Baseline carbon footprints were calculated using Agrecalc (Agricultural Resource Efficiency Calculator).[1] Agrecalc was developed by Scotland's Rural College and has been found to be among the best-performing carbon accounting tools in terms of transparency, methodology and allocation for use on UK farms (Sykes et al., 2017). The system boundary for Agrecalc is "cradle-to-grave," i.e., all emissions from agricultural production from the birth of the animal to the farm gate. The tool uses methods from the latest 2019 refinements to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and is certified to PAS2050 standards (2011). Agrecalc follows IPCC (2019) Tier 2 country-specific guidelines for all livestock and manure management CH_4 and N_2O emissions. Direct N_2O emissions from soil following fertiliser and manure application also used IPCC (2019) Tier 2 calculations. IPCC (2019) Tier 1 methodology was used to calculate N_2O emissions from crop residues and indirect N_2O emissions. DEFRA, (2021) EFs were employed for calculating emissions relating to energy usage. Emissions for imported feed and embedded fertiliser were based on values from the Dutch Feedprint database (Vellinga et al., 2013) and Kool et al. (2012), respectively. Data required to calculate sequestration estimates were not provided, therefore, carbon sequestration was not considered in this study.

For conversion of non-CO_2 gases, Agrecalc uses the global warming potential over a 100-year period (GWP100) published in the fourth assessment report (AR4) which are consistent with National Inventory reporting. Methane has a GWP100 of 25 and the value for N_2O is 298 (IPCC, 2007). It is important to note that these values are different from those in the most recent assessment report (AR6; IPCC, 2023).

Emissions from Agrecalc were expressed as both GHG emissions per unit of product (i.e., kg CO_2e/kg of deadweight (dwt)) and GHG emissions per unit of nutrition. To calculate the latter, the value of mg omega-3 measured in 100 g of fresh muscle, determined as described in Section 2.2, was converted to the equivalent in g omega-3 in 1 kg of fresh muscle. The calculated GHG emissions per kg dwt were then divided by this to give kg CO_2e/g omega-3, giving the GHG emissions per unit of nutrition.

2.5 Statistical analyses

For individual variables, models were fitted using mixed effects models in R (R Core Team, 2022). Models were fitted using the lme4 package (Bates et al., 2015) and value of *p*s were calculated using Satterthwaite's method from the lmerTest package (Kuznetsova et al., 2017). In all models, Farm was included as a random effect and models included diet, breed type and gender as factors. This approach allowed the analysis of the data that was unbalanced in breed and gender while controlling for any differences in these factors not of direct interest. Gender was not included for the *semimembranosus* models as all the lambs in this group were male. Pairwise differences were calculated using the emmeans package (Lenth, 2023) using a Tukey correction for multiple comparisons. After fitting diagnostic plots for all models were checked for any evidence of heterogeneity of variance or non-normality of errors. For a few variables a log (or log+1) transformation was applied to correct for heterogeneity of variance. Data were plotted using the ggstats package (Larmarange, 2023).

To assess the effect of diet on finishing system performance, a one-way ANOVA and Tukey pairwise-comparison were performed on individual key performance indicators (KPIs). A one-way ANOVA was conducted to assess the effect of diet on mass-based product emissions and a two-way ANOVA was used to test for an association between diet and muscle cut on nutrition-based product emissions. Multiple pairwise-comparison between the means of groups were then performed using Tukey multiple pairwise-comparisons. The level of statistical significance was set at 5% for all tests in this study.

3 Results

3.1 Farm and lamb production data

Lamb growth and weights varied between finishing diets. Lambs from the *forage crops* and *concentrates* diet had significantly higher liveweights at the start of the finishing period compared to lambs on *grass* and *grass and concentrates* diet (Table 1). Lamb age varied at the start of the finishing period to reflect the inherent differences in the production and seasonality of the different finishing systems according to industry practice. Lambs from the *grass and concentrates* diet had significantly higher liveweight gain and total weight gain over the finishing period than lambs from all other diets. Lambs on the *forage crops* diet had the highest liveweight at slaughter whereas the *grass* diet had the lowest liveweight at slaughter (Table 1). Killing out percentages did not vary significantly between diets. Lambs from the *grass* only diet had significantly lower carcass weights compared to lambs on all other diets (Table 1).

Although not directly related to the finishing diet and likely influenced by how lambs were selected, time on farm varied between lambs from different finishing systems. Lambs from the *concentrates* diet were on farm for the longest time (mean 9.2 ± 0.17 months) compared to lambs from: the *forage crops diet* which were on farm for 8.5 ± 0.19 month ($p > 0.05$), *grass* diet which were kept for 6.0 ± 0.22 months ($p < 0.001$) and *grass and concentrates* diet which were on farm for the least time at 5.2 ± 0.11 months ($p < 0.001$).

3.2 Nutritional composition of lamb meat

There was no significant difference between the amino acid content of *gluteus medius* across the four diets (Supplementary Table 1;

1 https://www.agrecalc.com/

$p > 0.05$). As expected, there were also no significant differences found in the iron content of both the *longissimus dorsi* and *semimembranosus* across all four diets ($p > 0.05$), the iron content of muscle is more associated with age than diet (Pannier et al., 2014). Additionally, there was no significant differences in the zinc content in the *semimembranosus* across all diets, however, diet did have an effect on the zinc content of the *longissimus dorsi* ($p < 0.001$).

Fat percentage varied significantly between finishing diets in both the *longissimus dorsi* and *semimembranosus* ($p < 0.05$). Differences were noted in the total fatty acid composition and saturated fatty acid in the *longissimus dorsi* across the four diets ($p < 0.05$); however, there were no differences found in total fatty acid content of the *semimembranosus* across diets (Table 2; discussed in Section 4.1). There were significant differences in the total omega-3 PUFA content in the *longissimus dorsi* across the four finishing diets ($p < 0.001$), with the highest and lowest being reported in muscle from the *grass* and *concentrate* diets, respectively. The analysis controlled for the differences in breed type (*longissimus dorsi* and *semimembranosus*) and gender (*longissimus dorsi* only). There was not a consistent pattern among fatty acids, with breed type and gender being significantly different in some but not all of the variables (full results can be found in Supplementary Table 2). For the variable of interest (omega-3 PUFA), breed type had a significant effect in the *semimembranosus* ($p < 0.05$) but not in the *longissimus dorsi* ($p > 0.05$). There was also a significant difference in omega-3 PUFA between genders in the *longissimus dorsi* ($p < 0.05$).

There were significant differences in levels of palmitic acid (C16:0) and stearic acid (C18:0) across the four diets in the *longissimus dorsi* muscle ($p < 0.05$), with no differences detected in the *semimembranosus* (Table 2). Linoleic acid (C18:2 n-6) was significantly greater in the *concentrate* diet and lowest in the *grass* diet in the *longissimus dorsi* muscle. There was no difference between C18:2 n-6 levels from lamb finished on the *forage crops* and *grass and concentrate* diet.

Lamb from the *forage crops* diet and *grass* diet had significantly higher alpha-linolenic acid (C18:3 n-3) in both the *longissimus dorsi* and *semimembranosus* with levels being reported as 62 and 61 mg/100 g and 71 and 73 mg/100 g, respectively, compared to the *concentrate* diet where 42 mg/100 g was reported for both muscles. There were differences in levels of eicosapentaenoic acid (C20:5 n-3; $p < 0.001$), docosapentaenoic acid (C22:5 n-3; $p < 0.05$) and docosahexaenoic acid (C22:6 n-3; $p < 0.001$) across diets in the *longissimus dorsi* muscle, however, no differences in any long chain omega-3 PUFA was noted in the *semimembranosus*.

Omega-3 PUFA is known to have a variety of health benefits such as reduced risk of cardiovascular disease and other inflammatory diseases (Swanson et al., 2012). Omega-3 PUFA composition of lamb is also known to vary significantly between animal diets, particularly between grass and concentrate feeding (Fisher et al., 2000; Warren et al., 2008). Our finding are in line with other previous studies. Grams of omega-3 in 1 kg of fresh muscle (kg CO_2e/g-omega-3) was selected as a functional unit to express emissions on a nutritional basis.

3.3 Mass-based and nutrition-based product emissions

Mass-based product emissions varied significantly from 21.8–36.4 kg CO_2e/kg dwt across finishing diets ($p < 0.001$). There were significant differences in mass-based product emissions between all diets ($p < 0.05$) apart from the *forage crops* and *grass and concentrates* diets ($p > 0.05$). Lambs from the *concentrates* diet had the lowest average mass-based product emissions (25.0 kg CO_2e/kg dwt) while those from the *grass* systems had the highest (28.1 kg CO_2e/kg dwt; Figure 1; $p < 0.001$). Variation in mass-based product emissions was also seen within the same diets, for example, *grass and concentrates* diet, highest mass-based product emissions (36.4 kg CO_2e/kg dwt) were more than 1.6 times higher than the lowest (22.2 kg CO_2e/kg dwt).

Further variation was seen when accounting for omega-3 content, with nutrition-based emissions ranging from 12.1–73.8 kg CO_2e/g omega-3. Nutrition-based emissions were greater for *longissimus dorsi* than for *semimembranosus* across all diets other than *for grass and concentrates*, although this difference was not statistically significant ($p > 0.05$). Significant differences in nutrition-based product emissions between the two muscle cuts were only found in the *forage crops* diet ($p < 0.01$; data not shown). The *semimembranosus* cut of lambs from the *forage crops* diet had the lowest average nutrition-based product emissions (19.2 kg CO_2e/g omega-3; Figure 1), whereas the *semimembranosus* cut of lambs from the *grass and concentrates* diet had the highest nutrition-based product emissions (29.4 kg CO_2e/g omega-3; $p < 0.001$).

4 Discussion

4.1 Omega-3 PUFA composition

Significant differences were found in the total fatty acid composition and saturated fatty acids in the *longissimus dorsi,* but not in the *semimembranosus* across the four finishing diets. This it is likely due to the *longissimus dorsi* having a higher total fat content than the *semimembranosus* (Supplementary Table 1). Differences were found in the fatty acid composition of the *semimembranosus* across finishing diets, however, these differences were not significant. This may be due to the lower number of *semimembranosus* samples analysed ($n = 203$) compared to the *longissimus dorsi* ($n = 444$), due to this study being part of a larger research trial looking at multiple variables, one being muscle/cut. Nonetheless, significant differences were found in C18:3 n-3 and the n-6/n-3 ratio in the *semimembranosus* of lambs across finishing diets, which was ultimately a key focus of the study.

The total fat content for lamb meat was highest in the *longissimus dorsi* from the *forage crops* diet and lowest in *semimembranosus* from the *grass and concentrates* diet. Pasture feeding is often associated with lower meat fat content as found by Fisher et al. (2000) and Nuernberg et al. (2008), who reported 1963 vs. 1853 mg/100 g and 2,100 vs. 1800 mg/100 g muscle in concentrate- and grass-fed lamb, respectively. Conversely, Demirel et al. (2006) reported lambs finished on grass hay had higher total fatty acid, compared to concentrate feeding. This is similar to the saturated fatty acid composition in the *longissimus dorsi* in the current study, where again the *grass and concentrates* diet was lowest. However, the saturated fatty acid composition did not differ significantly between the diets in the *semimembranosus.*

Levels of C18:2 n-6 were higher in lambs that had been fed *concentrates* as part of or as a sole dietary component. This is unsurprising as concentrates are rich in linoleic acid, whereas grass and forage crops would have relatively low levels. Lambs from the

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TABLE 2 Estimated marginal mean (± standard error) fatty acid composition of lamb meat from four finishing diets averaged over breed type and gender for *longissimus dorsi* and breed type for *semimembranosus*.

Fatty acid (mg/100 g)	*Longissimus dorsi*					*Semimembranosus*				
	Forage crops	Grass	Concentrates	Grass and concentrates	Value of *p*	Forage crops	Grass	Concentrates	Grass and concentrates	Value of *p*
C12:0	3.9 ± 1.05^{a}	9.8 ± 0.86^{b}	4.7 ± 0.94^{a}	7.3 ± 0.85^{b}	<0.001	4.5 ± 0.58^{a}	4.3 ± 0.69^{a}	4.8 ± 0.64^{a}	5.2 ± 0.51^{a}	0.484
C14:0	61.8 ± 9.72^{a}	104.5 ± 8.18^{b}	58.4 ± 8.12^{a}	78.4 ± 7.67^{a}	<0.001	58.4 ± 5.25^{a}	55.3 ± 6.21^{a}	57.1 ± 5.76^{a}	54.9 ± 4.62^{a}	0.927
C16:0	720 ± 44.2^{ab}	648 ± 36.6^{ab}	737 ± 38.2^{b}	622 ± 35.3^{a}	0.008	512 ± 41.4^{a}	521 ± 47.7^{a}	465 ± 41.3^{a}	453 ± 34.5^{a}	0.449
C18:0	537 ± 41.3^{a}	463 ± 33.8^{a}	542 ± 36.7^{a}	466 ± 33.3^{a}	0.030	407 ± 39.1^{a}	445 ± 44.2^{a}	342 ± 36.3^{a}	348 ± 31.1^{a}	0.219
C18:1 t11	109 ± 8.04^{ab}	130 ± 6.69^{b}	111 ± 6.87^{a}	107 ± 6.41^{a}	0.006	71.8 ± 10.09^{a}	95.1 ± 11.69^{a}	79.1 ± 10.25^{a}	79.6 ± 8.51^{a}	0.403
C18:1 n-9 cis	1,148 ± 73.1^{ab}	1,007 ± 60.3^{a}	1,179 ± 63.8^{b}	1,016 ± 58.4^{ab}	0.011	824 ± 56.3^{a}	885 ± 65.7^{a}	760 ± 58.6^{a}	740 ± 48.2^{a}	0.190
C18:2 n-6	104.6 ± 10.52^{ab}	89.1 ± 8.70^{a}	138.2 ± 9.54^{c}	121.4 ± 8.83^{bc}	<0.001	104.7 ± 15.5^{a}	92.1 ± 17.0^{a}	139.9 ± 12.9^{a}	130.7 ± 11.5^{a}	0.115
C20:4 n-6	44.9 ± 3.32^{a}	41.3 ± 2.73^{a}	45.3 ± 3.00^{a}	41.1 ± 2.74^{a}	0.221	42.3 ± 2.21^{a}	35.3 ± 2.61^{a}	41.9 ± 2.41^{a}	41.9 ± 1.94^{a}	0.080
C18:3 n-3	62.1 ± 4.45^{b}	60.5 ± 3.66^{b}	44.2 ± 4.03^{a}	52.7 ± 3.69^{ab}	<0.001	70.5 ± 8.43^{a}	73.0 ± 8.93^{a}	44.0 ± 6.38^{a}	50.3 ± 5.86^{a}	0.041
C20:5 n-3	26.5 ± 1.56^{bc}	29.4 ± 1.28^{c}	21.7 ± 1.40^{a}	24.1 ± 1.28^{ab}	<0.001	27.1 ± 1.98^{a}	29.7 ± 2.22^{a}	22.7 ± 1.79^{a}	23.1 ± 1.55^{a}	0.054
C22:5 n-3	35.1 ± 1.59^{ab}	34.7 ± 1.30^{b}	30.8 ± 1.41^{a}	31.1 ± 1.28^{ab}	0.009	34.2 ± 2.42^{a}	35.4 ± 2.62^{a}	29.3 ± 1.97^{a}	29.8 ± 1.77^{a}	0.179
C22:6 n-3	8.3 ± 0.90^{a}	12.1 ± 0.76^{b}	5.6 ± 0.82^{c}	7.6 ± 0.78^{a}	<0.001	4.8 ± 0.89^{a}	5.9 ± 0.97^{a}	5.7 ± 0.74^{a}	6.9 ± 0.66^{a}	0.110
Total SFA	1,399 ± 87.0^{ab}	1,288 ± 71.9^{ab}	1,404 ± 75.5^{b}	1,208 ± 69.4^{a}	0.031	1,024 ± 83.1^{a}	1,061 ± 95.7^{a}	902 ± 82.6^{a}	893 ± 69.2^{a}	0.324
Total MUFA	1,236 ± 75.6^{ab}	1,089 ± 62.4^{a}	1,271 ± 65.7^{b}	1,095 ± 60.4^{a}	0.008	890 ± 60.0^{a}	946 ± 70.0^{a}	830 ± 62.5^{a}	805 ± 51.4^{a}	0.244
Total PUFA	297 ± 15.0^{a}	274 ± 12.3^{a}	295 ± 13.5^{a}	284 ± 12.2^{a}	0.202	296 ± 28.9^{a}	286 ± 30.9^{a}	299 ± 22.5^{a}	296 ± 20.5^{a}	0.984
Total n-3	132 ± 6.7^{ab}	137 ± 5.5^{b}	102 ± 6.1^{c}	117 ± 5.5^{bc}	<0.001	138 ± 12.8^{a}	146 ± 13.7^{a}	103 ± 10.0^{a}	111 ± 9.1^{a}	0.067
Total n-6	157 ± 13.7^{ab}	138 ± 11.3^{a}	192 ± 12.4^{b}	170 ± 11.5^{ab}	<0.001	153 ± 17.0^{a}	132 ± 18.9^{a}	192 ± 15.0^{a}	178 ± 13.1^{a}	0.086
n-6/n-3	1.2 ± 0.20^{a}	1.0 ± 0.17^{a}	1.9 ± 0.18^{b}	1.4 ± 0.17^{a}	<0.001	1.2 ± 0.22^{ab}	0.9 ± 0.25^{a}	2.1 ± 0.21^{c}	1.8 ± 0.18^{bc}	0.002
PUFA/SFA	0.23 ± 0.025^{a}	0.23 ± 0.020^{a}	0.22 ± 0.022^{a}	0.24 ± 0.012^{a}	0.687	0.29 ± 0.023^{a}	0.25 ± 0.027^{a}	0.33 ± 0.025^{a}	0.32 ± 0.020^{a}	0.038
Total FA	3,080 ± 167^{ab}	2,816 ± 138^{ab}	3,095 ± 144^{b}	2,696 ± 133^{a}	0.016	2,291 ± 165^{a}	2,398 ± 191^{a}	2,117 ± 166^{a}	2083 ± 138^{a}	0.404

Different lower-case letters indicate statistically significant differences between diets within each muscle at the 5% level. Total SFA: Σ C6, C8 C10, C11, C12, C13, C14, C15, C16, C18, C20, C22, C23. Total MUFA: Σ C14:1, C15:1, C16:1c9, C17:1, C18:1n-9 t, C18:1n9c, C18:1 t11, C20:1 n-9, C22:1 n-9, C24:1 n-9. Total PUFA: Σ C18:2 t n-6, C18:2c n-6, C18:3 n-6, C18:3 n-3, C20:2, C20:4 n-6, C20:5 n-3, C22:2, C22:5 n-3, C22:6 n-3, Total n-3: Σ C18:3, C20:4, C20:5, C22:5, C22:6 LC n-3: C20:5, C22:5, C22:6, Total n-6: Σ C18:2 t, C18:2c, C18:3, C20:2, C22:2. C20:4. n-6/n-3: calculated by dividing total n-6 by total n-3. PUFA/SFA: calculated by dividing total PUFA by total SFA.

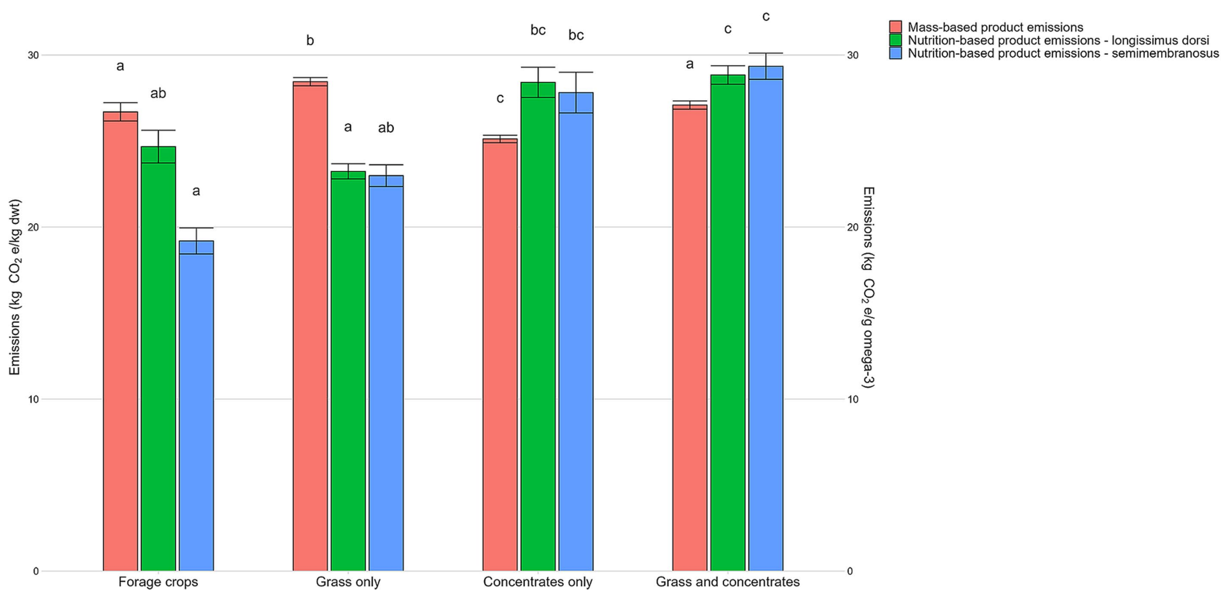

FIGURE 1
Mean emissions estimates (± standard error) for *longissimus dorsi* and *semimembranosus* muscle cuts for each finishing diet expressed as mass-based product emissions and nutrition-based product emissions. Different lower-case letters indicate statistically significant differences in diet within each individual emissions measure at the 5% level.

grass and concentrates diet had significantly less C18:2 n-6 compared to the *concentrates* diet. The mixture of grass and concentrates at dietary components will dilute the amount of C18:2 n-6 being deposited into muscle (Scollan et al., 2017). This dominant C18:2 n-6 influence is also reflected in the n-6/n-3 ratio, which is highest for the *concentrate* diet and lowest for the *grass* diet.

The total omega-3 PUFA composition varied across the four diets, with the *forage crops* and *grass* diet having the highest amount and the lowest being reported in the *concentrates* diet for both muscle cuts. Studies in lamb have reported total omega-3 PUFA as 102 and 44 mg/100 g of meat (Fisher et al., 2000), and 78 and 67 mg/100 g of meat (Kitessa et al., 2010) in animals fed on grass and concentrate diets, respectively. This was supported by a study concluding that lambs reared on grass had significantly higher total omega-3 PUFA levels compared to lambs reared on a grass and concentrate and concentrate and hay diet (Boughalmi and Araba, 2016).

Lamb from the *forage crops* diet and *grass* diet had significantly higher C18:3 n-3 in the *longissimus dorsi* compared to the *concentrate* diet. It is well acknowledged that grass is rich in C18:3 n-3. This is because plant chloroplasts can uniquely synthesise (*de novo*) long chain fatty acids (>18 carbons; Harwood, 1999). Levels of C18:3 n-3 in grass and other plants are influenced by season, species, location and environment (e.g., temperature and light exposure; Elgersma et al., 2003; Mir et al., 2006; Tsvetkova and Angelow, 2010; Yalcin et al., 2011; De Brito et al., 2017). This also explains why forage crops and other plant-based materials have high levels of C18:3 n-3. The 'grass effect' is reflected in the data presented, particularly by the titration effect seen between the *grass*, *grass and concentrates* and *concentrate* diets, where any impact is diluted. There were some significant differences reported for the long chain omega-3 PUFAs (C20:5, C22:5 and C22:6 n-3) across the four finishing diets which is contrary to the findings of others (Fisher et al., 2000; Demirel et al., 2006). Higher levels of long chain omega-3 PUFAs including C20:5 n-3 and C22:6 n-3 were found in the *grass and forage crops* in the *longissimus dorsi*. Although lamb diets consisting solely of grass have very little amounts of long chain omega-3 PUFAs (as pasture species are primarily dominant in C18:3 n-3), small increases are not surprising as conversion of C18:3 n-3 to longer chain omega-3 via elongation and desaturation processes can occur in the lamb (Bessa et al., 2015). Nutrition and genetics are the two most influencing factors affecting fatty acid composition in muscle (Scollan et al., 2014; Dervishi et al., 2019), meaning any variation seen is likely due to lambs being on a grass-based diet more so than the actual species composition in the grazed pastures (Dierking et al., 2010; Scollan et al., 2017).

Due to the differences in omega-3 PUFA composition between the four diets, grams of omega-3 was selected as a functional unit to express emissions on a nutritional basis. While the n-6/n-3 ratio was also considered for use as a nutritional functional unit, we focus on omega-3 PUFA because it accounts for absolute amounts, rather proportions of fatty acids present (EFSA Panel on Dietetic Products, Nutrition, and Allergies (NDA), 2010). Omega-3 PUFA is known to vary between grass and concentrate based diets (Fisher et al., 2000; Warren et al., 2008), and has been previously used as a functional unit to express emissions while comparing farming systems (McAuliffe et al., 2018b). Additionally, omega-3 PUFA is important in human nutrition with documented health benefits such as reducing the risk of cardiovascular disease and other inflammatory diseases (EFSA Panel on Dietetic Products, Nutrition, and Allergies (NDA), 2010; Swanson et al., 2012).

4.2 Mass-based product emissions

Mass-based product emissions varied significantly across finishing systems, which largely reflects the variation in efficiencies between the different diets. The *concentrates* diet had the lowest average mass-based product emissions while the *grass* systems had the highest. Although lambs from the *concentrates* diet were on farm for longer and the bought-in feed would lead to greater embedded GHG emissions, concentrates have a lower fibre content which can result in lower CH_4 production (Yan et al., 2010; van Wyngaard et al., 2018). Lambs on the *concentrates* diet also had higher carcass weights and KO% compared to the lambs form the *grass* diet, resulting in lower emissions per kg of product. Considerable variation was also seen in mass-based product emissions of finishing systems within the same diets. This highlights the difference in efficiencies of finishing systems within the same diet. This could be explained by animal health issues (e.g., lameness or gastrointestinal worm challenge), the quality of the diet offered, and genetic variation.

4.3 Nutrition-based product emissions

The significantly higher omega-3 PUFA content of the *forage crops* diet resulted in the *semimembranosus* cuts from this diet having the lowest nutrition-based product emissions. Similarly, *grass* systems had the lowest nutrition-based product emissions for the *longissimus dorsi* due to lambs from the *grass* diets having the highest omega-3 PUFA content of the *longissimus dorsi*. The *grass and concentrates* diet had the highest nutrition-based product emissions for both the *longissimus dorsi* and *semimembranosus*. This is likely a result of their initially higher mass-based product emissions and relatively lower omega-3 PUFA content compared to that of the *forage crops* and *grass* diets. The *concentrates* diet had lowest omega-3 PUFA content for both the *longissimus dorsi* and *semimembranosus* resulting in higher nutrition-based product emissions. However, as the concentrates diet had the lowest mass-based emissions to begin with, this effect is somewhat masked.

Across all diets except the *forage crops* diet, there was no significant difference in nutrition-based product emissions between the *longissimus dorsi* and *semimembranosus*. This is due to the similar average omega-3 PUFA content between *longissimus dorsi* and *semimembranosus*. For all systems, except for the *grass and concentrate* diet, nutrition-based product emissions were higher in the *longissimus dorsi* than in the *semimembranosus*. This could be explained by the *forage crops* and *grass* diets having higher omega-3 PUFA contents in their *semimembranosus* cuts than in their *longissimus dorsi*. This is likely due to *longissimus dorsi* having a higher SFA and lower PUFA content than the *semimembranosus*. Fowler et al. (2019) also found the *longissimus dorsi* of lambs in extensive systems had lower omega-3 PUFA content than the *semimembranosus*. However, the *forage crops* diet showed significant differences in nutrition-based product emissions between *longissimus dorsi* and *semimembranosus*. This result should be treated with caution due to the small number of farms in this study on the *forage crops* diet as well as the variation of feeds and therefore fatty acid composition of lambs within the *forage crops* diet. For example, the *forage crops* diet consisted of finishing systems feeding brassica, fodder beet and forage rape, which may all affect the nutritional composition of lambs differently. Even within diets that were finished on solely grass, grass quality will vary between farms and therefore this will likely impact the nutritional composition of lambs, particularly omega-3 PUFA content (Howes et al., 2015).

This study found marginally lower nutrition-based emissions for lamb production systems than previous studies. McAuliffe et al. (2018a) noted lambs on upland and lowland systems had nutrition-based emissions of 30.0 kg CO_2e/g omega-3 and 28.7 kg CO_2e/g omega-3, respectively. These values are higher than both cuts from the *forage crops*, *grass* and *concentrates* diets found in the present study. However, these differences must be interpreted with caution as different carbon footprinting tools have been used to calculate emissions estimates in this study. Additionally, our study found higher omega-3 PUFA content in lambs across some diets, e.g., 146 mg/100 g from the *semimembranosus* from the *grass* diet compared to published values, which reported levels of 103 mg/100 g of meat (Whittington et al., 2006).

The present study highlights the importance of nutritional functional unit when considering health and wellbeing implications of products, especially given the diversity in nutritional fatty acid composition in ruminant products. Using omega-3 PUFA as a nutritional functional unit demonstrated its value and warrants further consideration given the numerous reported benefits optimal consumption has on human health and well-being (Jacobson et al., 2012; Givens, 2015; Singh et al., 2016). Although the lamb in this study will unlikely have a nutraceutical effect at a normal portion size, the aim of this study was to explore the effect of finishing diet on the carbon footprint of lamb expressed on a nutritional basis rather than making recommendations on lamb portion sizes.

This study has uniquely used real farm data to highlight the importance of shifting from mass-based functional units to nutrient-based functional units. While mass-based functional units such as per kg dwt still have a valuable place in comparing production efficiencies of farms, they do not reflect the degree of nutrition provided by consumption of the meat produced from each system.

4.4 Limitations

Some appropriate assumptions had to be made to calculate carbon footprints for each finishing system where some farm data were unavailable. For example, although data were collected for diet type, actual feed consumption was not recorded. Although such assumptions and default values regularly have to be applied in farm carbon footprint studies (Edwards-Jones et al., 2009; Ripoll-Bosch et al., 2013; McAuliffe et al., 2018a), there may be an over- and/or under-estimations of emission estimates as a result. Ensuring a larger sample size with an equal number of finishing systems from each diet would reduce unequal variances between diets and improve the statistical power of results. Nonetheless, although breed type and gender were unbalanced between treatments, farms were selected for this study to represent a cross-section of lamb finishing systems, and therefore these differences in production and seasonality are reflected in the results. For example, hill breeds will more likely be associated with grass-based finishing systems as opposed to concentrates. However, for the variables such as breed type (e.g., hill and cross- breeds) which have lower numbers in each group, there will inevitably be a greater level of uncertainty in the results.

Using a single nutrient functional unit does not reflect the products' complete nutritive value. Focusing on a single nutrient functional unit could lead to an under or over-supply of other key nutrients. In this study, we have focused purely on omega-3 PUFA, however, there would likely be variation in a number of other fatty acids between finishing diets, for example, conjugated linoleic acid (CLA) which have a high nutraceutical value. Future studies should therefore consider CLA and indeed the full fatty acid profile. Moreover, lamb can provide a considerable range of nutritional benefits that were not considered in this study. Although many parameters (52 fatty acid parameters, 19 amino acid parameters, and two mineral parameters) were collected for this study, measurement of other key nutrients (e.g., vitamins and certain minerals) would generate a fuller nutrient density score (Fulgoni et al., 2009). Moreover, nutrient density scores often consider the daily recommended intake of each nutrient. Nutrients collected in this study were from 100 g of fresh muscle, so future work would need to consider cooking losses of meat if a nutrient density score was to be created. However, nutrient density scores are not without their limitations. The outcomes of nLCAs which employ a nutrient density score are highly dependent on the nutrients which are included in the metric. This means some metrics are more suitable for some foods than others, and other important aspects of nutrition (such as the bioavailability of nutrients and interaction between nutrients) are not captured (Bianchi et al., 2020). Moreover, foods are rarely consumed in isolation and therefore future nLCA studies should consider nutrition at a diet-level (McAuliffe et al., 2018b). Recently, some studies have taken a novel approach which involves a diet-level assessment that accounts for the foods' effect on human health. For example, Stylianou et al. (2016) developed the Combined Nutritional and Environmental Life Cycle Assessment (CONE-LCA). The CONE-LCA uses a traditional LCA approach and predicts health outcomes following changes in diet, using epidemiological data based on the nutritional quality of food. However, these outcomes will obviously depend on the initial diet and its nutritional status of the individuals making the dietary change.

As with all LCA studies, the results of nLCA depend upon the type of LCA (attributional vs. consequential), where system boundaries are drawn, and the allocation method they employ (Silva, 2021). Clearly, nLCAs also require an extra layer of data relating to the nutritional value of food, introducing additional sources of variation. Studies often rely on a range of external databases for this nutritional information. Although not an issue in this study, data availability and quality are major limitations of nLCA. This includes both primary data from agricultural production and secondary data from agricultural databases. When utilising primary data, there can be concerns of the representativeness of data, particularly if data comes from a single, specific year (Notarnicola et al., 2017). With secondary data, databases exhibit significant variability in terms of detail and completeness and are often biassed towards conventional production in high-income countries (Teixeira, 2015; Carvalho et al., 2023). Moreover, some nLCA studies may require additional information such as nutritional intake recommendation, interactions with other foods, and food processing and preparation (McLaren, 2021). Again, while this was not a limitation in the current study, the lack of available high-quality data will likely limit the wider use and application of nLCA.

Despite the assumptions and limitations of this study, a novel functional unit has been successfully used to compare four finishing diets of lambs and has highlighted the importance of considering nutrition when expressing GHG emissions.

5 Conclusion

This preliminary assessment is the first of its kind to use real farm and carcass data to assess the effect of finishing diet on lamb carbon footprints expressed on a nutritional basis. Despite recognised limitations, this study has demonstrated the need to consider nutrition when expressing carbon footprints. When a mass-based functional unit was employed, *grass* diets had on average the highest carbon footprint, however, when omega-3 PUFA content was accounted for, the *grass* diet had the lowest carbon footprint for the *longissimus dorsi*. While mass-based functional units can be useful for comparing efficiencies of different farming systems, they do not reflect the function of the final product, human nutrition. Therefore, future work should consider both mass-based and nutrition-based functional units when comparing different farming systems. Future studies should also collect a comprehensive set of carcass and nutritional parameters for emissions to be expressed through a full nutrient density score. This would allow us to accurately determine the role nutrient density of a product plays in environmental sustainability of livestock farming.

Data availability statement

The datasets presented in this article are not readily available because the data analysed in this study was obtained from Hybu Cig Cymru – Meat Promotion Wales. Requests to access these datasets should be directed to ET, ethomas@hybucig.cymru.

Ethics statement

The animal studies were approved by Hybu Cig Cymru – Meat Promotion Wales, Ty Rheidol, Parc Merlin, Glanyrafon Industrial Estate, Aberystwyth SY23 3FF. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the owners for the participation of their animals in this study.

Author contributions

LM: Data curation, Formal analysis, Visualization, Writing – original draft. LP: Data curation, Project administration, Writing – original draft. JG: Formal analysis, Writing – review & editing. NS: Funding acquisition, Supervision, Writing – review & editing. AN: Writing – review & editing. ET: Conceptualization, Investigation, Supervision, Writing – review & editing. ES: Data curation, Investigation, Writing – review & editing. CM: Investigation, Resources, Writing – review & editing. AW: Investigation, Resources, Writing – review & editing. SC: Investigation, Resources, Writing

– review & editing. LF: Conceptualization, Writing – review & editing. APW: Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1321288/full#supplementary-material

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