Estimation of human-edible protein conversion efficiency, net protein contribution, and enteric methane production from beef production in the United States

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ABSTRACT: A model was developed to estimate beef's contribution toward meeting human protein requirements using a summative model of net protein contribution (**NPC**) and methane production. NPC was calculated by multiplying the ratio of human-edible protein (**HeP**) in beef to the HeP in feedstuffs by the protein quality ratio (**PQR**). PQR describes the change in biological value of HeP that occurs when plant-derived HeP is converted to beef. An NPC > 1 indicates that the production system is positively contributing to meeting human requirements; systems with NPC < 1 reduce the net protein available to meet human requirements. Scenarios were arranged as a 2 × 2 factorial with two sets of dietary inputs and two sets of production parameters. Dietary inputs represented either inputs used in a previous report estimating HeP (previous diet; **PD**) or inputs more representative of conventional beef production systems (current diet; **CD**). Production parameters were either drawn from previous reports (previous parameters; **PP**) or chosen to characterize current industry standards (current parameters; **CP**). The HeP conversion efficiency (**HePCE**) for current industry diets and production parameters (CDCP) (kg HeP yield/kg HeP input) was greatest in the cow–calf sector (2,640.83) compared with stocker (5.22) and feedlot (0.34), and other scenarios followed a similar trend. In addition, the entire production system had an HePCE of 0.99 for CDCP; the previous model diets and production parameters (PDPP) scenario estimated HePCE to be 0.46, and other scenarios were in between. For the CDCP scenario, 56%, 10%, and 34% of the HeP were produced in the cow–calf, stocker, and feedlot sectors; PDPP was similar (59%, 13%, and 28%, respectively). PQR averaged 3.04, 3.04, and 2.64 for cow–calf, stocker, and feedlot sectors, respectively, indicating each sector enhances the biological value of the HeP fed. The NPC was greatest for the cow–calf sector (8,794), followed by the stocker and feedlot sectors (8.85 and 0.23, respectively). The entire beef value chain had a PQR of 2.68 and NPC ranged from 1.01 to 3.11, which correspond to PDPP and CDCP, respectively. Overall, 3.05 kg of CH_4 were produced per kilogram HeP for CDCP and 2.58 for PDPP, with the cow–calf sector being greater than the feedlot sector (4.53 vs. 0.94 kg CH_4/kg HeP, CDCP). Our results suggest that each individual beef sector and the entire value chain produce more high-quality HeP than is consumed in production. Accordingly, beef is a net contributor to meeting human protein requirements.

Key words: beef value chain, human-edible protein, methane, net protein contribution, protein quality

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INTRODUCTION

Beef products are frequently maligned by consumers as a source of protein in human diets due to concerns surrounding feed-food competition, environment, or inefficient production systems. Low-quality proteins found within plant biomass and coproducts are upcycled by cattle and converted into beef, a high-quality protein source for humans (Oltjen and Beckett, 1996; Wilkinson, 2011; Ertl et al., 2015a). Understanding the protein quality of beef relative to other protein sources in human diets is essential to understanding the impacts of the beef value chain on human food supply. Beef products provide a more complete source of dietary protein (i.e., greater biological value) than plant sources, which contain insufficient levels of indispensable amino acids (Young and Pellett, 1994).

Developing methods of accurately accounting for beef's contribution to human nutrient supplies and for the costs associated with beef production is essential for addressing societal concerns and optimizing sustainability. Bywater and Baldwin (1980) redefined feed efficiency of livestock by accounting for human-edible proteins (**HePs**) and energies consumed and produced, and Ertl et al. (2016a) built on Wilkinson's (2011) work by accounting for quality of HeP and by predicting net protein contribution (**NPC**). Ertl et al. (2016b) reported dairy cows and beef cattle to have the greatest NPC followed by poultry and swine.

Peters et al. (2014) utilized a systems approach to estimate feed efficiencies and land-use efficiencies for major livestock species in the United States. However, these estimates are based on atypical beef cattle diets. We are not aware of reported estimates of the NPC of beef cattle managed in conventional U.S. production systems. Therefore, the objective of this study was to accurately model the contribution of beef cattle to meeting human protein requirements and compare our estimates with the same measures used by Peters et al. (2014).

MATERIALS AND METHODS

Model Overview

A summative model of NPC was used to estimate beef's contribution to meeting human protein requirements. This model incorporates common production practices in the United States and prediction equations established by National Academies of Sciences, Engineering, and Medicine (NASEM) (2016). Calves from the cow–calf phase flowed into the stocker phase, and calves from the stocker phase flowed into the feedlot phase. Therefore, the cow–calf phase was representative of an entire production year, and the stocker and feedlot phases were representatives of the time the calves occupied those facilities.

In our model, we include production parameters consistent with common beef cattle practices combined with the systems approach of Peters et al. (2014). In addition, we use methodology presented by Wilkinson (2011) and Ertl et al. (2015b, 2016a, 2016b) to estimate the NPC to the human food supply from various beef cattle production scenarios in the United States.

Conversion Efficiency of Beef Cattle

Human-edible protein produced (**HeP_p**) was calculated for each production phase and for the whole production system. Estimation of body protein (**BP**) from empty BW (**EBW**) is a quadratic function where a greater proportion of gain is deposited as fat instead of protein as BW increases. Therefore, to predict HeP_p for each size of animal, BP was estimated from an equation presented in Simpfendorfer (1974) and NASEM (2016) using EBW:

$$\text{BP, kg} = \left(0.235\text{EBW} - 0.00013\text{EBW}^2 - 2.418\right)$$

EBW was defined as the weight of an animal with the gastrointestinal tract emptied of digesta. EBW includes inedible byproducts (**IBP**) such as the hide, skull, blood, feed, trachea, lungs, small intestine, large intestine, spleen, and mesenteric fat, which represent 25.0%, 24.2%, and 22.1% of EBW in steers, heifers, and cull cows, respectively (Terry et al., 1990; Apple et al., 1999). Accordingly, the inedible fraction of EBW was removed after calculation of BP using the equation:

$$HeP_p,\text{kg} = \text{BP} \times (1\text{-IBP})$$

In the cow–calf phase, HeP_p was estimated from weaned calves (excluding heifers kept as replacements), cull cows, and cull bulls. The amount of HeP_p in the stocker and feedlot phases was the difference in the calculated beginning and ending HeP_p. This difference results in the marginal gain of HeP_p during these time periods, and marginal gains were estimated such that HeP_p, in the form of beef, is related to HeP consumed (**HeP_f**) as feed during each phase by the production functions associated with feed utilization.

To quantify HeP removed from human food supply by the beef value chain, total HeP_f by the value chain is required. Intakes of all classes of beef cattle represented in the model system were estimated using equations from NASEM (2016). Feedstuffs with nutrient compositions presented by NASEM (2016) were classified as edible, partially edible, or inedible using criteria according to Wilkinson (2011) and Ertl et al. (2016b; Table 1). Calculations of HeP_f were conducted according to Ertl et al. (2016b). For partially edible feedstuffs (e.g., corn silage, which contains some amount of corn grain that is potentially edible by humans), a fraction of the feedstuff was estimated to be edible based on available literature (Wilkinson, 2011; Ertl et al., 2016a). In total, 54 of 176 feedstuffs available for use in our model were estimated to be at least partially human edible. If animals consumed multiple diets within a sector, HeP_f was summed. Similarly, to calculate total HeP_f for the value chain, HeP_f was summed across production sectors.

Conversion of HeP_f into beef is an important metric to compare. Calculation of the HeP conversion efficiency (**HePCE**; Ertl et al., 2016b) was as follows:

$$\text{HePCE} = \frac{HeP_p}{\text{HeP}_f}$$

The entire production system's HePCE was calculated as the sum of HeP_p from all phases divided by the sum of HeP_f from all phases.

Assessing Protein Quality Using Digestible Indispensable Amino Acid Score

To assess protein quality of human-edible feedstuffs commonly found in beef cattle diets and of human-edible beef, the following equation from FAO (2011) was used:

$$\text{DIAAS} = \frac{\text{mg of digestible indispensable amino acid in 1 g of dietary protein}}{\text{mg of same digestible indispensable amino acid in 1 g of reference protein}} \times 100$$

where, DIAAS = digestible indispensable amino acid score, %.

Digestible indispensable amino acids were considered as any of the 10 indispensable amino acids. There is limited information on human digestibility of indispensable amino acids from feedstuffs common in beef cattle diets; thus, the methods of Ertl et al. (2016b) were followed, and an equation to convert amino acid digestibility measured in swine to human amino acid digestibility estimates was used (Deglaire and Moughan, 2012). Similar to Ertl et al. (2016b), the reference protein used in this model was the requirement published by the FAO (2011) for children between the ages of 0.5 and 3 yr. Feedstuffs were assigned a DIAAS for each of the 10 indispensable amino acids. When formulating diets for cattle, a weighted average of the DIAAS for human-edible feed ingredients was calculated for each amino acid. The smallest DIAAS for a single indispensable amino acid was assigned as the diet DIAAS on the premise of first limiting amino acid and used in calculation of the protein quality ratio (**PQR**).

The output product, beef, has a DIAAS of 112, indicating that it has an amino acid profile that exceeds the requirements of a child (reference protein). PQR captures the change in biological value of HeP that occurs when plant-derived HeP is converted to beef:

$$\text{PQR} = \frac{\text{DIAAS of beef}}{\text{DIAAS of diet}}$$

A PQR was calculated for each sector of the value chain. When calculating the PQR of the beef value chain, the PQR was weighted based on the proportion of total HeP_f in each production sector.

Net Protein Contribution

NPC was calculated by multiplying the ratio of HeP in beef to the HeP in feedstuffs by the PQR:

$$\text{NPC} = \text{PQR} \times \text{HePCE}$$

An NPC greater than 1 indicates that the value chain is positively contributing to meeting human requirements, whereas an NPC less than 1 indicates

Table 1. Human-edible fraction and DIAAS of feed ingredient

Item	Human-edible fraction* (%)	DIAAS
Pasture	0	—
Bermudagrass, fresh	0	—
Cottonseed meal	0	—
Corn	100	36.8
Wheat forage fresh	0	—
Distillers' grains	0	—
Alfalfa hay	0	—
Corn silage	50	36.8
Steam-flaked corn	100	36.8
Distillers' grains with solubles	0	—
Molasses	100	5.9
Urea	0	—
Mineral per additives	0	—
SBM	100	96.0
Tallow	0	—

*Percent of feed ingredient that is human-edible.

the beef value chain is competing with humans for protein.

Scenario Design

Scenarios were arranged as a 2 × 2 factorial with two sets of dietary inputs and two sets of production parameters. Dietary inputs were either ingredients used in Peters et al. (2014; previous diet [**PD**]) or current diet (Table 2; current diet [**CD**]). Production parameters were from Peters et al. (2014; previous parameters [**PP**]) or parameters characterizing the current industry (Table 3; current parameters [**CP**]). Thus, scenarios compared were 1) diets and production parameters by Peters et al. (2014; previous model diets and production parameters [**PDPP**]), 2) current industry diets and production parameters by Peters et al. (2014; current industry diet, previous model production parameters [**CDPP**]), 3) diets by Peters et al. (2014) and current industry production parameters (previous model diet, current industry production parameters [**PDCP**]), and 4) common current industry diets and production parameters (**CDCP**). These four scenarios (PDPP, CDPP, PDCP, and CDCP) were compared based on a 1,000 cow herd.

Table 2. Composition of diets fed in model scenarios

Item	Dietary input*	
	Peters	Current
Cow–calf, % AF basis		
Pasture	99.99	
Bermudagrass, fresh		98.00
Cottonseed meal		1.99
Corn grain (filler in mineral)	0.01	0.01
Stocker, % AF basis		
Pasture	86.17	
Wheat forage fresh		97.50
Corn grain	13.83	1.00
Distillers' grains		1.50
Receiving period (in feedlot), % AF basis		
Alfalfa hay		16.70
Corn silage		26.36
Steam-flaked corn		18.01
Distillers' grains with solubles		35.24
Molasses		1.76
Urea		0.53
Mineral per additives		1.41
Finishing diet, % AF basis		
Pasture	8.65	
Alfalfa hay		2.12
Corn silage		20.43
Steam-flaked corn	85.35	42.24
SBM	6.00	
Distillers' grains with solubles		29.58
Urea		0.72
Molasses		2.79
Mineral per additives		1.49
Tallow		0.62

*Peters = diets from Peters et al. (2014); Current = current industry diets; AF = as-fed.

Production Parameters

Production parameters and BW of scenarios evaluated in this study are presented in Tables 3 and 4, respectively. A deterministic model with stocks and flows of cattle was constructed to represent the entire beef cattle value chain. The cow–calf sector contained a support population to produce calves and supply to the stocker sector. For all scenarios, the production period was 365 d (a full production cycle) for the cow–calf sector. For PP scenarios, BW and production parameters were used from Peters et al. (2014). For CP scenarios, calving rates, calf mortality rates before weaning, and weaning weights were estimated as the weighted average based on population sizes of southern and northern states using Standard Performance Analysis (SPA) and FINBIN data (Texas A&M AgriLife Extension, 2016; FINBIN, 2017). Mortality rates for cows were based on Rogers et al. (1972). Cow slaughter and cow inventory numbers reported by USDA-NASS (2017) were averaged for the past 10 yr and used to impute the culling rate. Replacement heifer retention rate was calculated using the 10-yr average for replacement heifers and beef cow inventory (USDA-NASS, 2017).

Cattle are transferred from the growing subsystem to the feedlot subsystem once cattle reached a desired placement weight. To accurately represent the industry, a portion of calves (22.8%) from the cow–calf subsystem flowed directly into the feedlot phase (calf-fed) for CP scenarios (USDA-NASS, 2017). In the growing subsystem, pasture was grazed for 120 d for PP, and wheat pasture was grazed for 154 and 129 d for PDCP and CDCP, respectively. Days on feed for PP scenarios in the feedlot subsystem were 155 d (Peters et al., 2014). For PDCP and CDCP, days on feed were 150 and 159 d, respectively (including a 28-d receiving and transition period). Days on feed for cattle in CP scenarios for both the stocker and feedlot phases were dependent on gain prediction equations from NASEM (2016), initial BW, and final BW. Cattle mortality rate for PP was 1.3%. Cattle placed at lighter weights (<272 kg) were assigned a greater mortality rate (2.00%) than cattle placed at heavier weights (1.3%; Engler et al., 2014).

Table 3. Production and management parameters for scenarios evaluated

	Dietary input*			
	Peters		Current	
	PDPP	PDCP	CDPP	CDCP
Cow–Calf Parameters				
Days on feed, d	365	365	365	365
Age of calf at weaning, d	207	207	207	207
Cows per bull	24	24	24	24
Calving rate, %	91.5	88.6	91.5	88.6
Calf mortality rate, %	3.6	4.0	3.6	4.0
Mortality rate, %	1.5	2.8	1.5	2.8
Cow culling rate, %	9.7	10.2	9.7	10.2
Calves sent direct to feedlot, %	0.0	22.8	0.0	22.8
Calves sent to stocker, %	100.0	77.2	100.0	77.2
Replacement heifers per cow	0.11	0.19	0.11	0.19
Stocker parameters				
Days on feed, d	120	154	120	129
Mortality rate, %	0.5	1.5	0.5	1.5
Feedlot parameters				
Days on feed, d	155	150	155	159
Mortality rate (heavyweight)†, %	1.5	1.3	1.5	1.3
Mortality rate (lightweight)†, %	1.5	2.0	1.5	2.0

PDPP = previous model diets and production parameters; CDPP = current industry diet, previous model production parameters; PDCP = previous model diet, current industry production parameters; CDCP = current industry diets and production parameters.

*Peters: diets from Peters et al. (2014); Current: current diets fed in the industry.

†Heavyweight = calves placed weighing more than 272 kg; Lightweight = calves placed weighing less than 272 kg.

Table 4. BW of each animal class in the production system used in the model

	Dietary input*			
	Peters		Current	
Item	PDPP	PDCP	CDPP	CDCP
BW, kg				
Mature cow	544	571	544	571
Bull	907	907	907	907
Weaned steer	254	253	254	253
Weaned heifer	238	240	238	240
Heifer at breeding	354	342	354	342
Steer entering feedlot	349	360	349	360
Heifer entering feedlot	316	326	316	326
Finished steer	603	649	603	649
Finished heifer	530	588	530	588

PDPP = previous model diets and production parameters; CDPP = current industry diet, previous model production parameters; PDCP = previous model diet, current industry production parameters; CDCP = current industry diets and production parameters.

*Peters: diets from Peters et al. (2014); Current: current diets fed in the industry.

Diet Descriptions

Diets and intake levels for each scenario considered in this article are presented in Tables 2 and 5, respectively. In the cow–calf subsystem, all scenarios assumed that cows, bulls, and replacement heifers all consumed pasture. Scenarios PDCP, CDPP, and CDCP also assumed calves grazed pasture while consuming milk each day, whereas PDPP assumed calves only consumed milk until weaning. In addition to pasture, all cattle in CD scenarios were fed a protein supplement (cottonseed meal) as well. Although PD scenarios only consumed pasture in Peters et al. (2014), mineral with a trace amount of corn was included in our model to allow for calculation of HePCE by creating a nonzero denominator.

During the stocker phase, PD scenarios grazed pasture and were supplemented corn, whereas the CD scenarios grazed winter wheat pasture and

Table 5. Intake estimates for each stage of production and scenario

	Dietary input*			
	Peters		Current	
	PDPP	PDCP	CDPP	CDCP
Cow–calf intakes, kg DM/d				
Heifer calf		3.27	3.26	3.28
Steer calf		3.41	3.42	3.42
Replacement heifers	8.16	7.18	7.39	7.20
Dry cow	11.62	10.38	10.01	10.40
Lactating cow	11.62	12.74	12.36	12.75
Bull	15.93	18.43	18.45	18.45
Stocker, kg DM/d				
Heifer	6.34	6.45	6.43	6.52
Steer	6.84	6.85	6.86	6.92
Feedlot, kg DM/d				
Heifer	7.95	9.72	8.15	9.21
Steer	8.87	10.73	9.17	10.17

PDPP = previous model diets and production parameters; CDPP = current industry diet, previous model production parameters; PDCP = previous model diet, current industry production parameters; CDCP = current industry diets and production parameters.

*Peters = diets from Peters et al. (2014); Current = current industry diets.

were supplemented a mixture of corn and dried distillers' grains (**DDG**).

Calf-fed cattle (CDCP and PDCP) received a growing ration consisting mainly of corn silage, corn stalks, alfalfa hay, DDG, and modified wet corn gluten feed. In the feedlot, PD scenarios were fed a total mixed ration containing forage, corn, and soybean meal (**SBM**). Common ingredients reported by Samuelson et al. (2016) were used when formulating diets for CD scenarios. Feedlot diets consisted of steam-flaked corn, DDG, alfalfa hay, and corn silage (Samuelson et al., 2016). Cattle newly received in feedlots rarely start out on their final finishing diet, thus over a 28-d period, cattle were fed a series of four different diets (7 d each) where roughage decreased from 40% to approximately 8% of DM (CD scenarios; Samuelson et al., 2016).

Enteric Methane Production

On the basis of diet consumed and proportion of forage, total enteric methane production (in kg) was calculated according to equations from NASEM (2016). The NASEM (2016) categorizes equations for methane production into three categories: 1) >40% forage in the diet, 2) 20% to 40% forage in the diet, and 3) <20% forage in the diet. Thus, equations presented in NASEM (2016) within each category were averaged according to percent of forage in the diet. Total enteric methane production was reported per kilogram HeP to scale environmental effects to human-edible production. Summation of enteric methane production and HeP was used to calculate enteric methane per kilogram HeP for the entire beef cattle value chain. Equivalents of CO_2 were calculated as methane (kilogram) multiplied by 25 (IPCC, 2007).

RESULTS AND DISCUSSION

Protein Quality and PQR

A DIAAS was estimated for each diet fed and the human-edible portion of a beef carcass, while protein quality conversion was quantified as PQR (Table 6). The DIAAS (%) represents the ability of a human-edible feedstuff to meet the protein requirements of a child 0.5 to 3 yr of age. Human-edible feedstuffs used in beef cattle diets have relatively low DIAAS (diet DIAAS ranged from 35.31 to 52.46), whereas beef is high quality (DIAAS of 112.00). Corn was the only HeP source fed in the cow-calf and stocker sectors for all scenarios evaluated; accordingly, the DIAAS of corn (36.81) was the diet DIAAS in both sectors. Furthermore, with the DIAAS of beef fixed at 112.00 both sectors, in all scenarios, had a PQR of 3.04. For the feedlot sector, the DIAAS of diets were 35.49 and 52.80 for CD and PD scenarios, respectively. In the PD scenarios, corn and SBM were the sources of HeP, whereas corn was the primary human-edible feedstuff in the CD scenarios. The protein source in feedlot diets was changed from SBM for PD to distillers' grains with solubles for CD based on survey data from Vasconcelos and Galyean (2007) and

Table 6. Estimation of PQR, HePCE, and NPC of scenarios*

	Dietary input†			
	Peters		Current	
Item	PDPP	PDCP	CDPP	CDCP
Cow–calf				
Diet DIAAS	36.81	36.81	36.81	36.81
PQR	3.04	3.04	3.04	3.04
Total HeP_f, kg/herd	9.85	11.66	10.78	11.36
Total HeP_p, kg/herd	32,660	30,004	32,660	30,004
HePCE	3,314.56	2,573.51	3,030.53	2,640.83
NPC	10,086.17	7,831.15	9,221.86	8,036.00
Stocker				
Diet DIAAS	36.81	36.81	36.81	36.81
PQR	3.04	3.04	3.04	3.04
Total HeP_f, kg/herd	15,380	9,653	1,356	1,021
Total HeP_p, kg/herd	7,300	5,319	7,300	5,328
HePCE	0.47	0.55	5.39	5.22
NPC	1.44	1.68	16.39	15.88
Feedlot				
Diet DIAAS	52.98	52.61	35.46	35.51
PQR	2.11	2.13	3.16	3.15
Total HeP_f, kg/herd	104,868	102,361	56,501	53,125
Total HeP_p, kg/herd	15,094	18,252	15,094	18,105
HePCE	0.14	0.18	0.27	0.34
NPC	0.30	0.38	0.84	1.07
Beef value chain				
PQR	2.20	2.19	3.16	3.15
Total HeP_f, kg/herd	120,258	112,026	57,867	54,128
Total HeP_p, kg/herd	55,054	53,575	55,053	53,437
HePCE	0.46	0.48	0.95	0.99
NPC	1.01	1.05	3.00	3.11

PDPP = previous model diets and production parameters; CDPP = current industry diet, previous model production parameters; PDCP = previous model diet, current industry production parameters; CDCP = current industry diets and production parameters.

*Results are estimated for a 1,000 cow herd.

†Peters = diets from Peters et al. (2014); Current = current diets fed in the industry.

Samuelson et al. (2016). SBM provides more digestible indispensable amino acids compared with corn, resulting in a greater DIAAS 96.00 vs. 36.81 for corn. Slight differences between CDPP (35.46) and CDCP (35.51) occurred because step-up and transition diets are commonly utilized in the feedlot sector (Samuelson et al., 2016; CP), but PP scenarios did not include this production practice. A slight difference in DIAAS and PQR occurred for PDPP (52.98 and 2.11) and PDCP (52.61 and 2.13) as well. Ultimately, PQR for PD and CD scenarios in the feedlot sector was 2.12 and 3.15, respectively. Across the entire beef value chain, PQR was 2.20 and 3.15 for PD and CD scenarios, respectively. The PQR for the entire beef value chain closely reflects the PQR of the feedlot sector because PQR was weighted based on where HeP was consumed with the feedlot consuming approximately 83% to 97% of HeP (PDPP and CDCP, respectively). Regardless of production sector or scenario, protein quality of beef (DIAAS of beef) was greater than the protein quality of the diet consumed by the cattle.

HeP Consumption, Production, and Conversion

Cow–calf operations typically graze pasture and rangeland, both of which are inedible to humans. However, a small amount of HeP was incorporated as a component of mineral supplementation in the cow–calf diets to avoid a HePCE of infinity, which would realistically be attainable for many cow–calf operations. Intake of HeP (HeP_f) was slightly lower for PDPP (9.85 kg of HeP_f) than CDPP (10.78 kg of HeP_f) because intakes in the CD scenarios were predicted from NASEM equations rather than assumed by Peters et al. (2014). In addition, slight differences in HeP_f

between PP and CP scenarios were a result of the CP scenarios accounting for calf intake of mineral. In the stocker sector, calves are often supplemented with human-edible grains while grazing pasture (Grigsby et al., 1991; Horn et al., 1995). HeP fed in the stocker sector averaged 1,189 kg for CD scenarios and was 10,716 kg of HeP_f for PD scenarios, resulting from a greater amount of corn being fed to stocker calves in PD than CD. In CP scenarios, 22.8% of weaned calves went directly to the feedlot, which resulted in lower HeP_f for CDCP (1,021 kg of HeP) and PDCP (9,653 kg of HeP_f) than CDPP (1,356 kg of HeP_f) and PDPP (15,380 kg of HeP_f). In the feedlot, HeP_f for PD scenarios was approximately 103,615 kg and 54,813 kg for CD. This corresponds to approximately 80% of the feedlot's diet being human-edible for PD scenarios and 40% of diet for CD scenarios. Human-edible feedstuffs are fed in the feedlot more than in other sectors of production because corn and other human-edible concentrates provide low-cost, readily available energy to promote growth and minimize time spent in the feedlot. Total system HeP_f was primarily driven by diet (55,998 and 116,142 kg of HeP_f on average for CD and PD, respectively), with the majority of HeP_f (ranging from 83% to 97%) being consumed in the feedlot phase.

Altering production parameters (PP vs. CP) was more influential in determining HeP_p by beef cattle than changing diets (Table 6). Weaned calves, cull cows, and cull bulls contributed to HeP_p in the cow–calf sector, where the greatest proportion of HeP was produced (56%). Production of HeP was less for CP than PP (30,007 vs. 32,660 kg of HeP_p) and resulted from lower calving rate, greater mortality rates of cows and calves, and greater heifer retention rates for CP scenarios. In the CP scenarios, 22.8% of calves went directly to the feedlot, resulting in lower HeP_p for CP than PP (5,328 and 7,300 kg of HeP_p, respectively) during the stocker phase. Accordingly, 33.9% of HeP_p was produced in the feedlot for CP and 27.4% for PP. While PP scenarios had greater HeP_p in cow–calf and stocker sectors, CP had greater HeP_p in the feedlot sector. Total HeP_p for the beef value chain was similar between scenarios at 55,054 and 53,440 kg of HeP_p for PP and CP, respectively.

HePCE in the cow–calf sector was the greatest for PDPP (3,315). Calf intakes were accounted for using NASEM (2016) equations in the CDPP scenario resulting in a lower HePCE of 3,031. The PDCP and CDCP scenarios had the lowest HePCE (2,574 and 2,641, respectively) because of increased mortality rates (causing decreased HeP_p) and increased BW (causing increased estimates of HeP_f) that more closely reflect the current industry and its practices. This should not be taken to suggest that current practices actually increase mortality rates vs. some other system; rather, the CP parameters reflect observed conditions rather than hypothetical systems represented by PP.

Stocker sector HePCE was 0.51 and 5.30 for PD and CD scenarios, respectively. The PDPP and PDCP had a HePCE below 1.00 (0.47 and 0.55, respectively), meaning these scenarios were consuming more HeP than was being produced. The HePCE was greater for PDCP because updating production parameters did not impact HeP_p as much as HeP_f. Lower amounts of HeP_f in CDPP and CDCP resulted in a greater HePCE in these two scenarios (5.39 and 5.22, respectively), where CDPP was greater than CDCP because of updating production parameters, specifically mortality rates. Although our estimates of HePCE for grazing systems were 5.22 (stocker) and 2,641 (cow–calf sector), Mottet et al. (2017) reported a ratio of 2.00 for grazing systems from 34 different countries, but it was estimated that 223 kg of concentrate were fed per animal per year, which was greater than what was estimated our model. All scenarios in the feedlot sector produced less HeP than consumed (HePCE of 0.23, on average). The CDCP scenario had the greatest HePCE (0.34), and PDPP had the lowest (0.14). Ertl et al. (2016b) evaluated Austria's growing–fattening bulls production system (similar to a feedlot system) and calculated a HePCE of 0.45, greater than these scenarios. Mottet et al. (2017) estimated HePCE of 0.24 in feedlots across 34 developed countries. In the CDCP scenario, 40% of the total feedlot diet was human edible; Mottet et al. (2017) estimated that 62% of feedlot diets were human edible worldwide. A possible explanation of this discrepancy is that nonhuman-edible feed ingredients such as distillers' grains that are widely available in the United States are not available in other countries because the United States produces nearly 45% of the biofuel produced worldwide (Makkar, 2012). It is also likely that these estimates are derived from indirect estimates or include certain grain coproducts (corn milling products, for example) as direct grain feeding, not accounting for the use of coproducts adequately.

Alternatively, production systems in other countries may not be as intensively managed, thus cattle require more days on feed and maintenance comprises a greater proportion of energy and protein use. In a model where cattle gained 1 kg/d, inclusion of 50% coproducts in the concentrate portion of diet increased HePCE from 0.70 to 1.3 (Flachowsky et al., 2017). Greater HePCE reported by Flachowsky et al. (2017) than in our model results from low inclusion level of concentrate (15%) in their modeled diets. Wilkinson (2011) reported a HePCE (0.33) similar to PD scenarios, mainly because a 96% of dietary ingredients fed were concentrates and 36% of protein fed was HeP. Clearly, accurate assessment of diets is imperative to the adequate representation of efficiency of protein production, especially in ruminant systems, where significant variability in dietary ingredient selection exists both within and among regions and production systems.

Overall, HePCE of the beef value chain was 0.47 for PD and 0.97 for CD, and CDCP produced 0.99 kg of HeP in beef for every 1 kg of HeP_f. Ertl et al. (2016b) reported a greater HePCE of 1.52 for the Austrian beef production system. Differences in our model compared with Ertl et al. (2016b) could be contributed to production practice differences between countries. The United States employs a more intensified system in the finishing stages, but cow–calf and stocker sectors are typically extensive systems with very few human-edible inputs (0.001% and 1.11% of dietary protein were human edible, respectively). In contrast, Austria's cattle production system (excluding the finishing phase) fed a greater amount (9%) of dietary protein as HeP. In an extensive production system, such as upland suckler beef production in the United Kingdom, HeP was fed in relatively large amounts as well (674 kg of concentrate per head) compared with the more extensive grazing-based production systems (cow–calf and stocker sectors) in the United States, which resulted in a HePCE of approximately 1.09 for that system (Wilkinson, 2011).

Net Protein Contribution

The cow–calf, stocker, and feedlot sectors positively contributed to meeting human protein requirements as indicated by NPC > 1 when CD scenarios were used. Overall, the cow–calf sector had the greatest NPC (8,793.80) when compared with stocker and feedlot sectors (8.85 and 1.01, respectively), The PDPP scenario had the greatest NPC (10,086.17) in the cow–calf sector, and updating parameters and diets resulted in an intermediate NPC of 8,036.00 (CDCP). For the stocker sector, an NPC of 1.56 and 16.14 for PD and CD, respectively, were estimated. A greater NPC for CD resulted from reduced utilization of feedstuffs containing HeP in the CD scenarios. In contrast, NPC of the feedlot sector for PDPP, PDCP, and CDPP was 0.30, 0.38, and 0.84, respectively. During the finishing phase, these three scenarios did not positively contribute to meeting human protein requirements and were competing with humans for HeP. However, the NPC for CDCP (1.07) was greater than one, indicating this scenario was positively contributing to addressing human protein requirements. Updating both diets and production parameters (CDCP) resulted in the greatest NPC for the feedlot sector (1.07). The growing–fattening bulls system in Austria had similar results to CDPP (0.84), where it was estimated that the NPC was 0.73 for the system (Ertl et al., 2016b), and these were not contributing to HeP supply.

NPC for the entire beef value chain was above one for all scenarios, indicating each scenario was positively contributing to human protein requirements. Although the feedlots were in competition with humans for HeP (NPC of 0.34 for PD scenarios), it was outweighed by the stocker and cow–calf sectors' ability to positively contribute to the human food supply by using less HeP and improving the protein quality. The CDCP had the greatest NPC (3.11), and PDPP had the lowest NPC (1.01). Ertl et al. (2016b) reported an NPC value of 2.81, which is slightly lower than the CD scenarios (3.05). Because the protein quality of HeP_f in Austria was likely greater than in our scenarios as indicated by the lower PQR (1.84 vs. 3.16) in Ertl et al. (2016b), this decreased the contribution of the production system to the human food supply relative to our model.

Enteric Methane Production

To illustrate the impact of increasing HePCE, enteric methane production was estimated. Approximately 81% of the total methane produced in the beef production system was produced by the cow–calf sector (Table 7). Similarly, Beauchemin et al. (2010) found 79% of methane emissions from beef production in western Canada came from the cow–calf sector. Stackhouse-Lawson et al. (2012) estimated lower values, where 69% to 72% of methane was produced by the cow–calf sector. In addition, a cow produces about 55 kg of methane per year (Crutzen et al., 1986; Capper, 2011), which is about half as much as our model estimated for cows in the cow–calf sector. Scenarios CDPP, PDCP, and CDCP (128,227 kg of methane) accounted for calf intake and methane production before weaning, whereas PDPP did not (114,118 kg). In the stocker sector, CDCP had the lowest methane production

Table 7. Effect of dietary inputs and production parameters on methane production in the beef cattle value chain*

	Dietary input†			
	Peters		Current	
Item	PDPP	PDCP	CDPP	CDCP
Cow–calf				
Methane, kg/herd	114,118	128,431	129,201	127,048
Methane, kg/kg of HeP_p	3.49	4.28	3.96	4.53
CO_2 equivalents/kg of HeP_p	87.35	123.80	108.26	127.67
Stocker				
Methane, kg/herd	13,498	12,326	13,446	10,085
Methane/kg of HeP_p	1.85	1.59	1.84	1.89
CO_2 equivalents/kg of HeP_p	46.22	39.70	46.05	47.32
Feedlot				
Methane, kg/herd	14,652	17,045	15,057	16,946
Methane, kg/kg of HeP_p	0.97	0.89	1.00	0.94
CO_2 equivalents/kg of HeP_p	24.27	22.19	24.94	23.55
Beef value chain				
Methane, kg/herd	142,268	157,802	157,704	154,079
Methane, kg/kg of HeP_p	2.58	2.86	2.86	3.05
CO_2 equivalents/kg of HeP_p	64.60	80.83	77.17	84.38

PDPP = previous model diets and production parameters; CDPP = current industry diet, previous model production parameters; PDCP = previous model diet, current industry production parameters; CDCP = current industry diets and production parameters.

*Results are estimated for a 1,000 cow herd.

†Peters = diets from Peters et al. (2014); Current = current diets fed in the industry.

(10,085 kg) because 22.8% of calves went directly to the feedlot and the diet was more digestible when compared with other scenarios (13,090 kg). In this case, both production parameters and diet impacted methane production. In the feedlot, PDCP and CDCP scenarios had greater methane production (17,045 and 16,946 kg, respectively) than PDPP (14,652 kg) and CDPP (15,057 kg). Greater feedlot methane values for CP vs. PP result from the direct placement of 22.8% of calves in the feedlot. In contrast to the stocker sector, the dietary composition of the high concentrate diet did not produce substantial changes in feedlot methane production. Overall, 152,963 kg of methane was produced in the beef value chain.

Methane was expressed per kilogram of HeP produced to weigh benefits and costs associated with beef production. In grass-fed production systems, Capper (2012) estimated 4.25 kg of methane per kilogram HeP_p, which agrees with our estimate of 4.53 kg of methane per kilogram of HeP produced for CDCP in the cow–calf scenario. The cow–calf sector produced 55% of HeP in the beef value chain, resulting in the cow–calf sector having a greater ratio of methane to HeP_p (4.53) than the stocker (1.89) and feedlot sectors (0.94). The stocker sector was intermediate to the cow–calf and feedlot sectors, the CDCP (1.89 kg of methane per kilogram of HeP_p) had a slightly higher ratio than all other scenarios (1.76 kg of methane per kilogram of HeP_p). In the feedlot, more HeP (kilogram) was produced than methane (kilogram; 0.94 kg of methane per kilogram of HeP_p in CDCP). Across the entire beef value chain, 3.05 kg of methane per kilogram of HeP was produced in CDCP, which is greater than the estimates of Capper (2011, 2012) of 2.76 and 2.51 kg of methane per kilogram of HeP_p for beef production in the United States in 2007.

In the entire beef value chain, CO_2 equivalents from enteric methane ranged from 61.60 (PDPP) to 84.38 kg (PDCP). A range from 75 to 170 kg of CO_2 equivalents per kilogram of HeP was suggested by de Vries and de Boer (2010), suggesting systems modeled in this study may have less of an environmental impact than production systems evaluated in the United Kingdom. Data used to estimate findings from de Vries and de Boer (2010) came from primarily European grass-fed studies, and Capper (2012) established more CO_2 equivalents were produced in grass-fed systems compared with a more intensive beef production system.

CONCLUSIONS

Cow-calf production consumes the least amount of HeP resulting in the greatest efficiency of HeP conversion and positively contributes to meeting human protein requirements. Mostly, methane and HeP were produced in the cow–calf sector, indicating that there are trade-offs between environmental costs and benefits of beef production. Of the three production phases evaluated, the feedlot sector competed the most with humans for HeP and did not contribute more HeP than consumed. However, as more HeP was incorporated into feedlot diets, methane production was decreased. Despite relatively less efficient conversions of HeP in the feedlot, this sector was still more efficient than nonruminant systems that are typically reported to have more efficient feed conversion (Mottet et al., 2017). When evaluated as a whole, the beef value chain is a net contributor to the HeP available for human consumption. Furthermore, the quality of the HeP produced was enhanced throughout the beef value chain. Although for some stocker scenarios and the feedlot sector, the HePCE was low (less than one), the ability of cattle to upcycle protein from low quality to high quality allowed for these sectors to have an NPC of greater than one. On the basis of the scenario of current industry diets and parameters, our results suggest that each individual beef sector and the entire beef value chain produce more high-quality HeP than is consumed in production as noted by an NPC above one. The beef production system is a net contributor to the human protein supply and likely a more efficient converter than nonruminant systems.

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