Agricultural Systems 217 (2024) 103915

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Greenhouse gas emissions from a diversity of sheep production systems in the United States

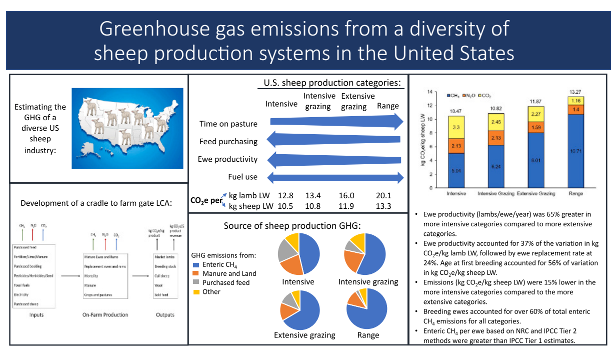
Erin B. Recktenwald [a], Richard A. Ehrhardt [a,b,*]

[a] Department of Animal Science, Michigan State University, East Lansing, MI 48824, USA
[b] Department of Large Animal Clinical Sciences, Michigan State University, East Lansing, MI 48824, USA

HIGHLIGHTS

- Distinct US sheep production systems were defined with different productivity levels, resource bases, production practices and marketing goals.
- A Life Cycle Analysis was developed to measure greenhouse gas (GHG) emissions and 3 calculation methods were evaluated.
- Ewe productivity, replacement rate, and age at first breeding had the greatest impacts on greenhouse gas emissions.
- Emissions intensity was lower in the more intensively managed operations than in the more extensively managed operations.
- The main factors influencing GHG emissions intensity were ewe productivity indicators, highlighting their importance in mitigation efforts.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Paul Crosson

Keywords:
Greenhouse gas
Sheep
Carbon footprint
Life cycle assessment
Enteric methane

ABSTRACT

CONTEXT: There is a diversity of sheep production systems in the United States (US), from intensive operations which house animals year-round with concentrated feeding to extensive operations that practice transhumance grazing with minimal inputs.
OBJECTIVE: The main objective of this study was to quantify the amount and variability of greenhouse gas (GHG) emissions from four distinct production categories that typify US sheep production: Intensive, Intensive Grazing, Extensive Grazing, and Range. An additional objective was to compare emissions estimates produced via three different methods for determining methane (CH_4) production and nitrogen (N) excretion.
METHODS: A cradle to farm gate life cycle analysis (LCA) was conducted on 17 sheep operations to determine their GHG emissions for producing sheep and wool. An LCA was also conducted on four feedlots to determine emissions related to finishing lamb from Range operations.
RESULTS AND CONCLUSIONS: The more intensive operations kept ewes for less time on pasture, purchased more feeds, and produced more weaned lambs/ewe/year ($P < 0.01$). Emissions intensity was lower ($P < 0.05$) in more intensive operations and ranged from 12.8 to 20.1 kg carbon dioxide equivalents (CO_2e)/kg lamb liveweight (LW) or 10.5–13.3 kg CO_2e/kg sheep LW. Enteric CH_4 was the major source of GHG across all categories, with the

* Corresponding author at: Department of Animal Science, Michigan State University, 474 S. Shaw Lane, 1287F Anthony Hall, East Lansing, MI 48824, USA.
E-mail address: ehrhard5@msu.edu (R.A. Ehrhardt).

https://doi.org/10.1016/j.agsy.2024.103915
Received 10 August 2023; Received in revised form 5 February 2024; Accepted 3 March 2024
Available online 14 March 2024

proportion of GHG as enteric CH_4 declining from most extensive (79%) to most intensive (46%) categories. More intensive operations emitted 44% more kg N_2O/sheep LW and 67% more CO_2/kg sheep LW than more extensive ones. Breeding ewes accounted for over 60% of total enteric CH_4 emissions across all categories. Incorporating a Feedlot component for Range lambs resulted in an emissions intensity of 15.1 kg CO_2e/kg lamb LW, 25% lower than that at the Range farm gate. The number of lambs weaned/ewe/year accounted for the greatest variation in emissions intensity on a lamb LW basis (37%), followed by ewe replacement rate (27%), while on a sheep LW basis, age at first breeding accounted for 56% of variation. Yearly ewe enteric CH_4 emissions and N excretion were higher using the NRC and the IPCC Tier 2 methods compared to the IPCC Tier 1 method ($P < 0.001$).
SIGNIFICANCE: Ewe productivity was the main driver of GHG emissions intensity in diverse US sheep production systems; therefore, its improvement will be crucial in reducing emissions. Further gains in extensive operations can be realized by a reduction in preweaning mortality while intensive operations have opportunities to improve manure management and utilize feeds produced with lower GHG emissions.

1. Introduction

The United States (US) sheep industry is uniquely diverse, with a range of productivity and management intensity from housed, highly prolific flocks, to those in either extensive grazing or transhumance systems with low to moderate prolificacy. The adoption of different management practices is often regional, but there is also a large range of management systems within a region related to many factors including land value, degree of infrastructure investment, farm size, and market focus. There are also clear regional differences based on climate zone and associated vegetation. This diversity poses a challenge to produce a one-size-fits-all emissions estimate for US sheep production. It also means that estimates from previous work have typically been in grazing situations with lower productivity than is common in some regions of the US (Dougherty et al., 2019; Jones et al., 2014; Dynes et al., 2019). The US also has a unique degree of variation in markets with the existence of two distinct markets often termed the traditional and nontraditional markets (Stepanek Shiflett et al., 2010). These markets provide lamb that fits the wide array of consumer demand and encompasses a large range of carcass weights and composition. In general, the traditional market consists of large lambs, often with carcass size typically over 25–30 kg, whereas the nontraditional market favors smaller, leaner lambs typically ranging widely in carcass size from 7 to 25 kg. Sheep operations in the US tend to focus on producing lamb that will fulfill the consumer demand for the particular market into which they sell.

There is considerable interest in reducing greenhouse gas (GHG) emissions, both globally and domestically in the US, due to its impact on warming temperatures (Intergovernmental Panel on Climate Change (IPCC), 2021). In the US, agriculture accounts for approximately 11% of all GHG emissions, and livestock production accounts for roughly half this amount (Environmental Protection Agency, 2022b). Ruminant livestock emit methane (CH_4) via enteric fermentation, which contributes approximately 25% of US CH_4 emissions. There are approximately 5 million sheep compared to 94 million cattle in the US; therefore, sheep are approximately 1% the size of the US cattle industry on a mass basis (USDA NASS, 2022; Place and Mitloehner, 2021). This is a much smaller agricultural footprint than found in countries with large sheep industries, such as New Zealand (NZ) and Australia (AU), where sheep contribute 12 and 2% of their GHGs, respectively (New Zealand Government, 2023; Sheep Sustainability Framework, 2023). Globally, AU has 63 million, NZ has 26 million, and the United Kingdom (UK) has 33 million sheep (FAOStat, 2023).

One objective of this study was to develop a cradle-to-farm gate life cycle analysis (LCA) for estimating GHG emissions from four types of sheep production systems typically found in the US, ranging from those with highly productive, intensive management practices to those with less productive, more extensive management practices. Another objective was to compare emissions estimates provided by two separate methods for determining sheep CH_4 and nitrous oxide (N_2O) production: the NRC (National Research Council (NRC), 2007) and IPCC (Intergovernmental Panel on Climate Change (IPCC), 2019a). The overall goal of this study was to determine the amount and variability of GHG emissions intensity and the sources of these emissions within four major US sheep production categories. In addition, the operational characteristics with the greatest impact on GHG emissions intensity were sought in order to identify potential mitigation strategies.

2. Methods

2.1. Identification of production categories

Four categories that are indicative of the diversity in US sheep production were formed based on the following characteristics: 1. Intensive production (I) – high prolificacy genetics and housed for the majority of their production cycle; 2. Intensive grazing (IG) – high prolificacy genetics in a pasture-based system under moderate-to-intensive pasture management; 3. Extensive grazing (EG) – moderate prolificacy genetics in pasture systems with less intensive management; 4. Range (R) – low prolificacy genetics managed on native pastures in a low input system, with lambs typically sold as feeder lambs to the lamb feeding industry. This study received Michigan State University Institutional Review Board approval (MSU study ID: MSU0004225).

Extension experts, industry leaders, and researchers were asked to provide potential participants that fit one of these categories for data collection. A goal of 4 operations per category was reached, with an additional operation included in the R category ($n = 4$ for I, IG, and EG categories; $n = 5$ for R category). There was no regional component inherent in the category descriptions, but all of the I operations were in the Midwest and Eastern US and all R operations were in the Western US, with IG and EG operations throughout the country. Once identified, the producer was asked a series of questions via electronic and telephone conversations that allowed sufficient records for analysis. Participants were asked to provide either an average of their last three years of records or those of a typical year's production, as weather incidents such as an unusual snowfall or market and labor abnormalities caused by the COVID-19 pandemic altered their production. After data collection, each operation was assigned a category determined by the best fit to the above descriptions, mainly based on ewe prolificacy and pasture management. In addition to the four main operation categories, four individual feedlots from different regions of the US were also selected to participate in the study. The reason for including these operations is because they receive lightweight lambs, often from range operations in the Western US, at approximately 40–50 kg liveweight (LW) and finish them to heavier weights (70–90 kg LW) prior to slaughter for the traditional lamb market. The inclusion of these operations allowed for a sequential analysis of GHG emissions related to lambs that exit R operations and finish on US feedlots.

2.2. Model description

2.2.1. System boundaries

Producer records were incorporated into a life cycle analysis (LCA) for each operation following LEAP (LEAP, 2016) and ISO (ISO, 2006; ISO, 2018) guidelines. The system boundaries included all activities by the flock and the acreage used for feed production (grazing and/or harvesting) and manure management (see Fig. 1 for a graphical representation of the LCA). Secondary emissions from materials brought onto the farm for sheep production were included within the boundary, such as purchased feeds and minerals, bedding, milk replacer, fertilizers, seed, pesticides/herbicides, and fuel.

2.2.2. Animal characteristics and population

Producer records regarding reproductive performance, such as conception rate and lambs born per ewe, mortality, cull rates, and number of animals sold were used to determine the number of animals in each productive category (breeding ewes and rams, ewe and ram replacements, and market lambs) throughout a typical production year. Ewe and ram lambs sold as breeding replacements were considered separately from market lambs with their own management and growth rates. Several operations sold all lambs to market, while a few operations sold a significant percentage of lambs as breeding stock.

2.2.3. Functional units

Lambs in the US are marketed at a variety of weights due to a spectrum of demand, from lightweight lamb entering the nontraditional (often called ethnic) market to heavy lamb entering traditional markets mainly geared toward US restaurants and retail (Stepanek Shiflett et al., 2010). Due to multiple marketing approaches practiced by operations across the US, multiple functional units (live weight [LW] of market lamb, total lamb, total sheep, and all products [LW and greasy wool] sold at the farm gate) were reported in this study rather than selecting only one.

2.2.4. Dry matter intake and energy requirements

Animals were grouped according to sex and productive state (breeding ewe in maintenance, pregnancy, or lactating stages; ram in breeding season or maintenance; growing ewe or ram replacement; growing market lamb) and their energy requirements were estimated according to National Research Council recommendations (National Research Council (NRC), 2007; Cannas et al., 2004). Daily metabolizable energy (ME) and metabolizable protein (MP) requirements for all animal groups were based on body weight (BW), animal age, wool production, animal activity, monthly ambient temperature, and dietary total digestible nutrient (TDN) and crude protein (CP) content. Activity included the estimated horizontal and vertical distance traveled based on averages for both grazing (Webber et al., 2015) and range (McGranahan et al., 2018) sheep. Milk yield and components were estimated according to the number of lambs and weaning age and were included in ewe nutritional estimates (Cardellino and Benson, 2002; Snowder and Glimp, 1991). Average daily gain (ADG) was based on producer records regarding age and weight of lamb at sale and was included in requirements for growing lambs. Tabular values were used for recommended dietary TDN (kg/d) and CP (g/d) for each animal group (National Research Council (NRC), 2007; National Research Council (NRC), 1985). Daily nitrogen (N) intake was determined by multiplying estimated dry matter intake (Cannas et al., 2004) by dietary CP content, and daily N retention was estimated to be 67% of maintenance MP requirements, 58% of lactation MP requirements, and 70% of both pregnancy and growth MP requirements (Cannas et al., 2004). Daily N excretion was determined by difference between N intake and N retention.

2.2.5. Enteric CH_4 emissions

Enteric methane (CH_4) production was estimated based on ME intake according to the Monomolecular equation published in Patra et al., 2016 (see Eq. (1)). Individual daily enteric CH_4 production was multiplied by the total number of animals in each group to estimate total yearly enteric CH_4 production. Lamb enteric CH_4 production began at 60 days of age and continued until either sale or entrance into the breeding flock (Ramsey et al., 1994; Patra et al., 2016).

$$CH_4\ (\mathrm{MJ/day}) = 5.699–(5.699–0.133)^{*}\ exp.(-0.021^{*}\ \mathrm{ME\ intake\ [MJ/day]}) \quad (1)$$

2.2.6. Manure-related GHG emissions

Daily manure N excretion was allotted to the appropriate storage or pasture situation to account for direct and indirect nitrous oxide (N_2O) production according to IPCC 2019 Tier 1 methods (Intergovernmental Panel on Climate Change (IPCC), 2019a). Mean annual temperature and precipitation data was used to determine climate zone and precipitation assignment for each operation (US Climate Data, 2020). Gross energy intake (GEI) was estimated from daily ME requirements using dietary TDN and assuming a conversion factor of 0.82 from DE to ME. Volatile solid (VS) production was estimated from GEI according to IPCC Tier 1 methods. The amount of CH_4 produced from manure was based on estimated VS production, climate zone, and manure storage system according to IPCC 2019 Tier 1 methods (Intergovernmental Panel on

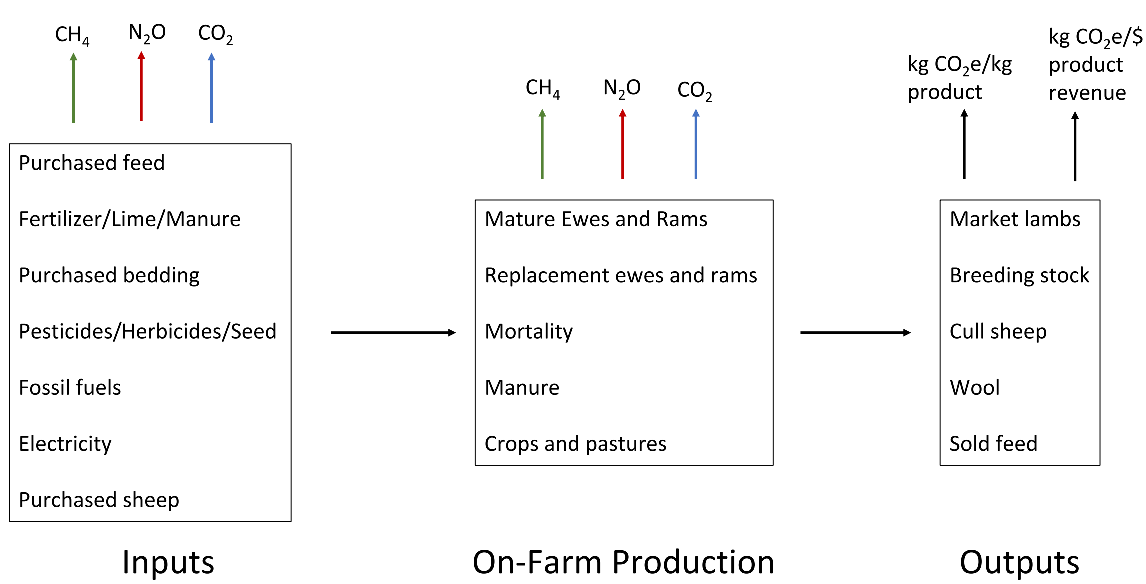


Fig. 1. Graphical representation of the life cycle analysis (LCA) developed to analyze the greenhouse gas emissions (methane [CH_4], nitrous oxide [N_2O], and carbon dioxide [CO_2]) from United States sheep operations. Emissions from outputs expressed in terms of kg carbon dioxide equivalents (CO_2e).

Climate Change (IPCC), 2019a).

2.2.7. Land applications

The amount of N_2O emitted due to synthetic fertilizer and manure application was estimated per IPCC 2019 Tier 1 methods (Intergovernmental Panel on Climate Change (IPCC), 2019a). Stored manure was applied to land used for sheep production in all but two Intensive operations which exported it to local crop production. The N_2O emissions from an equivalent amount of synthetic N fertilizer was credited to these operations (Stanley et al., 2018; Leip et al., 2019). All carbon from lime application was assumed to be emitted as carbon dioxide (CO_2; Intergovernmental Panel on Climate Change (IPCC), 2019b). Nitrous oxide formation from annual and terminated crop residues was determined using IPCC Tier 1 standards (Intergovernmental Panel on Climate Change (IPCC), 2019b).

2.2.8. Feed production and purchasing

For feeds produced on-farm, each operation's annual inputs such as fertilizer, lime, herbicide, seed, as well as fuel were used to determine the corresponding GHG emissions. For purchased feeds and other items such as milk replacer and bedding, published emissions values for each input were used (Table 1). Transportation for all items entering an operation was assumed to be 100 km via truck (6000 kg hauling capacity, 33 km/gal) and 500 km via semi-trailer (23,000 kg hauling capacity, 17 km/gal).

2.2.9. Energy and water usage

Emissions associated with annual electricity (0.386 kg carbon dioxide equivalents [CO_2e]/kWh), gasoline (8.78 kg CO_2e/gal), and diesel (10.2 kg CO_2e/gal) use were estimated according to EPA conversion factors (Environmental Protection Agency, 2022a). Electricity and fuel needs included ground water pumping, transportation within the operation, and irrigation needs, in addition to general operations. Electricity provided by solar panels was not included in emissions totals.

Table 1
Carbon dioxide equivalents estimates produced by production and transport of items brought onto sheep operations used in the Life Cycle Analysis to analyze the greenhouse gas emissions.

Input	Value	Units	Reference
Straw bedding	0.10	$kgCO_2e/kg$	Global Feed LCA Institute (GFLI), 2021
Milk replacer	12.1	$kgCO_2e/kgDM$	Rotz et al., 2019
Corn gluten meal	1.62	$kgCO_2e/kg$	Global Feed LCA Institute (GFLI), 2021
Corn grain, Iowa	0.39	$kgCO_2e/kg$	Global Feed LCA Institute (GFLI), 2021
Corn grain, Colorado	0.71	$kgCO_2e/kg$	Global Feed LCA Institute (GFLI), 2021
Salt and mineral	1.62	$kgCO_2e/kg$	Rotz et al., 2019
Soybean meal	0.69	$kgCO_2e/kg$	Global Feed LCA Institute (GFLI), 2021
Soyhulls	0.38	$kgCO_2e/kg$	Global Feed LCA Institute (GFLI), 2021
Alfalfa hay	0.16	$kgCO_2e/kgDM$	Global Feed LCA Institute (GFLI), 2021
Grass hay	0.15	$kgCO_2e/kgDM$	Rotz et al., 2019
Corn silage	0.08	$kgCO_2e/kgDM$	Environmental Working Group, 2011
Fertilizer N	3.9	$kgCO_2e/kgN$	Farm Energy Analysis Tool (FEAT), 2018
Fertilizer P	0.91	$kgCO_2e/kgP$	Farm Energy Analysis Tool (FEAT), 2018
Lime	0.35	$kgCO_2e/kg$	Farm Energy Analysis Tool (FEAT), 2018
Seed, generic	0.3	$kgCO_2e/kg$	Rotz et al., 2019
Seed, corn	3.8	$kgCO_2e/kg$	Farm Energy Analysis Tool (FEAT), 2018
Herbicide	16.5	$kgCO_2e/kg$ a.i.	Farm Energy Analysis Tool (FEAT), 2018

2.2.10. Protein and economic allocation

To allocate products according to protein production, the annual number of market lambs, breeding stock, and cull ewes and rams sold at the farm gate and their average LW as used to determine the total kg LW at the farm gate. The protein content of each animal was assumed to be 18% of LW (Wiedemann et al., 2016). The wool yield grade was supplied by approximately 40% of the operations and 70% of them recorded fleece weights, while the remaining were assigned a value based on averages for operations either in their region or with similar genetics. These values were used to determine the amount of clean wool, and the protein content of the clean wool was assumed to be 100% at 84% DM (Wiedemann et al., 2015). For the economic allocation, the total monetary value of product sold at the farm gate was based on LW and greasy wool weight, and GHG emissions were distributed according to the proportion of sale revenue from either product. The average national price per pound of LW based on the years 2020–2021 was used for each animal group (USDA NASS, 2022), and producers either supplied the average wool price they received or were assigned one based on wool type and region if it was unknown (USDA NASS, 2022).

2.2.11. Carbon footprint

The amount of CH_4 from enteric and manure emissions and the amount of N_2O from stored manure and field applications (manure, fertilizer, crop residues) were determined for each operation. The amount of carbon dioxide (CO_2) from purchases or inputs (feed, fuel, electricity, etc., plus their transportation to the farm) were reported separately from CH_4 and N_2O emissions. Since CH_4 and N_2O emissions are inherently included within some of these estimates, such as N_2O emitted during feed production, it should be noted that the value is reported as CO_2e rather than CO_2. Global warming potential (GWP) factors from the 6th Assessment Report (AR6) were used to designate CO_2e emissions over a 100-year period, which were 1 for CO_2, 27 for CH_4, and 273 for N_2O (Intergovernmental Panel on Climate Change (IPCC), 2021).

2.3. Sensitivity to nutritional method

An analysis was done to compare the sensitivity of GHG emissions due to the nutritional method used to estimate energy intake and N excretion. Three methods were compared, two from the IPCC guidelines (Tier 1 and Tier 2 methods; Intergovernmental Panel on Climate Change (IPCC), 2019a) and one based on NRC 2007, to estimate total enteric CH_4, manure CH_4, and manure N_2O emissions. For the IPCC Tier 2 method, daily GEI was predicted for each animal group, and enteric CH_4 production was estimated to be 6.7% of GEI (Intergovernmental Panel on Climate Change (IPCC), 2019a). Dry matter intake (DMI) was based on GEI, assuming a default of 18.45 MJ/kg DM, and N intake was determined from DMI and dietary CP. Nitrogen retention was assumed to be 10% of N intake, and direct and indirect N_2O formation was determined from N excretion as previously done using IPCC Tier 1 standards. Daily GEI from IPCC Tier 2 methods was used to estimate VS production and subsequent manure CH_4 emissions as done previously with daily GEI from NRC 2007 methods.

For the IPCC Tier 1 method, the amount of enteric CH_4 produced was estimated at 9 kg CH_4/head/year, and default values for daily VS production (8.2 kg VS/1000 kg BW/year) and N intake (0.35 kg N/1000 kg BW/d) were used for all animal groups based on body weight (BW) (Intergovernmental Panel on Climate Change (IPCC), 2019a). Nitrogen retention was assumed to be the default value of 10% of N intake. CH_4 and N_2O production from manure were estimated from VS production and N excretion, respectively, via IPCC Tier 1 standards as previously with NRC (Section 2.2.6) and IPCC Tier 2 (above) estimates. The sum of enteric CH_4, manure CH_4, and manure N_2O were then combined with the rest of the operation's emissions to provide total GHG emissions estimates using these two alternative methods in comparison to those produced using NRC 2007 estimates for the animal-derived GHG emissions.

2.4. Statistical analysis

The data analysis was performed using SAS software, Version 9.4 of the SAS System for Windows 11 (SAS Institute Inc, 2016, Cary, NC, USA). The general linear model (GLM) procedure was used for analysis of all farm characteristics, flock marketing indictors, flock performance indicators, emissions intensity, mass of GHGs, source of CO_2e and partitioning of flock enteric CH_4 data with the 4 operation categories as the independent variable (I, IG, EG, and R). The Tukey adjustment was used, as the number of operations in each category was uneven ($n = 4$ except in Range where $n = 5$). Pre-planned orthogonal contrasts were used to partition variance related to category as follows: Intensive and Intensive Grazing (I + IG) vs. Extensive Grazing and Range (EG + R), Intensive vs. Intensive Grazing (I vs IG), and Extensive Grazing vs. Range. (EG vs R). To determine the impact of nutritional method (NRC vs IPCC Tier 1 vs IPCC Tier 2), the GLM procedure was used, and method was included in the model along with its interaction with category. Stepwise selection was performed on 8 different variables using the GLMSELECT procedure. These variables were: number of breeding ewes, % of year breeding ewes are on pasture, kg feed/ewe/year, lambs weaned/ewe/year, replacement rate, age at first breeding, gas and diesel use, and average daily gain (ADG) of lambs. Significance was set at $P < 0.05$, and selected variables were then analyzed using the GLM procedure to determine their relative contribution on kg CO_2e/kg lamb LW and on kg CO_2e/kg sheep LW across all operations.

3. Results

3.1. Characteristics of the sheep operations

There were four operations in each category who participated in this study, with the exception of 5 operations in the Range category. Flock sizes varied considerably across all categories of operations, with 1000+ breeding ewes present in all categories except the EG category (Table 2). Breeding ewes in the more intensive (I + IG) operations spent a lower proportion of time over a production year on pasture compared to the more extensive (EG + R) categories (34 vs 91%, Table 2) and the flocks were fed more purchased feed (444 vs 76 kg/ewe/yr, respectively) ($P < 0.005$). Gas, diesel, and electricity use was not significantly different on a per ewe basis across all categories.

The ADG of lambs destined for market was higher in I than in IG ($P < 0.01$) and tended to be higher ($P = 0.07$) in I + IG than in EG + R categories. Across all operations, the majority of sold lambs were sold as

Table 2
Descriptive characteristics of the four sheep production categories. The range of values is indicated in parentheses. The *P* value of contrasts are indicated as: Intensive (I) and Intensive grazing (IG) vs Extensive grazing (EG) and Range (R); Intensive (I) vs Intensive grazing (IG); and Extensive grazing (EG) vs Range (R).

	Production Category					*P value of contrast*		
	Intensive	Intensive Grazing	Extensive Grazing	Range	*SEM*	I + IG vs E + R	I vs IG	EG vs R
Farm characteristics								
Number of breeding ewes	1366 (193–4818)	1594 (297–3890)	276 (120–393)	2841 (1470–4540)	421	0.92	0.84	0.03
Ewe body weight, kg	78.0 (70.5–81.8)	69.9 (61.4–81.8)	65.6 (61.4–68.2)	79.9 (75.0–84.1)	2.0	0.68	0.06	<0.01
Time grazing pasture by ewe flock, % of yr	13.2 (0–31)	65.1 (42–97)	88.8 (55–100)	94.0 (75–100)	9.1	<0.01	<0.01	0.68
Forage purchased, kg/ewe/yr	260 (0–635)	192 (0–672)	33 (0–119)	3 (0–15)	55	0.07	0.66	0.83
Concentrate purchased, kg/ewe/yr	313 (160–637)	123 (92–164)	97 (27–186)	17 (0–42)	38	0.01	0.03	0.31
Total feed purchased, kg/ewe/yr	573 (245–918)	315 (97–837)	131 (27–305)	20 (0–42)	74	<0.01	0.13	0.47
Fuel purchased, gallons/ewe/yr	3.33 (1.30–4.55)	4.72 (3.23–6.51)	1.97 (0.61–4.55)	3.18 (2.31–4.59)	0.4	0.06	0.19	0.23
Electricity, kWh/ewe/yr	42.7 (1.65–85.0)	34.9 (0–127.9)	15.7 (0–54.3)	18.5 (0–69.8)	9.4	0.28	0.79	0.92
Water pumped, gallons/ewe/yr	570 (318–821)	5946 (1–23,272)	262 (3–546)	23,096 (0–61,331)	4854	0.37	0.69	0.09
Flock marketing indicators								
Market lamb body weight, kg	55.0 (36–66)	53.9 (35–70)	45.6 (40–50)	42.0 (36–54)	2.8	0.07	0.89	0.61
Average daily gain, g/d	350 (337–374)	198 (160–265)	240 (204–276)	246 (210–277)	16	0.07	<0.01	0.81
Market lambs sold/all lambs sold, %	85.5 (48–100)	86.1 (67–100)	54.6 (30–72)	96.9 (85–100)	5.7	0.26	0.93	<0.01
Flock performance indicators								
Replacement rate, % of mature ewes/yr	24.1 (20–30)	22.9 (21–24)	22.0 (12–43)	20.7 (15–27)	1.8	0.59	0.84	0.81
Ewe lamb age at first breeding, yr	0.84 (0.78–0.91)	0.78 (0.78–0.79)	0.90 (0.78–1.20)	1.35 (0.78–1.76)	0.08	0.03	0.76	0.02
kg market lamb/ewe/yr	72.7 (42–101)	63.8 (44–102)	23.1 (10–33)	32.2 (18–46)	6.8	<0.01	0.51	0.48
Weaned lambs/ewe/yr	1.88 (1.6–2.2)	1.62 (1.5–1.7)	1.18 (0.9–1.5)	1.01 (0.8–1.3)	0.10	<0.01	0.10	0.24
kg lamb sold/ewe/yr	85.5 (69–101)	70.7 (44–102)	42.5 (34–52)	32.8 (22–46)	6.5	<0.01	0.19	0.36
Lambs sold/ewe/yr	1.60 (1.3–1.9)	1.37 (1.3–1.4)	0.93 (0.6–1.3)	0.78 (0.6–1.0)	0.10	<0.01	0.18	0.34

market lambs (>85%), either to slaughter or feedlots, however this proportion was lower in the EG (55%) than in the Range category (97%, $P < 0.01$).

Every operation self-supplied its own breeding ewe population instead of purchasing ewe lamb replacements. Ewe lambs were bred at older ages in the EG + R compared to the I + IG categories and also in the R compared to the EG category (1.35 vs 0.90 years, respectively $P < 0.05$, Table 2). The ewe replacement rate did not differ across comparisons (Table 2).

The I + IG operations weaned more lambs per ewe per year than the EG + R operations ($P < 0.01$). They also sold more kg market lamb and more kg of all lambs per ewe per year than the EG + R operations ($P < 0.01$). The difference between the I and R categories was 1.88 vs 1.01 weaned lambs/ewe/year, a difference of 86%. The number of lambs sold/ewe/year did not differ between the I and IG categories nor between the EG compared to R categories.

3.2. Greenhouse gas emissions

Emissions intensity (kg CO_2e/kg) was lower in the more intensive (I + IG) compared to the more extensive categories (EG + R) when allocated on a mass basis per kg CO_2 per kg of lamb LW (market lambs plus breeding stock) and sheep LW (inclusion of cull ewes and rams) ($P > 0.05$, Table 3). These differences in emissions intensity per kg sheep LW were also present when using both economic and protein allocation. No significant differences in emissions intensity were noted in I vs IG nor in EG vs R comparisons. Because most EG operations focused on breeding stock as well as market lamb sales, the emissions intensity on a market lamb basis was correspondingly high for this category (33.1 kg CO_2e/kg market lamb LW vs 15.0–21.1 kg CO_2e/kg market lamb LW in the other categories).

Wool accounted for a higher proportion of both revenue (8.3%) and protein sales (19.2%) in the R category compared to the EG category ($P < 0.01$). When allocating emissions on an economic basis, accounting for wool sales resulted in a lower emissions intensity from sheep sold by 1.2 kg CO_2e/kg sheep LW (12.1 vs 13.3 kg CO_2e/kg sheep LW, or 9%) in the R operations compared to an average reduction of only 0.1 kg CO_2e/kg sheep LW (11.0 vs 11.1 kg CO_2e/kg LW, or 0.9%) across the other categories. On a protein basis, emissions were 2.7 kg CO_2e/kg sheep LW lower in the R category (10.6 vs 13.3 kg CO_2e/kg LW), a 20% reduction when including allocation of protein to wool instead of only LW production. The reduction in emissions intensity was comparatively smaller in the other categories, averaging 0.8 kg CO_2e/kg sheep LW sold (10.3 vs 11.1 kg CO_2e/kg sheep LW), or 7%.

The emissions intensity of each contributing GHG in units of kg CO_2e/kg sheep LW are depicted in Fig. 2, and the emissions intensity of each in units of kg CH_4, N_2O, or CO_2/kg sheep LW are shown in Table 4. The emissions intensity of CH_4 was lower in the I + IG operations than in EG + R operations (0.21 vs 0.35 kg CH_4/kg sheep LW, respectively, $P < 0.001$), and R operations had higher values than EG operations ($P < 0.05$, Table 4). The emissions intensity of N_2O was higher in the I + IG operations compared to the EG + R operations (0.0079 and 0.0055 kg N_2O/kg sheep LW, respectively, $P < 0.05$), with no differences observed between the I vs IG nor EG vs R categories. The emissions intensity of CO_2 was higher for the I + IG operations compared to EG + R operations ($P < 0.05$), with the highest value observed in the Intensive category (3.30 kg CO_2/kg sheep LW, Table 4). Across all categories, emissions from CH_4, N_2O, and CO_2 accounted for 63, 16, and 21% of total CO_2e emissions, respectively.

3.3. Emissions profiles by source

Enteric CH_4 was the major source of GHG emissions for all categories (Table 5). The I + IG operations had a lower proportion of their total CO_2e emissions from enteric CH_4 compared to the EG + R operations (51.6 vs 73.9%, respectively, $P < 0.0001$). This proportion was also higher in the R compared to the EG category (78.9 vs 66.8%, respectively) and tended to be lower in the I compared to the IG category ($P = 0.08$). The proportion of GHG emissions from manure CH_4 and stored manure N_2O was higher in I + IG compared to the EG + R categories ($P < 0.01$), with the highest level observed in the I category (12.1%; Table 5).

The proportion of total GHG emissions from land applications, which included fertilizer use and manure deposition, was not significantly different between I + IG compared to EG + R operations, but IG operations had a higher proportion of land application emissions than I ($P < 0.05$). There were no differences in the proportion of total emissions from fuel and electricity across all categories, which ranged from 3.7 to 6.1% of total emissions (Table 5). The proportion of total emissions from purchased feed tended to be greater in I + IG compared to EG + R categories ($P = 0.08$) and in I vs IG categories ($P = 0.06$).

The majority of enteric CH_4 emissions came from the breeding ewe flock in all categories (>60% of total enteric CH_4), and there were no differences in this proportion among the comparisons made (Table 5).

Table 3
Means and standard error of greenhouse gas emissions per kg product on a mass, economic, and protein basis for the four sheep production categories. The P value of contrasts are indicated as: Intensive (I) and Intensive grazing (IG) vs Extensive grazing (EG) and Range (R); Intensive (I) vs Intensive grazing (IG); and Extensive grazing (EG) vs Range (R).

	Production category				*SEM*	*P value of contrast*		
	Intensive	Intensive Grazing	Extensive Grazing	Range		I + IG vs EG + R	I vs IG	EG vs R
Mass based allocation[1]								
$kgCO_2e$/kg market lamb LW	16.9	15.0	33.1	21.1	2.7	0.04	0.80	0.09
$kgCO_2e$/kg lamb LW	12.8	13.4	16.0	20.1	1.2	<0.05	0.85	0.20
$kgCO_2e$/kg sheep LW	10.5	10.8	11.9	13.3	0.4	0.03	0.76	0.21
$kgCO_2e$/kg weaned lamb LW	31.0	23.8	23.7	25.8	1.5	0.39	0.12	0.61
$kgCO_2e$/kg product (greasy wool and LW)	10.1	10.4	11.8	12.0	0.4	0.03	0.79	0.77
$kgCO_2e$/weaned lamb	587	563	564	618	26	0.78	0.76	0.49
Economic allocation[2]								
$kgCO_2e$/kg sheep LW	10.4	10.7	11.9	12.1	0.5	<0.05	0.81	0.77
$kgCO_2e$/kg greasy wool	1.1	3.9	1.6	10.9	1.3	0.03	0.11	0.01
% of revenue from wool	0.3	1.4	0.2	8.3	0.1	<0.01	0.46	<0.01
Protein allocation[3]								
$kgCO_2e$/kg sheep LW	9.6	9.7	11.6	10.6	0.3	0.03	0.90	0.25
$kgCO_2e$/kg greasy wool	25.4	26.5	24.6	25.9	0.6	0.69	0.55	0.66
% of protein from wool	8.2	10.0	2.4	19.2	1.8	0.36	0.51	<0.01

[1] Total operation emissions reported per mass of functional unit indicated.
[2] Total operation emissions allocated to proportion of revenue and expressed per mass of sheep LW or greasy wool.
[3] Total operation emissions allocated to proportion of protein production and expressed per mass of sheep LW or greasy wool.

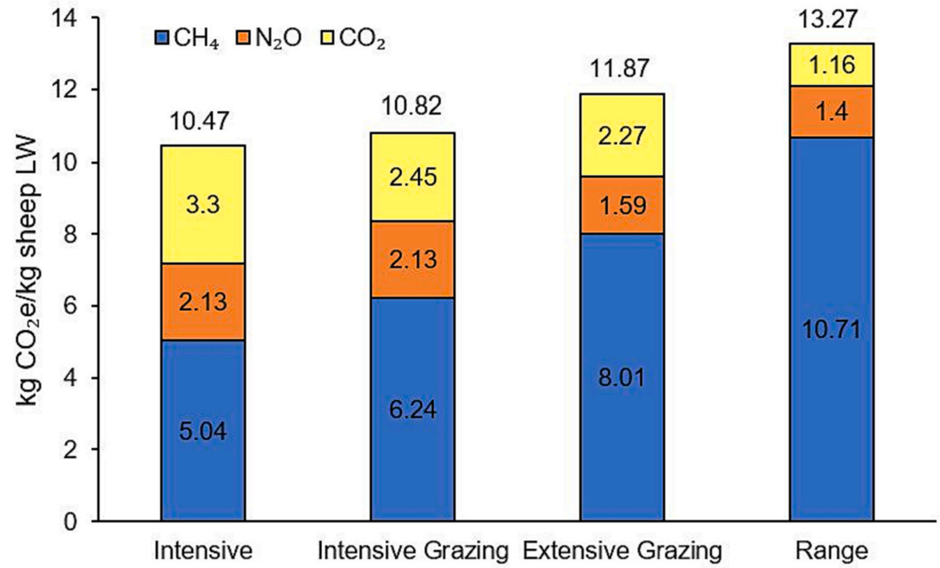


Fig. 2. Emissions intensity for three greenhouse gases (methane [CH_4], nitrous oxide [N_2O], and carbon dioxide [CO_2]) on four categories of sheep operations in the United States. Emissions intensity expressed in terms of kg carbon dioxide equivalents (CO_2e) per kg sheep liveweight (LW).

Table 4
Means and standard error of greenhouse gas emissions for the four sheep production categories. The P value of contrasts are indicated as: Intensive (I) and Intensive grazing (IG) vs Extensive grazing (EG) and Range (R); Intensive (I) vs Intensive grazing (IG); and Extensive grazing (EG) vs Range (R).

	Production category					*P value of contrast*		
Greenhouse gas	Intensive	Intensive Grazing	Extensive Grazing	Range	*SEM*	I + IG vs E + R	I vs IG	EG vs R
Kg CH_4/kg sheep LW	0.19	0.23	0.30	0.40	0.02	<0.01	0.28	0.02
Kg N_2O/kg sheep LW	0.0078	0.0079	0.0058	0.0051	0.001	<0.05	0.98	0.64
Kg CO_2/kg sheep LW*	3.30	2.45	2.27	1.16	0.30	0.04	0.27	0.13

* This value includes a minor amount of CH_4 and N_2O emissions inherent in the production of some inputs whose greenhouse gas emissions were reported according to the kg CO_2e/kg product emitted by their production.

Table 5
Mean and standard error of the proportion of total operation GHG emissions and enteric CH_4 emissions from four sheep production categories and four feedlots by source. The P value of contrasts are indicated as: Intensive (I) and Intensive grazing (IG) vs Extensive grazing (EG) and Range (R); Intensive (I) vs Intensive grazing (IG); and Extensive grazing (EG) vs Range (R).

	Production category						*P value of contrast*		
	Intensive	Intensive Grazing	Extensive Grazing	Range	Feedlot*	*SEM**	I + IG vs E + R	I vs IG	EG vs R
			% of total CO_2e from:						
Enteric CH_4	46.3	56.9	66.8	78.9	*42.3*	3.5	<0.01	0.08	0.04
Manure†	12.1	5.9	1.9	2.6	*10.5*	1.1	<0.01	<0.01	0.62
Land‡	10.0	15.5	12.9	9.4	*7.1*	1.0	0.38	0.05	0.19
Fuel and electricity	4.7	5.3	3.7	6.1	*1.8*	0.5	0.90	0.71	0.13
Purchased feed	19.8	8.5	11.5	2.6	*35.0*	2.3	0.08	0.06	0.11
Other±	7.1	7.8	3.7	0.5	*3.2*	0.9	<0.01	0.66	0.05
			% enteric CH_4 as:						
Breeding ewes	65.3	63.9	70.2	73.8		2.2	0.11	0.82	0.57
Rams	1.4	1.3	2.4	2.5		0.2	0.03	0.92	0.97
Market lambs	22.2	28.2	9.5	10.9		2.9	<0.01	0.39	0.84
Ewe and ram replacements	6.8	4.9	6.1	12.2		1.1	0.11	0.49	0.03
Breeding stock (sold)	4.2	1.7	11.7	0.7		1.7	0.29	0.56	0.02

* Feedlot operations not included in statistical comparisons.
† Consists of manure CH_4 emissions and N_2O emissions during manure storage.
‡ Consists of N_2O emissions from fertilizer and manure applications (by animal or mechanically spread after storage) and crop residues.
± Includes emissions associated production of purchased bedding, milk replacer, fertilizer, lime, seed, pesticides/herbicides and their transport onto the operation.

Market lambs contributed a larger proportion of enteric CH_4 in the I + IG operations compared to those in EG + R operations (25.2 vs 10.2%, respectively) and rams contributed a smaller proportion (1.4 vs 2.5%, respectively). The proportion of enteric CH_4 from breeding stock was higher in EG compared to the R category and lower from on-farm replacements ($P < 0.05$, Table 5).

3.4. Sensitivity to operation characteristics

Stepwise selection identified three characteristics that had a significant impact on kg CO_2e/kg lamb LW across all operations (Table 6). The number of weaned lambs per ewe per year accounted for 37% of the variation in this model. This metric had the strongest impact on emissions on a lamb LW basis, with a decrease of 8.5 kg CO_2e/kg lamb LW per unit increase (unit = 1 lamb) in yearly weaned lambs per ewe. Replacement rate accounted for 27% of the variation, and emissions intensity increased by 0.36 kg CO_2e/kg lamb LW for each percentage increase in replacement rate. The number of breeding ewes accounted for 14% of the variation in kg CO_2e/kg lamb LW, but its absolute impact on emissions intensity was relatively modest at 0.001 kg CO_2e/kg lamb LW per breeding ewe. Stepwise selection was also conducted on a sheep LW basis (Table 6), with the ewe lamb age at first breeding selected as the sole independent variable of significance, accounting for 56% of variation in kg CO_2e/kg sheep LW with an increase of 4.1 kg CO_2e/kg sheep LW per unit increase in ewe lamb age (unit = 1 year).

3.5. Sensitivity to nutritional method

Yearly enteric CH_4 production for each breeding ewe was significantly different using all three methods, with the highest produced by IPCC Tier 2 methods, followed by NRC, then IPCC Tier 1 (12.8, 12.0, and 9.0 kg enteric CH_4/ewe/year, respectively, $P < 0.01$, Table 7). There was a significant interaction between category and method for breeding ewe enteric CH_4 production, as operations with large yearly ewe enteric production estimates using NRC and IPCC Tier 2 methods were proportionally higher than those using the static IPCC Tier 1 value ($P < 0.001$). In terms of N excretion, all three methods produced different estimates, with NRC methods producing the highest, followed by IPCC Tier 2, then IPCC Tier 1 ($P < 0.01$). Differences due to method were not significant for either total enteric CH_4 (expressed as kg CO_2e) or total CO_2e emissions on a sheep LW basis (Table 7).

Table 7
Comparison of greenhouse gas (GHG) estimation methods on selected GHG emission metrics. Average yearly enteric CH_4 emissions and N excretion per ewe, and total farm enteric CH_4 and GHG emissions intensity on a kg sheep LW sold basis for the four production categories using three nutritional estimation methods (NRC, IPP Tier 1, and IPCC Tier 2) are indicated. The *P* value of the overall F test for each Method comparison and the interaction of Method and Category are also indicated.

	Means of each Method[‡]				*P value*	
	NRC	IPCC Tier 1	IPCC Tier 2	*SEM*	Method	Method*Category
Ewe estimates						
Enteric CH_4, kg CH_4/ewe/year	12.0^b	9.0^c	12.8^a	0.27	<0.01	<0.01
N excretion, kg N/ewe/year	11.6^a	8.7^c	10.6^b	0.23	<0.01	0.29
Farm estimates						
Enteric CH_4, kg CO_2e/kg sheep LW	7.5	7.1	7.6	0.36	0.55	0.72
Total GHG, kg CO_2e/kg sheep LW	11.7	10.8	11.5	0.27	0.19	0.72

[‡] Different letters designate significant differences among the three nutritional estimation methods (NRC, IPCC Tier 1, and IPCC Tier 2). Significance declared at $P < 0.05$.

4. Discussion

4.1. Greenhouse gas emissions

4.1.1. Emissions per product

Emissions intensity was less in the more intensive (I + IG) than in the more extensive operations (EG + R) on both a lamb and sheep LW basis. The I + IG operations also had higher productivity indicators, such as lower age of ewes at first breeding as well as the number and kg of lamb sold/ewe/year. Sensitivity testing demonstrated that emissions intensity was heavily influenced these productivity metrics, so it is not surprising that operations with higher productivity also demonstrated lower emissions intensity. There were no productivity nor emissions intensity differences between the I vs IG nor between the EG vs R categories, except a greater age at first breeding in the R compared to the EG category. Ewes on the I operations spent less time on pasture and there was greater concentrate purchasing per ewe compared to IG operations, but there were no differences in emissions intensity between these two categories. This suggests that the extent of grazing and concentrate purchasing is not necessarily related to emissions intensity on US sheep farms. Enteric CH_4 production was not adjusted based on diet quality in this study, but it is possible that adjusting these emissions according to diet, particularly in housed vs range sheep, may impact emissions intensity.

Our emissions intensity estimates across the four production categories, 10.5–13.3 kg CO2e/kg sheep LW, were on the lower range of those reported by others in the US (11–18 kg CO2e/kg LW; Dougherty et al., 2019), as well as in other countries including England and Wales (11–18 kg CO2e/kg LW; Jones et al., 2014), Canada (13–14 kg CO2e/kg LW; Dyer et al., 2014), and Spain (18–24 kg CO2e/kg LW; Pardo et al., 2023).

There are a few observations to be made regarding how emissions intensity changed due to functional unit choice. Across the four production categories, it ranged from 12.8 to 20.1 kg CO_2e/kg LW on a lamb basis and decreased to 10.5–13.3 kg CO_2e/kg LW with the inclusion of all sheep sold. Firstly, the inclusion of older sheep instead of only lambs predictably lowered emissions intensity as well as its variation, more so in operations that sell a significant proportion of stock as breeding stock or cull ewes. The range in mean emissions intensity was 7.3 kg CO_2e/kg lamb LW, approximately 47% of the overall mean, whereas the range was less than half this amount on an all-sheep-sold basis, at 2.8 kg CO_2e/kg sheep LW, or approximately 24% of the overall mean. This is in part due to the addition of cull ewes and rams to the denominator, which inherently minimizes differences, and was particularly evident in the EG

Table 6
Significant predictors of greenhouse gas emission intensity on a per lamb live weight (LW) and a per sheep sold functional unit basis. Forward stepwise linear regression analysis used Akaike's information criterion (AIC) as the selection and stop criteria to identify the significant predictors.

Dependent variables	Significant predictors	Beta	t Value	Significance	R^2	Adjusted R^2	F
kgCO_2e/kg sheep LW	Ewe age at breeding, yr	4.06	4.39	<0.001	0.56	0.53	19.3**
kgCO_2e/kg lamb LW	Lambs weaned/ewe/yr	−8.45	−5.08	0.002	0.78	0.73	15.4**
	Ewe replacement rate	0.359	3.90	0.002			
	Number of breeding ewes	0.0011	2.82	0.014			

** Significance at <0.001 level.

+ R categories. Several R operations reported mature ewe sales as part of their marketing strategy, and several EG operations had a high turnover of ewes due to rigid selection. Health also plays a large role in determining culling and sales, with diseases such as ovine progressive pneumonia (caused by the *Maedi-visna* virus) and mastitis often being the reason for sale (Doohoo et al., 1987; USDA APHIS, 2012). Another potential factor for culling or sale is demand for ewes as mutton, as there is a significant demand and high regard for mutton by the nontraditional market (Stepanek Shiflett et al., 2010). The importance of mature animals for the meat market in the US justifies their inclusion in emissions intensity metrics.

Using only market lambs in the emissions intensity estimate resulted in inflated values when a portion of lambs were sold as breeding stock. This was particularly evident in the EG category, whose operations sold an average of 45% of their lambs as breeding stock compared to an average of only 9% across the other categories. This impact of lamb marketing on emissions intensity was also observed in several Californian sheep operations, in which emissions intensity was reduced by approximately half on a lamb basis compared to a market lamb only basis (Dougherty et al., 2019). Emissions studies from countries other than the US typically do not differentiate between market lambs, breeding stock, and cull or mature sheep (Mazzetto et al., 2023; Dyer et al., 2014; Jones et al., 2014). Thus, it seems most appropriate to compare these estimates on a sheep LW basis.

Second, not surprisingly, BW has a large impact on emissions intensity. The emissions required for lambs to gain BW are relatively small compared to the overall flock emissions (<30% of total flock enteric emissions were produced by market lambs, Table 5), but this additional BW has a strong leveraging effect on emissions per kg LW. Therefore, operations that marketed lambs at heavier BWs had comparatively lower emissions intensity. This can be either a direct effect of selling market lambs at a heavier BW or an indirect effect of selling a large proportion of lambs as breeding stock, as these tend to be sold at higher BWs.

Market lamb BW varied widely within and among categories, with operations selling lightweight lambs (<40 kg BW) in all categories, but BW was an average of 25% higher in the I + IG categories than in the EG + R categories (Table 2). This was likely due to ewe flock genetics and marketing strategies. The EG operations utilized mainly hair-type breeds for the ewe flock which were smaller than the wool breeds found in the other operations. Market lambs from these operations were sold at lower weights and did not enter feedlots for further finishing. In the majority of the non-Range categories, light lambs tended to go directly to slaughter, whereas in the R operations, the majority were sent to feedlots for further finishing to much larger weights (>65 kg BW).

4.1.2. Feedlot finishing of range lambs

The ADG of lambs on Feedlots was 278 g/d with a range of 227–417 g/d. This was 20% lower than that observed in the I category (350 g/d) and 22% higher than the average of the other three categories (228 g/d, Table 2). The I operations fed lambs on concentrate diets, similar to those reported by the Feedlots, while some individual operations in the other categories also fed lambs concentrate diets, but this practice was less common. On both Feedlots and I operations, access to feed resources incentivized producers to feed lambs for fast and efficient growth, leading to higher ADG compared to grazing-based systems with lower inputs.

Including Feedlot emissions provides a more complete analysis of the impact of lambs from R operations. The R operations sold almost all lambs as market lambs, and the average value was 20.1 kg CO_2e/kg market lamb LW (Table 3). Using this emissions intensity to reach the average BW of 42 kg at the R farm gate and then the Feedlot emissions intensity value until reaching an average slaughter BW of 72 kg, the overall emissions intensity would be 15.1 kg CO_2e/kg BW (+/− 4.3 kg CO_2e/kg LW) from birth to slaughter. This value is 25% lower than that estimated when these lambs were sold as feeders (15.1 vs 20.1 kg CO_2e/kg LW). Therefore, inclusion of the Feedlot phase after exiting the R category decreases emissions intensity of these lambs. However, direct comparison of this inclusion to other categories is still impacted by finished weight, as these lambs are fed to BWs higher than those in all other categories (72 kg versus the 54 kg average observed for farm finished wool sheep), which comparatively deflates emissions per kg LW. Another consideration is that consumer preferences for lamb in the US vary considerably both in terms of carcass size and desired degree of carcass fat (Stepanek Shiflett et al., 2010). Hence, growing lambs to larger carcass weights may not be an optimal environmental strategy when lean growth becomes inefficient nor a sound marketing strategy if the consumer demand favors smaller and/or leaner carcasses. Identification of the point of growth inefficiency and degree of optimal body fatness are important aspects to define in GHG mitigation strategies.

4.1.3. Economic and protein allocation

Meat from market lambs, replacements, and cull animals contributed the vast majority of each operation's revenue (87–99% on individual operations that produced wool). When allocating on an economic basis, R operations observed the greatest decrease in kg CO_2/kg sheep LW due to the highest % of revenue from wool (Table 3), while the other categories had minimal change compared to allocation on a mass basis. The majority of EG operations raised hair sheep; thus, little change was observed in this category when allocating GHG to wool. There is a diversity of marketing goals and sheep genetics in US systems, with some operations choosing to produce a specific wool product while compromising meat production characteristics such as high prolificacy or size of lamb at market. Range operations in the US consistently produce sheep that are more highly valued for their wool, with fine wool breeds dominating most of their genetics compared to the other production categories. However, their proportion of revenue and protein production was still less than that observed in other countries whose focus has traditionally been fine wool production. A case study analyzing coarse, fine, and superfine wool operations in the UK, NZ, and AU observed a much lower range of economic value from meat than the current study (48–96% in Wiedemann et al., 2015). One factor that may account for the low value of wool in operations in the present study is the comparatively low price paid for wool in the US compared to the UK, NZ, and AU, which ranged from \$1.77–8.80 per kg greasy wool, while operations in the current study reported a much lower range of \$0.06–4.80/kg greasy wool. For several operations outside of the R category, wool price was as low at \$0.06/kg, thereby negating the impact of wool using an economic allocation.

The proportion of protein product at the farm gate in the form of wool ranged from 8 to 19% across the wool-producing operations. The R category produced a value 2.8 times higher than the other categories (19.2% of protein from wool vs an average of 6.9% across other three categories), which was similar to those observed in coarse wool operations in the UK and NZ (4 and 19% of protein production, respectively), but less than those in Australian fine wool operations (47 and 52%; respectively, Wiedemann et al., 2015). This may be due to a combination of production and clean yield. The yearly average wool production by each ewe in this study was 3.3 kg greasy wool for non-Range operations (26-μm fiber diameter average on reported values) and 4.5 kg for R operations (22-μm fiber diameter average on reported values). These values are much lower than those observed in medium to super fine Merino wool sheep in AU (8.2–10 kg; Wiedemann et al., 2016) with lower clean yields (54 vs 62% in US and AU, respectively), indicating that even though R operations focus more heavily on wool production, their production observed in this study was less than that in NZ and AU. In an LCA of NZ sheep, protein allocation resulted in 31% of emissions being assigned to wool production, and emissions intensity was lower than that observed across all categories in this study when allocating by protein production (9.6–11.6 kg CO_2e/kg sheep LW), at 6.0 kg CO_2e/kg LW (Mazzetto et al., 2023).

4.1.4. Emissions of individual GHG

The amount of CH_4 emitted per kg sheep LW increased from the most (I) to the least (R) intensive categories (Table 4). The proportion of total GHG from enteric CH_4 followed the same pattern (Table 5), indicating that not only is more CH_4 produced with less intensive systems, but this CH_4 contributes a greater proportion of total GHG emissions. This is also illustrated in Fig. 2, which displays the relative proportion of emissions intensity contributed by CH_4, N_2O, and CO_2. The contribution of CH_4 to total emissions intensity (as kg CO_2e/kg sheep LW) increased approximately two-fold from the I to the R categories (5.04 to 10.71 kg CO_2e/kg sheep LW, respectively, Fig. 2).

Since both enteric and manure CH_4 emissions are related to productivity, with higher productivity essentially creating more product with fewer animals over less time, these results demonstrate the potential to reduce CH_4 emissions via productivity increases. The same pattern was likely not observed regarding N_2O emissions intensity, as in addition to animal emissions (stored and deposited manure), it also included N_2O from fertilizer and crop residues. These additional sources of N_2O were more prevalent in the IG and EG categories, which used more fertilizer and managed grazing practices, and were minimal in the R category. Since R operations used minimal fertilizer and manure storage, the proportion of emissions intensity contributed by N_2O was the least in this category (1.4 kg CO_2e/kg sheep LW, Fig. 2).

The emissions intensity of CO_2 was higher in the I + IG categories, which is not surprising as these operations typically had more inputs, particularly that of feeds, but also included some emissions related to bedding and other inputs. It should be noted that these emissions include a small amount of the previous gases (CH_4 and N_2O) due to the inclusion of kg CO_2e/kg input (Table 1) for such items as feeds, bedding, and fertilizers. The emissions intensity values for CH_4, N_2O, and CO_2 observed in this study (average of 0.28, 0.0067, and 2.30 kg GHG/kg sheep LW) were higher than those reported for the NZ sheep industry (0.18, 0.0023, 0.35 kg GHG/kg LW, respectively; Mazzetto et al., 2023). But average emissions intensity was approximately 42% lower in that study (6.0 kg CO_2e/kg LW vs 10.4 in the current study with protein allocation), partly due to higher wool production by NZ sheep.

In terms of distribution of the 3 GHGs, our results were similar to those observed in Spanish sedentary and transhumance flocks (Pardo et al., 2023), as the average distribution among the I + IG operations was 53, 20, and 27% for CH_4, N_2O, and CO_2, respectively, and 74, 12, and 14% for the EG + R operations. This is explained by the higher inputs and more manure storage in the more intensive operations, which increased CO_2 and N_2O emissions, as well as higher productivity, which decreased CH_4 emissions. The proportion of GHG emissions from N_2O was also similar to that reported for case study farms in the UK, NZ, and AU (21, 18, and 10%, respectively) but the proportion as CO_2 was higher (7, 5, and 5%; Wiedemann et al., 2015). This again reflects the diversity of production systems within this study, since the averages are dissimilar, but the Range operations demonstrated a very similar GHG distribution (80, 11, and 9%) to the AU case study farms.

It should also be noted that direct comparisons between LCAs are confounded by differences in methodology and should be interpreted with caution. For instance, emissions from crop residues were included on all annual crops in this study, which accounted for up to 30% of the N_2O emissions on individual operations. Also, marketing decisions between selling breeding stock versus market lambs and the decision when to cull animals is farm dependent but impacts emissions intensity due to how and when sheep leave the farm. This study sought out operations which encompassed the breadth of the US sheep industry, which includes not only commercial market lamb production but also breeding stock sales in addition to that of lambs produced for meat consumption. This was particularly true for the EG category, which contained several farms that sold are large proportion of breeding stock, but was present to some extent in the other categories as well.

4.1.5. Influential factors on emissions

4.1.5.1. Ewe productivity. Three operation characteristics were found to significantly impact emissions intensity on a lamb LW basis, and only one on a sheep LW basis ($P < 0.05$). The characteristic that accounted for the most variation in kg CO_2e/kg lamb LW was the number of weaned lambs/ewe/year, which accounted for over one-third of the variation in emissions intensity. Indeed, the more intensive (I + IG) operations had a significantly higher number and kg of lamb sold/ewe/year than the more extensive (EG + R) operations as well as lower emissions intensity. Since emissions are distributed across the total amount of product, higher ewe productivity will reduce emissions per kg of product leaving the operation, essentially diluting the maternal flock emissions across more product. In the UK, the number of lambs reared per ewe was also demonstrated to have the greatest impact on emissions intensity, accounting for 27% of the variance in kg CO_2e/kg LW (Jones et al., 2014). Ewe productivity is often measured by the number of lambs weaned per ewe exposed to rams on an annual basis, as it integrates conception rate, lambs born per ewe, and lamb mortality to weaning. These three metrics are not recorded in all US operations, whereas the number of weaned lambs is often readily available, making it a more broadly useful productivity metric.

The average number of weaned lambs/ewe/year across all operations that participated in this study was 1.4, but there was wide variation among categories. The I and IG categories weaned more lambs/ewe/year (1.88 and 1.62, respectively,) than that in the EG and R categories (1.18 and 1.01, respectively). The national estimate of lambs born (or docked and/or branded) per ewe per year was 1.07 (USDA NASS, 2022), which was similar to what we observed in the EG + R categories.

In general, the more intensive operations utilized genetics with high prolificacy and supported them with greater resource inputs such as purchased feed and housing to efficiently achieve a high level of production. Providing greater nutritional inputs strategically, particularly prior to breeding to achieve larger litter size and in late pregnancy and lactation to improve lamb survival and growth, allows these operations to produce more weaned lambs per ewe. In addition, housing animals reduces the risk posed by predation and weather events, improving lamb survival to weaning. The EG + R categories are inherently more resource limited in terms of the nutritional inputs needed to support a higher level of production, however modest improvements in prolificacy are feasible within this resource base and a focus on reduction of mortality would clearly make a large impact on improved efficiency.

Genetic selection for low-methane-emitting sheep as a mitigation strategy has been demonstrated to reduce enteric CH_4 production by approximately 20% (Jonker et al., 2016). There is a large diversity of breeds across the US sheep industry that are well adapted to local conditions, ranging from smaller hair sheep to larger fine-wool producing sheep, to sheep with high prolificacy that are capable of breeding year-round. A comprehensive selection effort for all these different types of sheep may be challenging and take a significant amount of time. Selection for improved ewe productivity within these diverse breeds and regions is a tangible and ready-to-implement strategy that producers may use now to mitigate emissions in the ewe flock.

4.1.5.2. Breeding replacements. Another characteristic that impacted emissions intensity was ewe replacement rate, accounting for 27% of the variation in kg CO_2e/kg lamb LW. In this study, a reduction of 5% in ewe replacement rate would reduce emissions by 1.8 kg CO_2e/kg lamb LW (a 15% reduction across all categories). Replacement rate is an indicator of ewe longevity in the breeding flock. Removal from the flock is often determined by the ewe's ability to reproduce and wean lambs which can be impacted by disease state. Some operations maintained selection pressure on mature ewes for genetic improvement, making it difficult to separate this from culling decisions based on productivity concerns. When replacement rate is high, emissions increase due to growing these replacements and their lower reproductive performance compared to mature ewes, as well as causing a direct reduction in the number of lambs for sale (Dougherty et al., 2019). Increased selection pressure may, however, improve flock productivity in the longer term, thus offsetting this impact or perhaps even reducing emissions. More work is needed to understand optimization of selection pressure to minimize emissions.

Age at first breeding was a significant factor in emissions intensity on a sheep LW basis, accounting for 56% of the variation in kg CO_2e/kg sheep LW. Ewe lambs were bred at 9–11 months of age in all operations except in 1 EG and 4 R operations. This difference is explained in part by genetics and nutritional management. Ewes in R operations tend to have genetics that reach puberty later than the more prolific germplasm commonly found in more intensive operations. In addition, ewe lambs are developed on a lower plane of nutrition in R operations than those on more intensive systems, thus further delaying puberty (Foster and Olster, 1985). Therefore, R operations tend to delay exposure of ewes to rams until they are greater than one year of age to produce the best reproductive outcomes. Lowering the age at first breeding means less emissions prior to producing lambs but requires appropriate nutritional inputs and genetics to achieve adequate conception rates and reproductive outcomes. Therefore, this strategy to reduce GHG appears appropriate and feasible for the more intensive production systems but not for Range operations due to resource constraints.

4.1.5.3. Flock size. Another factor that explained a small but significant amount of variation in emissions (14%) was the number of breeding ewes. For each increase of 1000 breeding ewes, emissions intensity increased by approximately 1 kg CO_2e/kg lamb LW. The magnitude of this change is inconsistent with observations by Jones et al., 2014 in the UK, who found that larger flocks resulted in more efficient use of resources. The current finding needs to be considered carefully as the largest flocks were in the R category, which had lower productivity and numerically higher emissions intensity. An evaluation of emissions intensity with more operations of different sizes within and among categories is needed to confirm or refute this observation.

4.2. Emissions profile

4.2.1. Enteric CH_4 and manure

Enteric CH_4 was the major source of GHG emitted across all categories, accounting for <45% of total GHG emissions (Table 5). The I + IG categories emitted a lower proportion of GHG as enteric CH_4 compared to the EG + R categories. This is likely due to higher productivity (kg lamb LW/ewe/year), which results in fewer animals over a shorter period to produce product, leading to comparatively less enteric CH_4 production as a proportion of total GHG emissions. Similarly, these operations had greater GHG emissions from manure due to storing manure compared to the more extensive operations, especially in the I operation category which housed ewes for 87% of their production cycle.

The proportion of total emissions from enteric CH_4 in this study was within the range observed in case studies in California (68–79%; Dougherty et al., 2019), New Zealand (83%; Mazzetto et al., 2023), and in Australian wool production sheep (76–89%; Wiedemann et al., 2016). In intensive production farms in Spain, the proportion of total GHG emissions from enteric CH_4 was significantly lower than those observed on transhumance farms (62 vs 72–74%, respectively; Pardo et al., 2023), which corresponds to the pattern between intensive and extensive operations in this study (Table 5). Operations in the R category practiced transhumance, either moving to seasonal pastures by truck or on foot, but they did not have as much concentrate feeding as those surveyed in Spain (17 vs 109 kg/ewe, respectively).

Housing is common in the Northern US during pasture dormancy, which is often close to half of the year, with most operations feeding under housing at least part of year. In addition, housing is used for all cold weather lambing, and many of the I operations had a winter lambing period. Housing allows greater intensity of production and is often associated with the use of use of genetics with greater productivity, precise feeding management, and lower lamb mortality. This results in many more lambs sold per ewe per year and thereby lower emissions intensity than in extensive systems. Housing also increases manure storage; however, these extra emissions may be offset by greater production efficiency. Mitigation options directed at manure storage will be helpful in reducing emissions on more intensive operations, but these practices are limited to solid storage options in nearly all operations due to size constraints and housing options.

4.2.2. Feed, land, and fuel emissions

An objective of this study was to measure GHG emissions in US operations that differed in resource use. The I + IG categories purchased significantly more concentrates and total feed per ewe per year than the EG + R categories, with the I category purchasing the most feed on average (573 kg/ewe/year). There was a large range in both forage and concentrate purchasing within each category except the R category, which had consistently low feed purchasing. Intensive operations almost exclusively housed their ewes and lambs and often finished lambs to varying weights using concentrate-based diets. However, there were operations in both the IG and EG categories that also fed lambs indoors or in a dry lot situation with concentrate-based diets, so this practice was not exclusive to the I category. The amount of concentrate feeding observed in the IG and EG categories (average of 110 kg/ewe/year) is similar to observations in the UK (Edwards-Jones et al., 2009) and in Spanish transhumance operations (Pardo et al., 2023). Range operations purchased very little feed (<45 kg/ewe/year) and kept animals almost exclusively on pasture, moving animals seasonally and supplementing as needed during winter or lambing. This amount of concentrate is similar to reported farms in NZ and AU (<50 kg feed/ewe/year), although grazing practices are specific to the region (Wiedemann et al., 2016; MPI Technical Paper 2017/57, 2024).

It should be noted that the proportion of GHG from enteric CH_4 in Feedlots was similar to that for I operations (42.3 vs 46.3%, respectively), but with a higher proportion of GHG from feed purchasing compared to I operations (35.0 vs 19.8%, respectively). Most of the Feedlots used purchased feed exclusively (3 out of 4), and the lower enteric CH_4 emissions can be largely explained by the exclusion of the ewe flock component. These factors made the proportions of total GHG emissions from feed purchases on the Feedlots nearly equivalent to that from enteric CH_4 emissions.

The proportion of total emissions from land applications was higher in I vs IG operations. These emissions include applications (manure, fertilizer, lime, and herbicides/pesticides) and crop residue decomposition (Intergovernmental Panel on Climate Change (IPCC), 2019b). The proportion of emissions from land sources in I operations was similar to that in R operations, despite applying fertilizer and other products. This is likely explained by the transportation of manure in two I operations to neighboring cropland that was not used for sheep production, of which an equivalent amount of N_2O emissions were credited to back to land applications. It can be presumed that lower emissions due to land applications on these operations are offset by increased emissions through purchased feeds that utilize either manure or synthetic fertilizer.

Reference emissions intensity values were used for each kg of feed purchased (see Table 1). These values may vary depending on cropping practices. Climate-friendly or sustainable management practices may reduce emissions from producing feeds. Thus, it is important to recognize these efforts when evaluating mitigation efforts, particularly in operations which purchase the majority of their feeds, such as I operations, but also in grazing operations that supplement their animals

Fuel use did not differ among any of the comparisons. Some fuel and fertilizer use may be inherent within the purchased feed category, as crop production requires these inputs. But in terms of on-farm use, the intensity of production was not related to fossil fuel use. Fuel was used for different purposes between the production categories, with the more extensive operations (EG + R) typically using fuel for farm-use vehicles, transporting animals, and pumping water while the intensive ones (I + IG) reported greater use for facilities, feeding, and manure handling equipment. The wide ranges in fuel and electricity use for each category indicate that this metric varies greatly among all operations with no impact of production system per se.

4.2.3. Productivity and partition of emissions between lambs and ewes

Enteric CH_4 emissions were produced predominantly by the breeding ewe flock across all categories (>60%, Table 5). This finding again emphasizes the importance of ewe productivity, as higher productivity means fewer ewes are required to produce the same amount of lamb, essentially diluting the flock overhead. Mitigation strategies focused on this population are a practical target for lowering emissions. A variety of feed additives such as 3-NOP and seaweed have been demonstrated to reduce enteric CH_4 production (Beauchemin et al., 2022; Wasson et al., 2022). But their supplementation to the ewe flock presents challenges, as most of these animals are on pasture in all but the I operations and therefore cannot receive a controlled dose of additive throughout the year.

The proportion of enteric CH_4 contributed by ewe and ram replacements was <15% across all categories. R operations had the highest value, mainly due to older age at first breeding, increasing the time for emissions until the ewe lamb becomes part of the breeding flock. The proportion of enteric CH_4 by breeding stock was lower than that by replacements across most categories, indicating that most operations kept more animals for incorporation into the breeding flock than selling them as breeding stock. The exception to this was the EG category, which only sold 45% of its lambs as breeding stock, leading to nearly 3 times the proportion of enteric CH_4 from breeding stock as any other category. On average, lambs (market, replacements, and breeding stock) accounted for 30% of enteric CH_4 across all categories.

The impact of dietary changes on enteric CH_4 emissions is relatively unknown in sheep, as most studies have fed forage-only diets. In an analysis of 71 experiments, the inclusion of equations specific to mixed diets led to only modest improvements in predicted enteric CH_4, but only 16% of these experiments fed non-forage components (Belanche et al., 2023). When lambs were fed up to 65% of diet DM as corn grain, enteric CH_4 production (g/d) and yield (g/kg DMI) responded in a quadratic fashion (Jonker et al., 2016), suggesting that sheep may not have a dramatic reduction in enteric CH_4 yield as observed in cattle. However, further research is required to investigate the impact of high concentrate diets such as those unique to the US sheep industry.

4.3. Impact of nutritional methodology on emissions intensity

Yearly enteric CH_4 production by breeding ewes was significantly different among the three estimation methods. Estimates using IPCC Tier 2 and NRC methods were 42 and 33% higher, respectively, than the IPCC Tier 1 static value of 9 kg CH_4/ewe/year. Because both methods use energy requirements as the basis of their enteric CH_4 emissions estimates, they can account for differences in animal size and productivity compared to the static IPCC Tier 1 value based on a 40 kg ewe in a high productivity system. The average BW of ewes in this study was 74 kg, which is much higher than the IPCC Tier 1 assumption. In addition, higher productivity (more lambs/ewe/year) and/or older weaning ages will indirectly increase breeding ewe enteric CH_4 emissions. These ewes were either in late pregnancy or lactation for up to 35% of the year, both of which increase energy intake, and thus, enteric CH_4 emissions. These factors of BW and productivity combine to produce variation in ewe enteric CH_4 emissions which are not accounted for in IPCC Tier 1 methods.

Differences in N excretion were significantly different by method, with IPCC Tier 2 and NRC methods producing estimates 22 and 34% higher, respectively, than those produced by IPCC Tier 1 values. Again, higher BW and productivity in ewes in the present study likely resulted in estimates higher than the global standard. Manure N_2O emissions only contributed <15% of total GHG emissions across all categories in this study, so these differences have a relatively minor impact on total GHG emissions.

There was no significant effect of method on either kg enteric CH_4 (as CO_2e) or total CO_2e per kg sheep LW, despite being numerically lower when using IPCC Tier 1 methods. Apparently, the differences in higher enteric CH_4 production and N excretion (and its consequent impact on N_2O emissions) by breeding ewes were not enough to result in significant changes when expressed as total farm emissions intensity. However, since ewe enteric CH_4 and N excretion were significantly impacted by method, it seems appropriate to recommend using either the NRC or IPCC Tier 2 methods to predict enteric CH_4 and manure CH_4 and N_2O emissions, which adapt to an operation's animal size and productivity.

5. Conclusion

Emissions intensity (kg CO_2e/kg product sold) in US sheep operations was lower in the more intensive (Intensive and Intensive Grazing) categories than in the more extensive (Extensive Grazing and Range) ones (10.6 vs 12.6 kg CO_2e/kg sheep live weight, respectively). There was wide variation among categories in both descriptive characteristics and productivity, indicating good representation of the diversity in the US sheep industry. The largest proportion of emissions in all categories originated from enteric CH_4 production, with a gradient in this proportion from most extensive (79%) to most intensive (46%) production categories evident. The breeding ewe population contributed over 60% of enteric CH_4 emissions across all categories, and the number of lambs weaned/ewe/year, ewe replacement rate, and age at first ewe lamb breeding were the most influential farm characteristics on emissions intensity, indicating that productivity of the ewe flock should be an important target for mitigation efforts. Strategies to improve ewe productivity include increasing lambing rate, improving ewe health, and lowering the age at first breeding and are immediately available and broadly applicable across the range of sheep production systems in the US. Use of IPCC Tier 1 methods for estimating breeding ewe enteric methane provided lower estimates than either IPCC Tier 2 or NRC 2007 methods and fail to adequately account for the diversity of flock genetics and production systems present in the US. A method that determines emissions accounting for these differences will not only be more accurate but will allow for better measurement of mitigation efforts.

Funding

Research reported in this publication was supported by the American Lamb Board, Denver, Colorado and Michigan State University AgBioResearch and the United States Department of Agriculture (USDA) National Institute of Food and Agriculture (Hatch MICL02445 to R.A.E.).

Research data for this article

Due to the sensitive nature of the records collected in this study, participants were assured raw data would remain confidential and only aggregated information would be published.

CRediT authorship contribution statement

Erin B. Recktenwald: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Richard A. Ehrhardt:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author owns and manages a sheep farm. R.A.E.

Data availability

The data that has been used is confidential.

Acknowledgements

We thank Barbara Makela for assistance with the editorial review and Guanqi Lu from the MSU CANR Statistical Consulting Center for assistance with statistical analysis of this work. We also appreciated the constructive comments provided by the 5 reviewers on this paper allowing us to improve our interpretation and presentation of the data.

References

Beauchemin, K.A., Ungerfeld, E.M., Abdalla, A.L., Alvarez, C., Arndt, C., Becquet, P., Benchaar, C., Berndt, A., Mauricio, R.M., McAllister, T.A., Oyhantcabal, W., Salami, S.A., Shalloo, L., Sun, Y., Tricarico, J., Uwizeye, A., De Camillis, C., Bernoux, M., Robinson, T., Kebreab, E., 2022. Invited review: current enteric methane mitigation options. J. Dairy Sci. 105 https://doi.org/10.3168/jds.2022-22091.

Belanche, A., Hristov, A.N., van Lingen, H.J., Denman, S.E., Kebreab, E., Schwarm, Yanez-Ruiz, D.R., 2023. J. Clean. Prod. 384, 135523 https://doi.org/10.1016/j.jclepro.2022.135523.

Cannas, A., Tedeschi, L.O., Fox, D.G., Pell, A.N., Van Soest, P.J., 2004. A mechanistic model for predicting the nutrient requirements and feed biological values for sheep. J. Anim. Sci. 82, 149–169.

Cardellino, R.A., Benson, M.E., 2002. Lactation curves of commercial ewes rearing lambs. J. Anim. Sci. 80, 23–27.

Doohoo, I.R., Heaney, D.P., Stevenson, R.G., Samagh, B.S., Rhodes, C.S., 1987. The effects of Maedi-Visna virus infection on productivity in ewes. Prevent. Veterin. Med. 4, 471–484.

Dougherty, H., Oltjen, J.W., Mitloehner, F.M., DePeters, E.J., Pettey, L.A., Macon, D., Finzel, J., Rodrigues, K., Kebreab, E., 2019. Carbon and blue water footprints of California sheep production. J. Anim. Sci. 97, 945–961.

Dyer, J.A., Verge, X.P.C., Desjardins, R.L., Worth, D.E., 2014. A comparison of the greenhouse gas emissions from the sheep industry with beef production in Canada. Sus. Ag Res. 3 (3), 65–75.

Dynes, R.A., Scobies, D.R., Vibart, R.E., Rennie, G., Hutchinson, K.J., Taylor, A., Moss, R. A., Dennis, S., Wall, A., 2019. Carbon footprint of two unique farms, compared with industry averages. NZ J. Anim. Sci. Prod. 79, 118–124.

Edwards-Jones, G., Plassmann, K., Harris, I.M., 2009. Carbon footprinting of lamb beef production systems: insights from an empirical analysis of farms in Wales, UK. J. Agric. Sci. 147, 707–719. https://doi.org/10.1017/S0021859609990165.

Environmental Protection Agency, 2022a. Emission factors for greenhouse gas inventories. https://www.epa.gov/climateleadership/ghg-emission-factors-hub (accessed 13 April 2022).

Environmental Protection Agency, 2022b. US GHG Inventory. Chapter 5. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjS-svpm9f-AhXHBzQIHdM1D7IQFnoECD8QAQ&url=https%3A%2F%2Fwww.epa.gov%2Fsystem%2Ffiles%2Fdocuments%2F2022-04%2Fus-ghg-inventory-2022-chapter-5-agriculture.pdf&usg=AOvVaw1eJaKVovZzbEYKqKkfWOHv (accessed 23 March 2023).

Environmental Working Group, 2011. Meat eaters guide to climate change and health. In: Lifecycle Assessments: Methodology and Results. https://www.ewg.org/consumer-guides/ewgs-quick-tips-reducing-your-diets-climate-footprint (accessed 13 Dec 2019).

FAOStat, 2023. Food and Agriculture Organization of the United Nations. FAOSTAT Statistical Database. Crops and livestock products. https://www.fao.org/faostat/en/#search/sheep%20inventory (accessed 1 May 2023).

Farm Energy Analysis Tool (FEAT), 2018. G.G.T. Camargo, G.M. Malcolm, M.R. Ryan, T. L. Richard. Version 1.2.7. Nov 2018. Pennsylvania State University. https://www.ecologicalmodels.psu.edu/agroecology/feat/download.htm (accessed 24 June 2020).

Foster, D.L., Olster, D.H., 1985. Effect of restricted nutrition on puberty in the lamb: patterns of tonic luteinizing hormone (LH) secretion and competency of the LH surge system. Endocrinology. 116 (1), 375–381.

Global Feed LCA Institute (GFLI), 2021. GFLI Database. https://globalfeedlca.org/gfli-database/ (accessed 20 May 2022).

Intergovernmental Panel on Climate Change (IPCC), 2019a. Chapter 10. Emissions from livestock and manure management. Refinement to the 2006 IPCC Guidelines for national greenhouse gas inventories. In: Agriculture, Forestry, and Other Land Use, p. 4. https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html (accessed 10 Dec 2019).

Intergovernmental Panel on Climate Change (IPCC), 2019b. Chapter 11. N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. Refinement to the 2006 IPCC Guidelines for national greenhouse gas inventories. In: Agriculture, Forestry, and Other Land Use, p. 4. https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html (accessed 6 April 2020).

Intergovernmental Panel on Climate Change (IPCC), 2021. Climate change 2021: The physical science basis. Contribution of Working Group 1 to the Sixth Assessment Report of the IPCC. Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity. https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-7/ (accessed 21 April 2023).

ISO, 2006. International Standard 14044:2006(E). Environmental management – Life cycle assessment – Requirements and Guidelines. ISO, Geneva, Switzerland.

ISO, 2018. International Standard 14067:2018(E). Greenhouse gases – Carbon footprint of products – Requirements and Guidelines for Quantification. ISO, Geneva, Switzerland.

Jones, A.K., Jones, D.L., Cross, P., 2014. The carbon footprint of lamb: sources of variation and opportunities for mitigation. Ag Syst. 123, 97–107.

Jonker, A., Lowe, K., Kittelmann, S., Janssen, P.H., Ledgard, S., Pacheco, D., 2016. Methane emissions changed nonlinearly with graded substitution of alfalfa silage with corn silage and corn grain in the diet of sheep and relation with rumen fermentation characteristics in vivo and in vitro. J. Anim. Sci. 94, 3464–3475. https://doi.org/10.2527/jas2015-9912.

LEAP, 2016. Environmental performance of large ruminant supply chains: guidelines for assessment. Food and Agriculture Organization, pp. 1–99. http://www.fao.org/3/a-i6494e.pdf (accessed 8 April 2020).

Leip, A., Ledgard, S., Uwizeye, A., Palhares, J.C.P., Aller, M.F., Amon, B., Binder, M., Cordovil, C.M.D.S., De Camillis, C., Dong, H., Fusi, A., Helin, J., Hortenhuber, S., Hristov, A.N., Koelsch, R., Liu, C., Masso, C., Nkongolo, N.V., Patra, A.K., Redding, M.R., Rufino, M.C., Sakrabani, R., Thoma, G., Vertes, F., Wang, Y., 2019. The value of manure – manure as co-product in life cycle assessment. J. Enviro. Mgmt. 241, 293–304 doi:10.1016.j.jenvman.2019.03.059.

Mazzetto, A.M., Falconer, S., Ledgard, S., 2023. Carbon footprint of New Zealand beef and sheep meat exported to different markets. Environ. Impact Assess. Rev. 98, 106946.

McGranahan, D.A., Geaumont, B., Spiess, J.W., 2018. Assessment of a livestock GPS collar based on an open-source datalogger informs best practices for logging intensity. Ecol. Evol. 8 (11), 5649–5660. https://doi.org/10.1002/ece3.4094.

MPI Technical Paper 2017/57, 2024. Analysis of Supplemental Feed Use in the New Zealand Sheep industry. ISBN No: 978–1–77665-677-6. https://mpi.govt.nz/dmsdocument/20909-analysis-of-supplemental-feed-use-in-the-new-zealand-sheep-industry.

National Research Council (NRC), 1985. Nutrient Requirements of Sheep, Sixth revised edition. National Academy Press, Washington, D.C.

National Research Council (NRC), 2007. Nutrient Requirements of Small Ruminants: Sheep, Goats, Cervids, and New World Camelids. The National Academies Press, Washington, D.C.

New Zealand Government, 2023. New Zealand's Greenhouse Gas Inventory: Snapshot, 1990–2021. https://environment.govt.nz/publications/new-zealands-greenhouse-gas-inventory-19902021-snapshot/#emissions-trends-by-sector.

Pardo, G., Casas, R., del Prado, A., Manzano, P., 2023. Carbon footprint of transhumant sheep farms: accounting for natural baseline emissions in Mediterranean systems. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-023-02135-3.

Patra, A.K., Lalhraitpuii, M., Debnath, B.C., 2016. Predicting enteric methane emission in sheep using linear and non-linear statistical models from dietary variables. Anim. Prod. Sci. 56, 574–584. https://doi.org/10.1071/AN15505.

Place, S.E., Mitloehner, F.M., 2021. Pathway to climate neutrality for US beef and dairy cattle production. https://clear.ucdavis.edu/news/climate-neutrality (accessed 3 May 2023).

Ramsey, W.S., Hatfield, P.G., Wallace, J.D., Southward, G.M., 1994. Relationships among ewe milk production and ewe and lamb forage intake in Targhee ewes nursing single or twin lambs. J. Anim. Sci. 72, 811–816.

Rotz, C.A., Asem-Hiablie, S., Place, S., Thoma, G., 2019. Environmental footprints of beef cattle production in the United States. Ag. Syst. 169, 1–13.

SAS Institute Inc, 2016. SAS 9.4. SAS Institute Inc., Cary, NC.

Sheep Sustainability Framework, 2023. Annual Report 2023. https://www.mla.com.au/globalassets/sheep-sustainability/media/bh.33.sheep-sustainability-2023_july_web.pdf (accessed Nov 29 2023).

Snowder, G.D., Glimp, H.A., 1991. Influence of breed, number of suckling lambs, and stage of lactation on ewe milk production and lamb growth under range conditions. J. Anim. Sci. 69, 920–923.

Stanley, P.L., Rowntree, J.E., Beede, D.K., DeLonge, M.S., Hamm, M.W., 2018. Impacts of soil carbon sequestration on life cycle greenhouse gas emissions in Midwestern USA beef finishing systems. Ag. Syst. 162, 249–258. https://doi.org/10.1016/j.agsy.2018.02.003.

Stepanek Shiflett, J., Williams, G., Rodgers, P., 2010. Nontraditional lamb market in the United States: Characteristics and marketing strategies. https://www.sheepusa.org/resources-publications (accessed 24 April 2023).

US Climate Data, 2020. https://www.usclimatedata.com/ (accessed 4 April 2020).

USDA APHIS, 2012. Part II: Reference of marketing and death loss on US sheep operations. Available from. https://www.aphis.usda.gov/animal_health/nahms/sheep/downloads/sheep11/Sheep11_dr_PartII.pdf (accessed 3 July 2023).

USDA NASS, 2022. Sheep and Goats. ISSN:1949–1611. Released January 31, 2022. https://usda.library.cornell.edu/concern/publications/000000018?locale=en.

Wasson, D.E., Yarish, C., Hristov, A.N., 2022. Enteric methane mitigation through *Asparagopsis taxiformis* supplementation and potential algal alternatives. Front. Anim. Sci. 3, 999338 https://doi.org/10.3389/fanim.2022.999338.

Webber, B.L., Weber, K.T., Clark, P.E., Moffet, C.A., Ames, D.P., Taylor, J.B., Johnson, D. E., Kie, J.G., 2015. Movements of domestic sheep in the presence of livestock Guardian dogs. Sheep Goat Res. J. 30, 18–23.

Wiedemann, S.G., Ledgard, S.F., Henry, B.K., Yan, M.-J., Mao, N., Russell, S.J., 2015. Application of life cycle assessment to sheep production systems: investigating co-production of wool and meat using case studies from major global producers. Int. J. Life Cycle Assess. 20, 463–476.

Wiedemann, S.G., Yan, M.-J., Henry, B.K., Murphy, C.M., 2016. Resource use and greenhouse gas emissions from three wool production regions in Australia. J. Clean. Prod. 122, 121–132.