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Carbon and blue water footprints of California sheep production[1]

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ABSTRACT: While the environmental impacts of livestock production, such as greenhouse gas emissions and water usage, have been studied for a variety of US livestock production systems, the environmental impact of US sheep production is still unknown. A cradle-to-farm gate life cycle assessment (**LCA**) was conducted according to international standards (ISO 14040/44), analyzing the impacts of CS representing five different meat sheep production systems in California, and focusing on carbon footprint (carbon dioxide equivalents, CO_2e) and irrigated water usage (metric ton, **MT**). This study is the first to look specifically at the carbon footprint of the California sheep industry and consider both wool and meat production across the diverse sheep production systems within California. This study also explicitly examined the carbon footprint of hair sheep as compared with wooled sheep production. Data were derived from producer interviews and literature values, and California-specific emission factors were used wherever possible. Flock outputs studied included market lamb meat, breeding stock, 2-d-old lambs, cull adult meat, and wool. Four different methane prediction models were examined, including the current IPCC tier 1 and 2 equations, and an additional sensitivity analysis was conducted to examine the effect of a fixed vs. flexible coefficient of gain (k_g) in mature ewes on carbon footprint per ewe. Mass, economic, and protein mass allocation were used to examine the impact of allocation method on carbon footprint and water usage, while sensitivity analyses were used to examine the impact of ewe replacement rate (% of ewe flock per year) and lamb crop (lambs born per ewe bred) on carbon footprint per kilogram market lamb. The carbon footprint of market lamb production ranged from 13.9 to 30.6 kg CO_2e/kg market lamb production on a mass basis, 10.4 to 18.1 kg CO_2e/kg market lamb on an economic basis, and 6.6 to 10.1 kg CO_2e/kg market lamb on a protein mass basis. Enteric methane (CH_4) production was the largest single source of emissions for all CS, averaging 72% of total emissions. Emissions from feed production averaged 22% in total, primarily from manure emissions credited to feed. Whole-ranch water usage ranged from 2.1 to 44.8 MT/kg market lamb, almost entirely from feed production. Overall results were in agreement with those from meat-focused sheep systems in the United Kingdom as well as beef raised under similar conditions in California.

Key words: carbon footprint, GHG, life cycle assessment, livestock emissions, sheep, water footprint

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INTRODUCTION

With animal agriculture under increased public scrutiny as a source of greenhouse gases contributing to climate change, it is important to

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quantify the specific direct and indirect environmental impacts of different production systems (Pitesky et al., 2009). Life cycle assessment (**LCA**) can be used to identify sources of a product or system's environmental impacts, and to compare different production systems within the same industry (Garnett, 2014). The California sheep industry consists of many system types found elsewhere in the United States, but the carbon footprints of these systems are unknown. Livestock usage of irrigated water is a key metric of interest on physical and political scales. By using a case study methodology, similar to that of Weidemann et al. (2015), this study examines the environmental impacts of diverse systems of sheep production in California While a prior LCA by DeLonge (2016) examined the impacts of wool production and processing, neither meat production nor water usage were considered. As California is the leading sheep producer in the United States (USDA NASS, 2017), a proactive benchmark of the environmental impacts of sheep production in California is important to the future of the industry as well as to a sustainable food supply. Reducing carbon footprint is also highly correlated with increasing production system efficiency and hence profitability (Jones et al., 2014), and so understanding the drivers of carbon footprints within a system could be used by future researchers to improve not only system-level sustainability, but in an economically feasible manner. Many production systems found in California reflect systems found in other parts of the United States, and so the results of this study may also serve as a starting point for future research examining similar sheep production systems in other parts of the United States.

The objectives of this study were to (i) create a model for attributional cradle-to-farm-gate LCA of different systems within the California sheep industry focusing on carbon and irrigated water footprints, using representative CS from five different system types within California; (ii) to examine the environmental impacts of California sheep production systems when evaluated across a range of systems and co-product allocation methods; (iii) to compare the results from California vs. LCAs of other sheep production systems outside of the United States as well as other California-produced livestock products; and (iv) to conduct a partial sensitivity analysis on the impact of ewe replacement rate and lamb crop on market (meat) lamb carbon footprint, the impact of fixed vs. flexible growth coefficient (k_g) for mature ewes, and of the use of different enteric CH_4 models on whole-ranch carbon footprint.

MATERIALS AND METHODS

Due to the diversity of sheep production systems in California, data were collected from producer records for five major system types within California, and a case study (**CS**) was created to represent each system type (Table 1). Briefly, the five system types consisted of a market lamb flock in the north coastal range (CS 1), a flock in the Sierra foothills focusing on "hothouse" lambs sold at weaning (CS 2), a hair sheep flock in Northern California that produced breeding stock as well as pasture-finished intact ram lambs for local ethnic markets (CS 3), a large commercial market lamb flock in the Sacramento Delta region (CS 4), and a large commercial market lamb flock that practiced seasonal transhumance throughout the year (CS 5).

Once major system types were identified, the authors worked with cooperative extension advisors and producer groups to identify ranchers within each system type that would have sufficiently detailed records to participate in the study. Ranch records from the most recent three lamb cycles were used as inputs (i.e., from 2013 to 2014, 2014 to 2015, and 2015 to 2016) and averaged to create a representative year of production.

Model Description

A model to conduct LCA was built in Microsoft Excel using data derived from producer records, university cooperative extension reports, and secondary data conforming to ISO 14040/44 standards (Finkbeiner et al., 2006; International Organization for Standardization 2006a, 2006b; Finkbeiner, 2014). Emission factors and literature data used were California specific if available, otherwise United States or North America-specific values were used. An overview of the system boundary used in this LCA is provided in Figure 1, and a diagram of overall model structure in Figure 2.

The animal model was created in Excel using the current sheep National Research Council (**NRC**) guidelines (NRC, 2007) to predict required energy and DMI for each stage of production in the model, based on producer records of performance and diet quality. Within the animal model, the representative year was divided into ram flock, ewe flock, and lamb flock sections. Each flock subgroup was further divided into stages of production that covered the whole year of production, and animals moved between stages as diets or physiological status changed. Age classes of adult breeding stock included ewe lambs, yearling ewes, second-year

Table 1. Overview of case studies in this analysis

	CS 1	CS 2	CS 3	CS 4	CS 5
Breed	Targhee (× Dorset, × Montadale)	Cheviot × Coopworth, Cheviot × Coopworth × Bluefaced Leicester mule ewes, Mule ewes × Shropshire, Shropshire	Dorper and White Dorper	Whiteface composite	Rambouillet (× Suffolk, × Rambouillet)
Operation goal and environment	Market lamb, spring lambing, north coastal range	Light/hothouse lambs, spring lambing, Sierra foothills	Seedstock and ethnic market lambs, spring and fall lambing flocks, Northern CA	Market lamb, large commercial flock, spring and fall lambing, delta region	Market lamb, large commercial flock, fall lambing, Southern CA, Sierra Nevada, seasonal transhumance
Stages	Sheep–lamb, off-site background, off-site feedlot	Sheep–lamb, sale at weaning	Sheep–lamb, pasture finishing	Sheep–lamb, on-site background, on-site feedlot	Sheep–lamb, off-site background, off-site feedlot
Average ewe flock size	431	61	317	1,683	4,725
Ewe weight, FBW at BCS 3, kg	74	59	77	68	79
Ewe age at first breeding, month	18	18	7	8	18
Annual replacement rate, cull + death	0.34 (ewes), 0.33 (rams)	0.20 (ewes); 0.13 (rams)	0.23 (ewes), 0.33 (rams)	0.18 (ewes); 0.5 (rams) including stock sold off farm for breeding	0.12 (ewes), 0.50 (blackface rams), 0.33 (whiteface rams)
Wool animal^{-1} year^{-1}, kg greasy, tags included	3.39	2.25	0 (hair sheep)	4.51	4.24
Lambs born/ewe bred	1.27	1.50	1.51	1.41	1.30
Total lambs marketed/ewe bred	0.72	1.16	1.26	1.15	1.12
Market lambs sold/ewe bred	0.72	1.13	0.54	1.04	1.12
Major diet characteristics	Native rangeland, irrigated pasture, rangeland background, corn-based feedlot	Native rangeland and irrigated pasture	Irrigated pasture, almond hulls	Native rangeland, crop residues, onsite feedlot	Native rangeland, alfalfa stubble, clover background, offsite feedlot
Average ewe diet					
CP, g/kg DM	136	117	146	136	154
ME, Mcal/kg DM	2.36	2.31	2.62	2.45	2.52
Average lamb diet postweaning					
CP, g/kg DM	124	113	139	132	187
ME, Mcal/kg DM	2.57	2.22	2.59	2.18	2.63

ewes, mature ewes, ram lambs, yearling rams, and mature rams, depending on flock characteristics.

Energy requirements and emissions for the midpoint of a given stage were predicted and then midpoint requirements and emissions were used to calculate feed consumption, energy intake, and emissions per stage. To account for energy required for grazing, maintenance energy requirements were adjusted by either +15% or +20% for hilly terrain, depending on steepness and +10% for flat terrain when animals were not being hand-fed concentrate or were not in barns or feedlots. Maintenance energy requirements for rams were increased by 10% during the breeding season as per NRC (2007) recommendations. Current guidelines suggest that the coefficient of gain (k_g) of 0.6 for mature ewes gaining weight during lactation may also be used for nonlactating mature ewes. Base model results use k_g values derived from feed composition for mature ewes gaining weight but not lactating.

Lamb enteric CH_4 emissions simulation began at 50 d of age (Schoenian, 2015). Enteric CH_4 was predicted using the Monomolecular equation based on ME intake (MEI, MJ/animal per d) as reported by (Patra et al., 2016) equation 1.

$$CH_4\left(\mathrm{MJ{\cdot}animal^{-1}{\cdot}d^{-1}}\right) = 5.70(\pm 1.94) - \left[5.70(\pm 1.94) - 0.133(\pm 0.047)\right]\cdot \exp\left[-0.021(\pm 0.0071)\mathrm{MEI}\right] \quad (1)$$

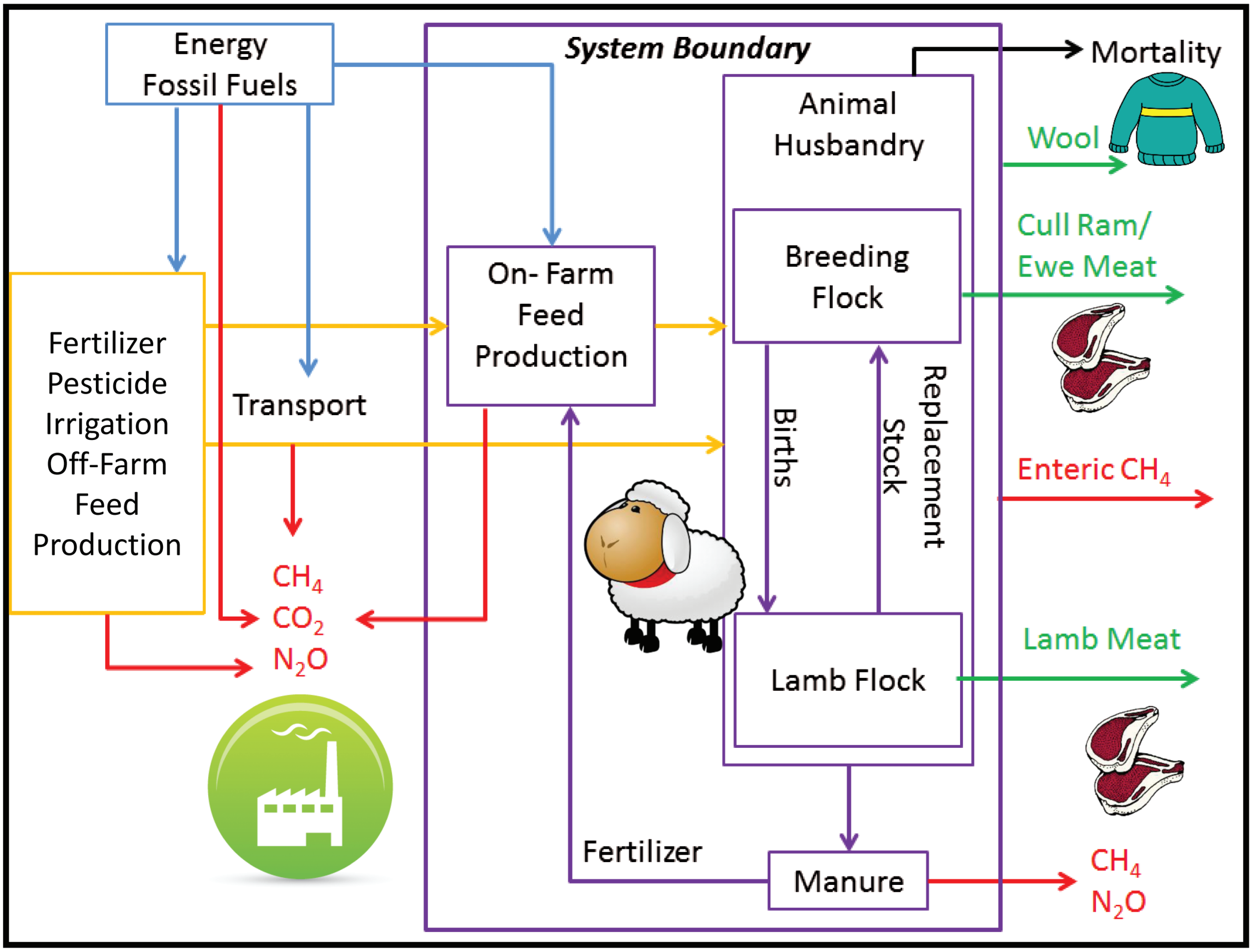

Figure 1. Overview of system boundaries.

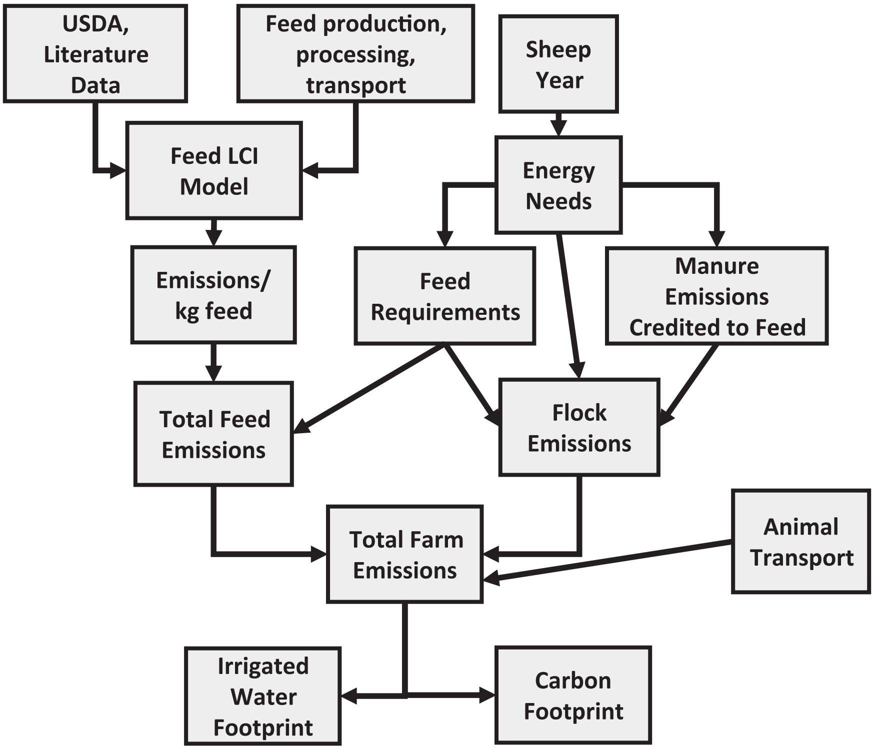

Figure 2. Overview of model structure. *LCI = life cycle inventory.

Manure emissions were calculated in all scenarios according to UN Intergovernmental Panel on Climate Change (IPCC) guidelines for calculating emissions from livestock and manure management (IPCC, 2006), using US-specific emission factors wherever possible (US EPA, 2017). All enteric and manure CH_4 emissions were credited to animal production. Nitrous oxide (N_2O) emissions from manure deposited directly onto pasture were considered an input to managed soils used for feed, as per IPCC guidelines, while N_2O emissions from manure and bedding in barns and feedlots were split between animal and feed, as per FAO Livestock Environmental Assessment and Performance Partnership (**LEAP**) and IPCC guidelines (IPCC, 2006; FAO 2016a, 2016b). For CS 4, emissions from burnt straw bedding were modeled using the emission factors for wheat straw presented in Li et al. (2007). Emission factors were 28 kg CO_2e/kg CH_4 and 265 kg CO_2e/kg N_2O, respectively, using 100-yr global warming potential (Myhre et al., 2013; IPCC, 2014).

Lactation curves were calculated by scaling the Targhee lactation curve from Borg (2004) using Targhee data from Ramsey et al. (1998), with estimated lamb requirements at days 10 and 30 to set initial and peak lactation, respectively. Energy in milk was calculated based on Agricultural Research Council (ARC, 1980) recommendations as used by Borg (2004). Slope of lactation curve after 30 d of lactation was calculated using the ratio of peak lactation yield to final lactation yield presented in Borg (2004). Lactation of ewes with twins and triplets was 60% and 100% greater than that of ewes with singles, respectively (Borg, 2004). When BW gain during pregnancy was not available, weight gain was calculated based on McCann (2005), where ewes with single lambs gained 10% of BW during pregnancy, and ewes with twins gained 18%. This logic was extended for ewes bearing triplets to ((1.18/1.1)…1.18) times ewe BW at the end of flushing (if present) or times ewe standard reference weight (**SRW**). The SRW for ewes and rams was defined as the average weight of mature rams and ewes, as measured between normal weaning and breeding times each year. Producer records of average BCS at each SRW were used as model inputs. Body condition score at model SRW varied from 2.5 to 3.5 depending on CS and sex of animal. Emissions and feed intake from replacement stock prior to breeding were summed and amortized evenly across the reproductive lifetime of the animal, as was pre-breeding wool production. Reproductive lifetime of the animal was calculated from animal replacement rates per sex under steady-state conditions.

Due to lack of data regarding fat-free weight gain, overall protein content of liveweight (**LWT**) was assumed 18% for all classes of animals and CS, as per Weidemann et al. (2015) based on Sanson et al. (1993). Protein deposition in clean wool was estimated as in Weidemann et al. (2015), using flock-specific values for the ratio of clean wool to greasy wool where available, and adjusting for the DM content of clean wool (84%) where clean wool on a 100% DM basis was 100% protein. Nitrogen (N) balance in the animal was calculated as

$$N_{ex} = N_{in} - N_{ADG} - N_{wool} - N_{milk} \qquad (2)$$

where N_{ex} is nitrogen excreted (kg N/animal^{-1}·d^{-1}), N intake is calculated from N content of the feed multiplied by DMI, N_{ADG} is N deposited in LWT gain or freed by tissue mobilization, N_{wool} is N deposited in clean wool growth, and N_{milk} is N excreted in milk.

Due to lack of available data, emissions from on-ranch electricity and vehicle fuel use were omitted, but emissions from animal and feed transport between sites were accounted for based on producer records. Where sheep drank water from pumped or hauled water, emissions from pumping and transport of drinking water were calculated assuming water consumption of 7.57 L·sheep^{-1}·d^{-1} for adult sheep, and 3.79 L·lamb^{-1}·d^{-1} for lambs, except for CS 5, where producer records indicated sheep and lambs consumed 7.57 L·animal^{-1}·d^{-1} during the desert grazing period, and 3.79 L·animal^{-1}·d^{-1} for the remainder of the year. Site-specific values for pumped water vs. natural water consumption by livestock were calculated from producer data, and only pumped water consumption was considered in this assessment.

Feed Production Model Description

Feed production was modeled using data from California cooperative extension reports and literature data based on known feeds from ranch records, and in compliance with LEAP guidelines for environmental performance of animal feeds supply chains (FAO, 2016b). A life cycle inventory (**LCI**) database for carbon footprints of common California livestock feeds was created and used to calculate the emissions from feed production and processing (A. Naranjo, University of California, Davis; Davis, California; unpublished data). Case study-specific production and transport values were combined with LCI database outputs to model CO_2 emissions and irrigated water usage associated with feed production for each CS. Site-specific emission factors for irrigated pasture were calculated using an updated version of the irrigation energy model described in Marvinney (2016). This irrigation model calculates weighted energy use for irrigation for a given area, with model inputs based on producer records regarding feed sources. Where site-specific irrigation data were unavailable, region-specific literature values were used, such as those from crop production cost studies published by University of California Cooperative Extension (Orloff et al., 2012, as an example).

Rangeland forage energy and protein data were obtained from sheep and cattle fecal near-infrared spectroscopy (NIRS) datasets (Jinks, 2001; USDA NRCS, 2004), and producer records of prior use of fecal NIRS for forage and production analysis. Range data were mapped by location and season in QGIS version 2.18.13 using the GRASS plugin version 7.2.1 (GRASS Development Team, 2017; QGIS Development Team, 2017) to create a CS-specific forage calendar for each CS where grazing on rangeland occurred (CS 1, CS 2, CS 4, and CS 5). Fecal NIRS analysis was conducted by Texas A&M's Grazing Animal Nutrition Lab, which was previously validated for California-specific forages, as discussed in Jinks et al. (2010). Irrigated pasture data were determined from producer responses regarding pasture species composition. A "sheep-year" map of feed available was created for each CS and used to calculate average ME (MJ/d), GE (MJ/d), %TDN, and CP (g/d) intake for each stage of production.

System Boundaries

The functional units of this LCA were 1 kg market lamb (live weight basis, LWT), 1 kg cull adult (LWT), 1kg breeding animal sold off-ranch (LWT), and 1 kg greasy wool, and per kg 2-d old lamb sold off-ranch (CS 3 only). Emissions from downstream processes such as slaughter, cleaning, and distribution were not considered. While the ability of grazing practices to alter soil carbon sequestration has been studied, carbon sequestration was considered to be at equilibrium to comply with LEAP guidelines.

As per LEAP guidelines, all purchased replacement stocks were treated as raised on-ranch. For CS 5, purchased rams were raised in a different environment from the CS 5 flock itself. For range flocks such as CS 5, rams were not typically raised on-farm, but purchased from ram sellers who raised rams in a drylot environment, and pasture and grain may be fed. To represent these differences, ram growth and emissions prior to entry into the breeding flock in CS 5 were modeled based on a partial LCA derived from additional data collected from ram producers.

Emissions Allocation

For economic allocation, total flock output and representative price data for each product were used to calculate total gross income attributed to sheep production for each CS. Emissions were then allocated between products based on percentage of gross flock income provided by each product. Price data were specifically based on market prices of livestock and wool, and secondary services such as the economic value of targeted grazing or of manure as an input to crop production were not considered as inputs to economic allocation. Market lamb prices were based on values obtained from consultation with the Livestock Marketing Information Center (LMIC, 2017). For market lambs sold outside of traditional market channels, data from producer records were used. Breeding stock prices were calculated based on producer records and local breeding stock sale averages. Wool prices per pound, greasy, were based on yearly averages as reported by the USDA (USDA NASS, 2017). Emissions were also allocated based on percentage of total protein sold per CS. Where different groups of product had the same estimated yield and protein mass per kilogram, such as the case of lambs sold to market vs. for breeding, economic allocation by percentage within that specific subcategory was used to further allocate emissions.

Sensitivity Analysis

A partial sensitivity analysis was conducted on the model, focusing on two variables: ewe replacement rate (percent of ewe flock replaced per year) and lamb birth rate (lambs born/ewe exposed to a ram) and their impacts on whole-flock carbon footprint. When ewe replacement was varied, deaths were kept constant as a percentage of ewes in the flock, and sale (meat) cull ewes were calculated as the difference between replacement rate and death rate. Values were reported as kg CO_2e/kg market lamb sold, where the amount of deaths was kept at baseline percentage of lambs born and the raw number of lambs sold as breeding stock per CS was considered fixed. The number of lambs sold off-ranch for meat production varied in both analyses, due to variation in number of lambs kept as replacements or in total lambs born, respectively.

An additional sensitivity analysis was conducted regarding the use of a varying coefficient of energy utilization for gain (k_g) in mature ewes vs. a fixed coefficient. While the 2007 sheep NRC reports that the fixed k_g of 0.6 can be used for lactating as well as non-lactating mature ewes, we applied this value only when ewes were gaining weight while still lactating, and used the k_g calculated from feed values the remainder of the year. A comparison of this change vs. an always-fixed k_g was conducted for the mature ewe flock for all CS. This analysis considered the impact on whole-farm carbon footprint (expressed as MT CO_2e/ewe).

A final sensitivity analysis was conducted comparing the impact of enteric CH_4 prediction model on whole-ranch carbon footprint, while all manure and feed emissions were kept as in the base model values. Enteric CH_4 was predicted using the Monomolecular equation based on ME intake (MJ·animal^{-1}·d^{-1}) (Patra et al., 2016) equation 1, above; equation 3, a Mitscherlich equation based on ME intake (MJ·animal^{-1}·d^{-1}), also from Patra et al. (2016); the GEI-based equations used by the IPCC (2006) for tier 2 enteric CH_4 predictions from sheep, equation 4 for adult sheep and equation 5 for lambs <1 yr of age, respectively; and the California Air Resource Board (**CARB**) estimate of 8 kg CH_4·animal^{-1}·yr^{-1} using the IPCC tier 1 method (IPCC, 2006; CARB, 2017).

$$CH_4\left(\text{MJ}\cdot\text{animal}^{-1}\cdot\text{d}^{-1}\right) = 3.133(\pm 0.558)\cdot \left\{1 - \exp\left[-0.0463(\pm 0.0089)\cdot\text{MEI}\right]\right\} \quad (3)$$

$$CH_4\left(\text{MJ}\cdot\text{sheep}^{-1}\cdot\text{d}^{-1}\right) = (\text{GEI} \times 6.5\%) \quad (4)$$

$$CH_4\left(\text{MJ}\cdot\text{lamb}^{-1}\cdot\text{d}^{-1}\right) = (\text{GEI} \times 4.5\%) \quad (5)$$

RESULTS AND DISCUSSION

Case Study Traits

Case studies considered for this analysis varied in production goals and flock characteristics (Table 1). For CS 3, more lambs were sold off-farm as breeding stock than as market lambs, but the producer still occupied an important local niche providing intact ram lambs for slaughter, primarily for local ethnic markets. This had the effect of concentrating emissions per kilogram of market lamb when compared with other CS, as breeding stock was not produced in two out of five CS and was a lesser output for the other two. Case study three also sold approximately 12 lambs per year at 2 d of age: the carbon footprint attached to these lambs therefore more accurately represents the carbon footprint associated with inputs to another system, such as show lambs. Both spring and fall lambing flocks were represented in this study, and CS 3, CS 4, and CS 5 had separate groups lambing in both seasons.

Case studies also varied in replacement rates and cull rates. For CS 4, mature rams were sold off-ranch as breeding stock, as were some mature ewes, leading to a greater ram replacement rate that also reflected production as inputs into another system. This is in direct contrast to the other CS, where cull adults sold off-ranch were considered terminal and unlikely to reproduce again. Case study 5 used whiteface and blackface rams as breeding stock, but whiteface rams were typically culled after 3 yr, while blackface rams were considered to have difficulty surviving under range conditions and so remained only 2 yr in the flock on average.

Diet quality and composition also varied between CS, and weighted average energy and protein content for ewes and postweaning lambs are reported in Table 1. Case study 5 had the greatest CP content and second greatest energy content for ewes, while ewes in CS 2 had the least dietary CP and energy concentration in diets. Both CS 5 and CS 4 moved ewes to alfalfa stubble for part of lactation, and during late pregnancy for ewes in CS 5, allowing access to high-quality crop stubble capable of supporting the high energy and protein needs of the ewes during that portion of gestation. Ewes in CS 5 also benefited from the high protein and energy content of the desert shrubs and forbs found in the Mojave Desert, which averaged 167 g CP/kg DM and 2.48 Mcal ME/kg DM during spring months. Because of the seasonal transhumance practiced by ranchers in CS 5, sheep were moved to coincide with peak forage quality available whenever possible. The preference of sheep for forbs and shrubs also allows them to thrive under conditions unsuitable for cattle. These factors contribute to the overall high quality of the diet at the cost of increased emissions associated with transportation of animals between sites. As seasonally transhumant flocks such as those in CS 5 account for the majority of ewes in California, with average flock sizes over 4,000 breeding ewes, it is encouraging that ewes under these conditions were able to take advantage of high-quality forage for the majority of the year.

Carbon Footprint: Sources and Trends

Whole-ranch carbon footprints ranged from 0.6 to 1.1 MT CO_2e/mature ewe (Table 2), averaging 0.9 MT CO_2e/mature ewe. In general, CS 1 to 3, which grazed on irrigated pasture for at least a portion of the year, had greater carbon footprints per kilogram product on a mass basis than CS 4, which did not graze irrigated pasture, and CS 5, where irrigated pasture was only used by the farm raising replacement rams prior to sale and during lamb backgrounding.

Enteric methane was consistently the largest source of emissions across all case studies, accounting for 72.3% of emissions on average (Figure 3). Manure directly deposited on pasture or kept in barns and applied later was credited to feed production, as were direct emissions from feed processing and transport. Manure emissions credited to feed were consistently the second largest source of emissions. Emissions from manure credited to the animal included CH_4 emissions from manure and emissions from stored manure. Therefore, case studies where a portion or all of the flock lambed in barns had greater emissions in this category, as did CS 5, where all but replacement rams were lambed outdoors, but which sold lambs to a feedlot for finishing prior to sale.

Transportation emissions were negligible for most case studies, as animals were transported between sites or stages by vehicle only for CS 1 and CS 5. Lambs from CS 1 traveled approximately 255 km during their lifetime, between sheep–lamb, backgrounding, and feedlot stages, or 0.3% of final system carbon footprint. Case study 5 represents a system that practices seasonal transhumance, as sheep follow the seasonal cycles of green forage and feed availability—as such, transport accounted for 3.8% of the final carbon footprint. For the sheep–lamb phase of CS 5, emissions from animal transport exceeded emissions from off-ranch feed production and transport by 5%, as the majority of feed was rangeland or crop residues, and breeding adults traveled 1,061 km per year on average, while lambs sold to a feedlot traveled 585 km.

Table 2. Whole-farm annual carbon and water footprints by case study (**CS**)

	North coastal range flock	Foothill hothouse lambs	Hair sheep market lambs and seedstock	Large commercial delta flock	Large commercial transhumant flock
	CS 1	CS 2	CS 3	CS 4	CS 5
On-ranch production					
Market lamb produced, metric ton (**MT**) LWT	17.4	1.8	9.3	105	382
Total lamb + breeding stock sold off-ranch, MT LWT	17.4	1.9	19.7	121	382
Total LWT sold off-ranch, MT LWT	22.8	2.5	24.3	136	405
Total wool sold off-ranch, MT greasy	3.4	0.2	0 (hair sheep)	14.7	28.6
Total ranch production, MT product/year	26.2	2.7	24.3	150	434
Carbon emissions					
Whole-ranch emissions, MT CO_2e/year	404	36.4	284	1,525	5,304
MT CO2e/mature ewe	0.94	0.60	0.90	0.91	1.12
kg CO_2e/kg market lamb	23.2	19.8	30.6	14.5	13.9
kg CO_2e/kg total lambs	23.2	19.0	14.4	12.6	13.9
kg CO_2e/kg total LWT	17.7	14.8	11.7	11.2	13.1
kg CO_2e/kg total product	15.4	13.7	11.7	10.1	12.2
Blue water usage					
Whole-ranch blue water usage, million MT H_2O/year	0.17	0.05	0.42	0.22	1.07
MT H2O/mature ewe	385	838	1314	129	226
MT H_2O/kg market lamb	9.52	27.8	44.8	2.06	2.80
MT H_2O/kg total lambs	9.52	26.6	21.1	1.79	2.80
MT H_2O/kg total LWT	7.27	20.8	17.2	1.60	2.64
MT H_2O/kg total product	6.33	19.2	17.2	1.44	2.46

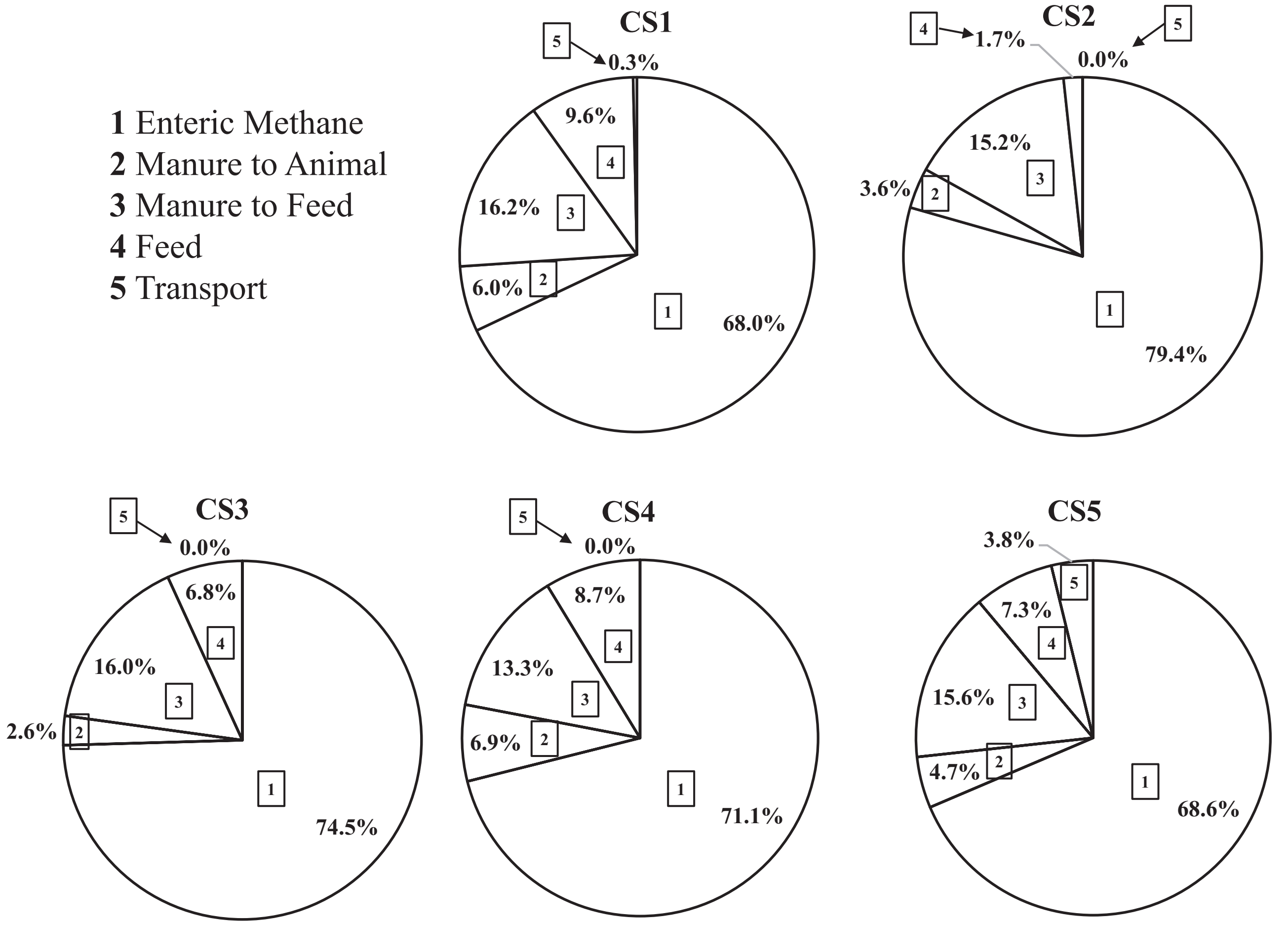

Figure 3. Whole-ranch carbon footprint by source and case study. CS 1 = north coastal range flock; CS 2 = foothill hothouse lambs; CS 3 = hair sheep market lambs and seedstock; CS 4 = large commercial delta flock; CS 5 = large commercial transhumant flock.

Irrigated Water Footprint

Blue water consumption was primarily from feed production, particularly irrigated pasture and hay. Case study 4, which utilized grazing on native rangeland and dryland crop residues, had the least water usage across categories, while CS 2 and 3, which utilized irrigated pasture as a major source of dietary forage, had the greatest water use (Table 2). Among feeds, water usage for irrigated pasture averaged 1.21 MT blue water per kilogram pasture (100% DM), while alfalfa hay averaged 0.71 MT blue water per kilogram (100% DM).

For CS 1, CS 4, and CS 5, corn grain produced in-state was fed as a major component of the feedlot ration, requiring 0.59 MT of water per kilogram (100% DM). The use of in-state corn for the lamb feedlot stages of CS 1, CS 4, and CS 5 represents a major difference compared to beef feedlots in California, which typically import Midwestern corn. Midwestern corn requires less water to produce (0.36 MT water per kilogram corn on a 100% DM basis) than corn produced in California, and therefore the use of in-state corn, which was used to some extent in all case studies except CS 2, may represent an overestimation of irrigated water usage compared to other sheep or beef production systems elsewhere in the state which may use corn imported from other states.

While for CS 1 and 5, the sheep–lamb phase dominated overall emissions, there were differences in which stage contributed the most to water usage. For CS 1, where the sheep–lamb phase involved phases of grazing on native rangeland, irrigated pasture, and alfalfa hay fed during a barn lambing phase, the sheep–lamb portion of the life cycle accounted for 88% of yearly water usage. CS 5, where ewes lambed outdoors on alfalfa stubble and grazed primarily on rangeland or crop residues, only consumed 7% of total yearly water usage during the sheep–lamb phase. Despite the two case studies selling lambs to the same feedlot, the backgrounding and feedlot phases accounted for 12% of total water usage for CS 1 but 93% of total water usage for CS 5. This difference is primarily because of management programs in the sheep–lamb phase and increased time on irrigated pasture prior to feedlot entry by lambs produced in CS 5, who spent 60–100 d on clover-ryegrass pasture (50% white and ladino clover, 50% ryegrass) owned by the feedlot prior to entry or sale directly off clover-ryegrass pasture, while lambs from CS 1 were backgrounded on native pasture.

Impact of Allocation Method

All case studies had market lamb production as a major system goal, unlike the wool-focused systems seen in other countries. This is reflected by the impact of economic allocation on carbon and water footprints per category (Tables 3 and 4). Lamb and breeding stock, if present, had the greatest carbon footprints per kilogram of product, though wool was often close in terms of carbon footprint. This was due to a similarity between wool and lamb prices for most case studies, but as a result of less annual production, wool contributed less overall to total sales per CS. For CS 3, which sold rams and lambs as breeding stock, lambs were allocated a greater share of emissions per kilogram, largely because of differences in sale weight and sale price.

While none of these systems considered wool production a major goal of their ranch, all case studies with the exception of CS 3, which produced hair sheep, sold at least some wool. The high protein content of wool led to a relative inflation of the carbon and water footprints of wool on a protein basis, and therefore to a corresponding decrease in emissions and water assigned to other products.

Cull adults had the least amount of carbon emissions and water use allocated to that specific category, regardless of allocation method. This is a result of the low price per kilogram relative to other system outputs under economic allocation, while under protein allocation it is likely a result of the greater weight assigned to wool at the expense of other products, particularly as cull adults accounted for a relatively small proportion of total protein sold off-ranch.

The large difference in carbon footprint based on allocation method highlights the importance of clear communication regarding allocation methods when reporting values. For example, 1 kg of lamb (LWT) from CS 2 would have a carbon footprint of 19.8 kg CO_2e on a mass basis, but 15.4 on an economic basis, and 9.64 on a protein allocation basis. Similar trends were seen regarding blue water footprint as a function of allocation method, particularly when both breeding stock and market lambs were produced in the same CS. Economic allocation is said to reflect the product's value to society, or the return to producer from a given product (Rotz et al., 2010), leading to the greater emissions and water use allocated to breeding stock as compared with market lambs, though total kilogram of market lambs sold per year exceeds that of breeding stock for all CS except CS 3.

Sensitivity Analysis: Ewe Replacement Rate

Sensitivity analysis was used to examine the impact of ewe replacement rate on carbon footprint per kilogram of market lamb. For the purposes of this study, replacement rate is defined as the annual percent of ewes removed from the flock due to culling or death and replaced by ewes entering the breeding flock for the first time (Figure 4). As a result, total emissions per kilogram market lamb

Table 3. Carbon footprint by allocation method, kg CO_2e/kg product

	North coastal range flock	Foothill hothouse lambs	Hair sheep market lambs and seedstock	Large commercial delta flock	Large commercial transhumant flock
	CS 1	CS 2	CS 3	CS 4	CS 5
Economic allocation					
Market lamb (LWT)	18.1	15.4	10.9	10.4	12.8
Market lamb (HCW)	37.5	30.8	22.8	21.8	26.7
Lambs sold at 2 d old	—	—	20.4	—	—
Breeding stock (LWT)	—	38.8	16.4	9.03 (adult), 20.1 (lamb)	—
Cull adult (LWT)	5.28	3.98	2.36	3.05	3.31
Wool (greasy)	17.8	13.4	Hair sheep	10.3	11.2
Wool (clean)	32.7	23.6	Hair sheep	19.0	19.9
Protein allocation					
Market lamb (LWT)	10.1	9.64	9.41	6.60	9.48
Market lamb (HCW)	20.8	20.1	19.6	13.7	19.7
Lambs sold at 2 d old	—	—	17.5	—	—
Breeding stock (LWT)	—	24.2	14.1	13.8 (adult), 12.7 (lamb)	—
Cull adult (LWT)	9.17	9.40	10.9	4.64	8.69
Wool (greasy)	53.1	56.8	Hair sheep	37.9	5.17
Wool (clean)	97.3	99.7	Hair sheep	70.1	92.1

Table 4. Water footprint by allocation method, MT water per kilogram product

	North coastal range flock	Foothill hothouse lambs	Hair sheep market lambs & seedstock	Large commercial delta flock	Large commercial transhumant flock
	CS 1	CS 2	CS 3	CS 4	CS 5
Economic allocation					
Market lamb (LWT)	7.4	21.6	16.0	1.48	2.59
Market lamb (HCW)	15.4	45.1	33.4	3.09	5.39
Lambs sold at 2 d old	—	—	29.9	—	—
Breeding stock (LWT)	—	54.4	24.0	1.28 (adult), 2.85 (lamb)	—
Cull Adult (LWT)	2.2	5.6	3.45	0.43	0.67
Wool (greasy)	7.3	18.9	Hair sheep	1.46	2.26
Wool (clean)	13.4	33.1	Hair sheep	2.70	3.98
Protein allocation					
Market lamb (LWT)	4.13	13.5	13.8	0.94	1.91
Market lamb (HCW)	8.55	28.2	48.2	1.95	3.98
Lambs sold at 2 d old	—	—	25.7	—	—
Breeding stock (LWT)	—	34.0	20.7	1.95 (adult), 1.80 (lamb)	—
Cull adult (LWT)	3.76	13.2	16.0	0.66	1.75
Wool (greasy)	21.8	79.7	Hair sheep	5.39	10.4
Wool (clean)	39.9	140	Hair sheep	9.96	18.6

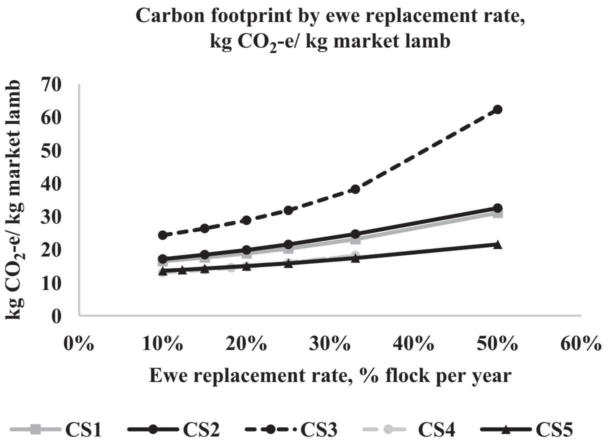

Figure 4. Sensitivity analysis of ewe replacement rate vs. market lamb carbon footprint. CS 1 = north coastal range flock; CS 2 = foothill hothouse lambs; CS 3 = hair sheep market lambs and seedstock; CS 4 = large commercial delta flock; CS 5 = large commercial transhumant flock.

produced increased nonlinearly as ewe replacement increased.

This nonlinear increase is because of three factors: reduced time for amortization of pre-breeding emissions, differences in energetic requirements between yearling and mature ewes, and differences in the number of total lambs born kept back as replacement stock. Because emissions from birth prior to first breeding are amortized over the reproductive lifespan of the ewe, increasing ewe replacement rate correspondingly decreases the time period over which her prebreeding emissions are divided. The increase in emissions per kilogram market lamb is not linear; however, as yearling ewes have greater emissions per year than mature ewes. These greater emissions are because yearling ewes must produce lambs while growing to meet their own mature weight, leading to greater feed intake and a corresponding increase in carbon footprint as compared with mature ewes. Increasing the amount of ewe lambs kept back as replacements also decreased the quantity of market lambs sold. The combination of these factors led to a concentration of emissions per kg market lamb. While baseline replacement rates varied from 34% of the ewe flock per year in CS 1 to a low of 12% per year in CS 5 (Table 1), the other three case studies had replacement rates relatively close to 20%, despite differences in overall production goals and environments.

For CS 4, where replacement lambs were only kept from the first lambing group, a 50% ewe flock replacement rate per year exceeded lambs born to this group; therefore, this level of analysis was omitted for CS 4. However, under such a high replacement rate in the field, producers would adjust for the high replacement rate by purchasing more stock from outside the flock, increasing effective whole-flock lambing rate as per LEAP guidelines. This sensitivity analysis has practical applications for producers as it demonstrates an additional, environmental aspect of adjusting replacement rate as part of a flock genetics plan.

Sensitivity Analysis: Lamb Crop

A sensitivity analysis was conducted to examine the impact of lamb crop (lambs born/ewe exposed to a ram) on carbon footprint per kilogram market lamb by varying lamb crop from 1.0 to 1.9 lambs born/ewe/year (Figure 5). Range for the sensitivity

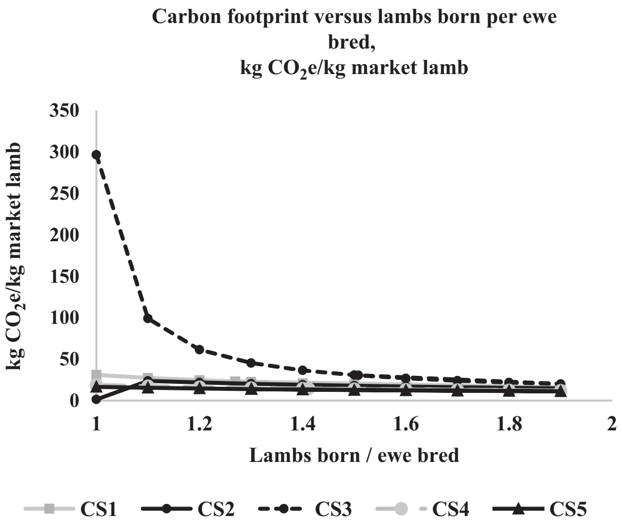

Figure 5. Sensitivity analysis of lambs born/ewe bred vs. market lamb carbon footprint. CS 1 = north coastal range flock; CS 2 = foothill hothouse lambs; CS 3 = hair sheep market lambs and seedstock; CS 4 = large commercial delta flock; CS 5 = large commercial transhumant flock.

analysis was chosen to represent extremes of “good years” of high fertility and the risk of severely reduced fertility due to drought or disease. Ewe and ram replacement rates, the number of animals sold as breeding stock, pregnancy rates, triplet rate, and lamb grafting rate (% of total flock) were held steady at flock baseline rates per CS due to a lack of covariance information, while increases in lamb crop were primarily accounted for by adjusting the twinning rate within the model (Figure 5).

For CS 2 and CS 3, when lambing rates were set to 1.0 and 1.1 lambs born per ewe exposed to a ram, baseline flock rates of ewes birthing triplets led to a negative number of ewes expected to be raising single or twin lambs. Under these cases, the percentage of ewes expected to birth triplet lambs was set to zero. Similarly, for CS 4, where group-specific lamb crop numbers were available, ewe lambs had a lamb crop 78% of that of mature and second-year ewes. Therefore, expected percentages of ewes raising triplets and twins were set to zero at levels 1.0 and 1.1, and triplets set to zero at 1.2, while the triplet percentages of mature and second-year ewes had to be increased when whole-flock lamb crop was 1.9, reducing the number of ewes with single lambs to zero. We recognize that under these situations, increased grafting or use of milk replacer would likely occur, and therefore this represents an unrealistic situation.

As discussed previously, most lambs produced by CS 3 were sold as breeding stock. For this sensitivity analysis, the number of total lambs sold as breeding stock was kept fixed at the flock baseline. Therefore, decreasing overall lamb crop decreased the number of market lambs available for slaughter to a greater extent than in other case studies where breeding stock was a smaller proportion of total flock production. This decrease concentrated the emissions allocated to a decreasing proportion of the overall flock, making their burden appear inflated relative to other case studies at the same lambing rate. The apparent concentration is a clear indicator of how flock management goals can influence carbon footprint results when comparing across systems within the same industry using the same allocation methods.

Increasing lamb crop without increasing replacement rates leads to a dilution of carbon footprint per kilogram market lamb produced as whole-system emissions and resource usage were proportioned across more lambs sold. This is especially true for emissions from lactating ewes, as the milk yield of a ewe with twins is only 60% greater than that of a ewe rearing one lamb, and that of a ewe rearing triplets only double that of a ewe rearing a single (Borg, 2004). Therefore, even if weaning or sale weights are reduced in real-world conditions, there are environmental and economic benefits to increasing twinning rate, either because of genetic selection, improved flock health and nutrition, or a combination of the factors. These results are in agreement with prior research by Jones et al. (2014), who found that number of lambs reared per ewe was a major contributor to both on-farm productivity and carbon footprint.

Sensitivity Analysis: Coefficient of Growth for Mature Ewes (k_g)

For all case studies, if mature ewes gained weight during lactation, the efficiency of growth (k_g) was set to 0.6, as per NRC recommendations. The NRC also suggests that this fixed efficiency may be used year-round for mature ewes, instead of the k_g calculated from dietary ME content. For mature ewes, the replacement of a dietary k_g value with a fixed value of 0.6 led to a reduction in whole-farm carbon footprint per ewe of 0.2% to 2.4%.

The greatest reduction in carbon footprint per ewe occurred for CS 2, where ewes gained 0.3 kg·ewe^{-1}·d^{-1} (16.5% of pre-flushing BW total) during the 30-d flushing period prior to the breeding season. Whole-ranch emissions were also reduced by 1% for CS 1, where ewes were flushed to gain 8% of pre-flushing BW over a period of 17 d, with an average daily gain of 0.33 kg·ewe^{-1}·d^{-1}. For case studies where ewes were not flushed and mature ewes only gained weight during pregnancy or between weaning and breeding, reduction in carbon footprint per ewe averaged 0.26%.

This sensitivity of whole-ranch carbon footprint to ewe growth coefficients suggests that the use of a fixed k_g outside of gain during lactation may lead to an underestimation of energy requirements and therefore carbon emissions, and that a k_g calculated from diet composition may be more appropriate. The importance of calculating this in an on-ranch context could be further explored by additional research including feed intake and performance in flocks that flush breeding animals vs. flocks that do not, to establish under which conditions a fixed k_g may be more or less appropriate.

Sensitivity Analysis: Methane Prediction Model

Sensitivity of predicted whole-farm carbon footprint (kg CO_2e/kg market lamb LWT) by which model was used to predict enteric CH_4 emissions followed a fairly consistent pattern across case studies (Figure 6). The monomolecular and IPCC tier 2 models were fairly close in estimates, differing by 6% on average. Mitscherlich predictions were consistently less than monomolecular estimates, and close in value to those predicted under IPCC tier 2, with an average difference of 8% relative to the Mitscherlich model. On average, the difference between minimum predicted emissions and maximum predicted emissions was 16% of baseline (monomolecular) predictions.

However, differences were observed with regard to the tier 1 IPCC method currently used by the CARB. This method assumes a fixed 8 kg $CH_4 \cdot animal^{-1} \cdot yr^{-1}$, regardless of age at slaughter or at sale. For most case studies, this led to CARB predictions having the least whole-farm emissions per model analyzed. However, for CS 2, where lambs were sold at 111 d of age, CARB estimates were greatest, at 23.0 kg CO_2e/kg LWT market lamb. This difference is a result of the fact that predicted lamb emissions under the base model were 2 kg $CH_4 \cdot lamb^{-1} \cdot yr^{-1}$, one-fourth of CARB predicted emissions. While it was true for CS 2 that base model adult predictions were 131% and 147% of CARB predictions for ewes and rams, respectively, the overprediction of enteric emissions from lambs under CARB methodology, specifically 15.9 MT CO_2e of enteric methane emissions from all lambs vs. 4.0 MT CO_2e under baseline model conditions, led to the differences seen for this particular CS.

Differences were also observed for CS 2 where values predicted by IPCC tier 2 estimates, which were 14% greater overall compared with the base model. This difference is related to the CS 2 sensitivity to mature ewe k_g discussed above, and is largely due to the impact of flushing on CH_4 emissions but also a result of the fact that as energy intake increases, IPCC tier 2 predicts greater emissions than those predicted by the Monomolecular model, such as during conditions of high daily gain on forage where the difference between ME- and GE-based estimates becomes more evident. Emissions as expressed per kilogram market lamb were inflated somewhat for CS 3 because of the fact that more lambs from CS 3 were sold as breeding stock than as market lambs.

General Discussion

The impacts of sheep production on the environment are especially relevant to ruminant production in California, as the Short-Lived Climate Pollutant (**SLCP**) document (California Air

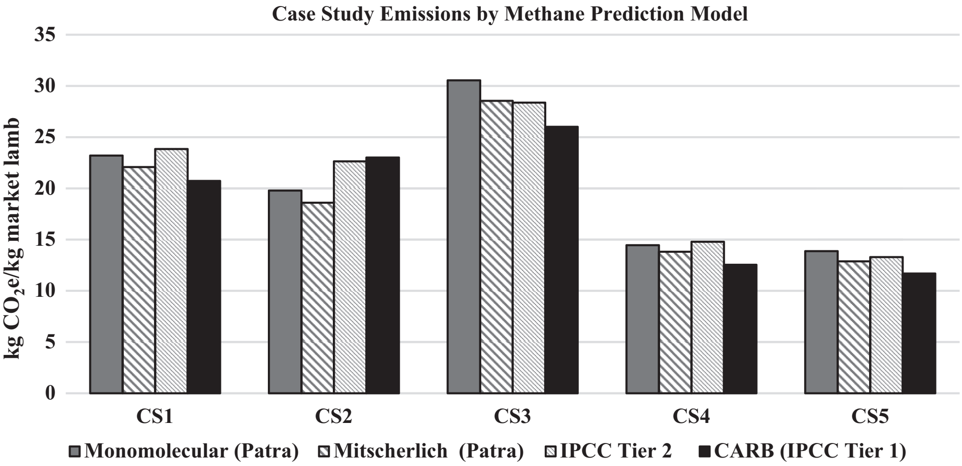

Figure 6. Sensitivity analysis of whole-ranch carbon footprints by CH_4 prediction model (kg CO_2e/kg market lamb). CS 1 = north coastal range flock; CS 2 = foothill hothouse lambs; CS 3 = hair sheep market lambs and seedstock; CS 4 = large commercial delta flock; CS 5 = large commercial transhumant flock.

Resources Board, 2016) estimates that SLCPs contribute 40% of climate forcing. Methane, an SLCP, was estimated to be responsible for 20% of current climate forcing and is a high-priority target for mitigation efforts. This is particularly pressing in light of the updated global warming potential factors for CH_4 in the most recent IPCC report (Myhre et al., 2013; IPCC, 2014). These new factors increase the impact of CH_4 from 25 to 28 on a 100-yr basis, and from 72 to 84 on a 20-yr basis, increases of 12% and 16.7%, respectively.

Because sheep production is under the same regulatory pressure as other livestock industries, such as dairy and beef, proactive benchmarking of sheep production helps one understand the current state of production as well as targets for future mitigation. Carbon footprint calculations have been used in quantifying the environmental impacts of livestock production, such as in the comparative study of grass-fed dairies by O'Brien et al. (2014). This study assessed the relationships between ranch characteristics and the carbon footprint of milk production and discussed management changes to improve efficiency and carbon footprint without negatively impacting overall performance. Jones et al. (2014) performed a similar study for sheep production systems in England and Wales. These researchers noted that future studies should quantify the variation between types of production systems to arrive at a more accurate carbon footprint estimate. Differences among production strategies and ranch characteristics leading to changes in carbon footprints could help identify mitigation strategies and suggest interventions to improve overall production efficiency, as reducing carbon footprints is highly correlated with improved production.

As opposed to other CS, where phases of production were less separated, CS 1 and CS 5 had three distinct phases of production, specifically sheep–lamb, backgrounding, and finishing in a feedlot setting. Lambs from CS 4 were also finished in an onsite feedlot; however, there was not the distinct separation in location and management as seen in CS 1 and CS 5. These three phases are similar in goals and management as the cow–calf, stocker, and feedlot phases seen in beef production, as discussed by Stackhouse-Lawson et al. (2012). For these case studies, the sheep–lamb phase contributed the most toward total carbon footprint per CS, and enteric CH_4 the most overall. These findings concur with results from an LCA of beef production in California conducted by Stackhouse-Lawson et al. (2012), who noted that the high-forage diet consumed during the cow–calf phase generates increased enteric CH_4 as opposed to other stages, a finding supported by the present study. Diets with greater GHG-generating potential per kilogram, combined with the year-round maintenance needs of the breeding flock, indicate that this phase is a key area of sheep production to target for future mitigation efforts.

This finding is particularly important for sheep production, because crop residues are a common dietary component, particularly for the large, transient flocks that lamb in fields of alfalfa stubble in winter, represented in CS 5. These flocks, which account for the majority of sheep produced in California, though not the majority of operations, rely on alfalfa stubble as a safe place to lamb in fall while providing a vital feed source for pregnant and lactating ewes. Alfalfa stubble provides enough nutrients to support the energetic demands of late pregnancy and early lactation, while the sheep can be used to control pests and unwanted weeds during the dormant season (Lenssen et al., 2006). Similar integrated sheep-crop residue grazing occurs around the United States, and despite the greater methane-generating potential of residues compared with concentrate-based diets, these practices are a key component of livestock-crop-soil symbiosis.

Use of crop residues and rangeland by livestock such as sheep also leads to further sustainability gains when the water and energetic cost of producing feeds such as hay or grain are considered. California contains 14.1% of the nation's total irrigated acres, second only to Nebraska, and is the nation's leading producer of alfalfa hay (Putnam et al., 2008, USDA ERS, 2017). As a result, when state-level sustainability is considered, it is important to consider the irrigated water footprint of the livestock concurrently with that of crops fed to livestock.

Grazing on native rangeland, as occurred in all but CS 3, is another vital part of livestock production and ecosystem health in California. Grazing by livestock helps maintain soil health and reduces wildfire risk on native rangelands, and grazing can create conditions beneficial to the survival of endangered species such as burrowing owls (Huntsinger and Bartolome, 2014). While all case studies purchased feed from offsite, CS 4 and CS 5, which relied primarily on use of rangeland and crop residues, as opposed to irrigated pasture, had smaller carbon footprints and water usages than case studies that grazed a mix of pasture and rangeland, or just pasture. This further highlights the importance of grazing to ecosystem sustainability and favorable environmental impacts of livestock production, with the caveat that it is ecosystem-specific and extremely reliant on matching forage quality to the needs of the animal. Because that is not always possible, particularly in times of drought, producers may choose to manage risk by including access to irrigated pasture in their grazing plans. This tradeoff highlights the need of any solution to be economically sustainable to producers, as well as the point that no CS in this study can be considered to be explicitly better than any other.

Comparison with Other Studies

Angus beef produced under similar conditions in California had a carbon footprint of 13.5 ± 1.2 kg CO_2e per kilogram shrunk BW (**SBW**) if a stocker phase was present, which involves practices similar to the backgrounding stage seen in CS 1 and CS 5, and 12.7 ± 1.2 kg CO_2e per kilogram SBW for steers directly entering a feedlot without a stocker phase (Stackhouse-Lawson et al., 2012). The results of the present study, ranging from 13.9 to 30.6 kg CO_2e per kg LWT market lamb on a mass basis, show that while beef systems had less overall impacts when measured in terms of carbon footprint, there was agreement regarding the overall impacts of the two systems. Some of the rangeland data quality used in the present study came from a combination of cattle and sheep grazing, which may lead to some erasure of species-specific differences in the data available for the present study, as sheep are typically fed poorer quality diets and graze more marginal land than cattle. However, the present study is an encouraging step toward future research comparing the carbon footprint and ecosystem impacts of cattle and sheep on rangeland. Further potential differences in performance and emissions between cattle and sheep grazing California rangeland, due to grazing behavior or somatosensory preferences, could also be modeled if additional sheep-specific data were to be collected as part of a future study.

The present results are also comparable to those reported by Jones et al. (2014) regarding lamb production in England and Wales. As in the present study, economic allocation placed the primary burden on market lamb production, and mean carbon footprint per kg market lamb ranged from 10.9 to 17.9 kg CO_2e per kg market lamb, with flocks in hilly regions having a greater carbon footprint. This is indicative of commonalities among meat-focused systems, despite differences in diet available.

CONCLUSION

While there is unlikely to be any “one size fits all” solution to environmental impacts, given the diverse nature of California’s ecosystems and the production systems that have adapted to the wide variation in climate and terrain, the present study provides an important first step toward benchmarking current production systems, and some suggestions for future work. Carbon footprint and water usage were less in case studies that did not use irrigated pasture, which may not be feasible under all conditions but which reinforces the role of crop residues and rangeland use by livestock as a larger part of a sustainable food system, a common and vital part of sheep production in California.

Carbon footprint and water usage also varied significantly with the allocation method (i.e., mass, economic, and protein) used to report results. A study by of sheep production in the United Kingdom, Australia, and New Zealand by Weidemann et al. (2015) reported a high sensitivity of carbon footprint based on the method used to allocate emissions between total live weight sales and wool, as was seen in the present study. The study found that protein mass allocation increased the carbon footprint of wool and decreased that of total live weight sales, while economic allocation led to a more even split between wool and live weight. These trends were also observed in the present study, though due to less wool production per animal in the present study, economic allocation weighted lamb correspondingly greater. This difference in emissions and water use credited to different products depending on allocation methods highlights the need for transparent reporting of assumptions used and co-products analyzed in reporting environmental impacts of livestock production.

Sensitivity analysis of ewe replacement rate and total lamb crop further highlighted the importance of flock management and reproductive strategies to overall carbon footprint and sustainability, and as part of overall production goals. A further sensitivity analysis of methods used to predict enteric CH_4 production by sheep indicated that current IPCC tier 1 methods used by CARB underestimate CH_4 emissions, while the IPCC tier 2 method based on gross energy intake was in generally in accordance with the metabolizeable energy-based equations also used in the present study. Further investigation into the use of a fixed growth efficiency for non-lactating mature ewes is also warranted, as the model was sensitive to its use vs. that derived from feed when mature ewes were gaining weight during flushing.

The present LCA, while the first in the United States to explicitly study the environmental impacts of sheep meat production, nevertheless found results agreed with those of meat-focused sheep production in the United Kingdom, as well as to that of beef raised under similar conditions in California. The results further suggest that while there is ample opportunity for mitigation, particularly of the sheep–lamb phase of production, the current state is comparable to what has been found elsewhere. These results also provide a proactive benchmark for the previously unknown environmental impacts of current sheep production systems in California, which could be used to spur research into other US sheep production systems.

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